

Implications of Carbon Capture and Storage in Thermoelectric Power Plants

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Abstract: The increase in the concentrations of Greenhouse Gases (GHG) which includes Carbon dioxide (CO₂) as the main GHG is considered one of the most important environmental problems for this reason, opportunities must be identified to improve carbon capture and management. The objective of this research is to present an approach to the topic of carbon capture and storage (CAC), analyzing the Colombian thermoelectric sector and looking at the existing opportunities for its possible application. This is done through a literature review that includes topics from environmental management and carbon management to fossil fuel-based energy generation and capture, likewise, a review is made of recent reports on climate change and CO₂ emissions ending with the implementation of a CO₂ capture system in a power generation project located in the Zulia area, in the Department of Norte de Santander (Colombia). In the results we find that Colombia does not currently have long-term solutions for carbon management in the energy sector based on fossil fuel. Likewise, the evaluation of the implementation of a CAC system could be developed for those plants that are located near industries that require significant amounts of CO₂ and/or in the vicinity of areas that have the potential and geological characteristics required to store the CO₂ captured.

Key words: Captures carbon, greenhouse gases, environmental management, thermoelectric plants, Zulia area, Colombia

INTRODUCTION

Global warming refers to the recent and continuous increase in the global average temperature near the Earth's surface which is mainly caused by the increase in the concentrations of greenhouse gases in the atmosphere (Ming *et al.*, 2014; Anwar *et al.*, 2018; Sierra and Barrios, 2013). Global warming is causing climate patterns to change, however, global warming itself is only one aspect of climate change (Akorede *et al.*, 2012; Cotana *et al.*, 2014; De-Richter *et al.*, 2017). On the other hand, Carbon dioxide (CO₂) is the main greenhouse gas that contributes to global warming which is produced by anthropogenic activities such as the burning of fossil fuels to generate energy, deforestation, industrial type and some agricultural practices (Akorede *et al.*, 2012; Cotana *et al.*, 2014; De-Richter *et al.*, 2017; Semenchuk *et al.*, 2019).

According to the above and to the extent that organizations worldwide have achieved greater knowledge about the environmental impact due to CO₂ emitted by the development of their activities, it has been observed that the quantification and management of CO₂ in terms of quantities total is a factor of relevance for the development of its businesses in scenarios of low carbon production (Winter, 2014; Ozgen and Caserini, 2018).

Currently, there are studies and methodologies developed to be applied to companies from different sectors of the economy which have structures on carbon management (Jurburg *et al.*, 2018). Within these structures or principles include: measurement of CO₂ emissions, establishment of objectives, reduction, prevention, change of fuel, sequestration or capture of emissions assessment of the goals set, compensation of residual emissions and review. Other studies address the issue from the framework of environmental management,

grouping and addressing criteria for planning, implementation, control and auditing (Hannis *et al.*, 2017; Quattrocchi *et al.*, 2013; Becken and Mackey, 2017; Mendiara *et al.*, 2018).

In relation to companies in the energy sector, the Intergovernmental Panel on Climate Change (IPCC) has recommended the following options to reduce or mitigate CO₂ emissions: improvement in energy efficiency (including transport and power generation), increase in the use of renewable solar, wind, biomass, geothermal energy, change to less carbon intensive fossil fuels, continue the combustion of fossil fuels using carbon capture, improvement of biological sinks and reduction of GHG emissions other than CO₂ (Onyebuchi *et al.*, 2018; Anonymous, 2007).

Similarly, the International Energy Agency (IEA), also recommends the energy sector to implement a series of complementary policies including improving energy efficiency, motivate the preference of fuels that depend less on carbon, increase the participation of nuclear energy and non-conventional renewable energy sources, together with the massification of the implementation of CAC technology -CO₂ capture and storage (Kajaste and Hurme, 2016; Croci *et al.*, 2007).

Although, the developing countries are not part of the member countries that have internationally binding commitments regarding CO₂ emissions under the Kyoto Protocol, probably in the coming years, these countries will face greater demands at the international level to reduce its level of emissions (Kaygusuz, 2012; Anonymous, 2012; Huenteler *et al.*, 2016; Manni *et al.*, 2018).

Given that in Colombia, the capacity to generate energy based on processes that use fossil fuels (thermoelectric plants), corresponds to about 30% of the total (Guerra *et al.*, 2019) and that an increase in installation and operation of these is required. For the medium and long term, due to the reliability needs of the electrical system, international options and trends such as CAC technology should be considered within the analysis of investment in Colombia by electric power generating companies.

The objective of this study is to analyze the implications of the implementation of a carbon capture and storage system in the carbon management programs of thermoelectric plants located in the national territory. For the development of this researcher, an approach was made to the incidence of CO₂ emissions in the thermoelectric sector in Colombia and its current management, reviewing mitigation options and costs through carbon capture and storage technology and finally providing recommendations on the program of management and management of coal in thermoelectric plants.

Table 1: Profile by processes or industrial activities of the large stationary sources of CO₂ from around the world with emissions of more than 0.1 million tons of CO₂ (MtCO₂) per year

Process	No. of sources	Emissions (MtCO ₂ /year)
Fossil fuels		
Energy	4942	10539
Cement production	1175	932
Refineries	638	798
Steel industry	269	646
Petrochemical industry	470	379
Refining of oil and gas	Not available	50
Other sources	90	33
Biomass		
Bioethanol and bioenergy	303	91
Total	7887	13468

Carbon capture and storage (CAC): The concepts presented in this section address a brief description of the sources of CO₂ emissions, the recommended CO₂ mitigation options for use in the energy sector, description and state of the art of CAC technology, implementation experiences to global level and implementation costs.

Sources of Carbon dioxide (CO₂) emission: Human activities have caused the increase of CO₂ and other greenhouse gases during the industrial era (Anonymous, 2007; Liu *et al.*, 2016; Abdul-Wahab *et al.*, 2015; Anderson *et al.*, 2016). The observed increase in CO₂ concentrations does not reveal the real scope of human emissions, since, it only shows 55% of the CO₂ released by human activity, since, 1959 (De Larminat, 2016; Surugiu *et al.*, 2012; Wang and Zhao, 2018; Marescaux *et al.*, 2018), the rest has been absorbed by land plants and oceans of natural form in all cases, the balance between sources (gas emissions from human activities and those from natural systems) and sinks (the absorption of a gas from the atmosphere by conversion to a different chemical compound), determines atmospheric concentrations of greenhouse gases and their increases (Marescaux *et al.*, 2018; Adua *et al.*, 2016; Zhao *et al.*, 2016).

Of the figures presented by the Intergovernmental Panel on Climate Change (IPCC) as of 2007, 7.887 stationary sources of CO₂ were inventoried globally, whose emissions total 13.468 million tons of CO₂ per year which 78.25% come from sources of power generation as shown in Table 1.

The sources of power generation include power plants with technologies that transform natural gas, liquid fuels and coal, the latter being based on coal which have the highest CO₂ production in their processes. The emission factors of a coal plant correspond to 860 g CO₂/kWh (Anonymous, 2002).

CO₂ mitigation options for the energy sector: Mitigation and adaptation are two types of climate change response

policies which can be complementary, substitute or independent of each other. The technical mitigation potential is the amount in which it is possible to reduce GHG emissions by using a technology or practice that has already been demonstrated (Zhang *et al.*, 2017; Harde, 2017; Huo *et al.*, 2015; Feron, 2009).

The sector of electricity generation based on fossil fuels or that produce CO₂ during its transformation has a significant mitigation potential because it uses a wide range of technologies, therefore, for the energy sector, the IPCC has recommended the following options to reduce or mitigate CO₂ emissions (Giuliano *et al.*, 2018):

- Improvements in energy efficiency, including transportation and power generation
- Increase in the use of solar, wind, biomass, geothermal renewable energy
- Change to less carbon intensive fossil fuels
- Continue the combustion of fossil fuels using carbon capture
- The improvement of biological sinks (land use, land use change and forestry or by fertilization of the oceans)
- The reduction of greenhouse gas emissions other than CO₂

The IPCC indicates that the uptake and storage of CO₂ has considerable potential and that the costs derived from climate change mitigation measures can be reduced, compared to strategies that only consider other traditional mitigation options such as the exclusive incorporation of energies. Non-conventional renewable energy efficiency among others.

The generalized application of CAC will depend on the technological maturity reached, the costs of project development, the global potential of using this technology, the diffusion and transfer of technology to developing countries and their capacity to incorporate it. Regulations at the national and international levels, environmental issues and public perception of this technology.

On the other hand, in 2011, in the report of the conference of the parties at its seventh session held in Durban, the modalities and procedures for including the CAC as a project activity which are part of the mechanism for a clean development were approved. (CDM) which improves the possibilities of access to financing for this type of project. Together, it is established that the following technical requirements must be met in CCS project activities:

- Selection and characterization of the geological storage site

- Evaluation of risks and safety
- Surveillance
- Financing requirements
- Responsibility
- Environmental and socio-economic impact assessments

In the energy sector, most scenarios foresee that the primary energy supply will continue to be dominated by fossil fuels, until at least the middle of the century which places the CO₂ capture and storage (CAC) technology in a privileged position to achieve the objectives of stabilization in the emission levels of CO₂ globally (Anonymous, 2007; Stanger *et al.*, 2015; Muresan *et al.*, 2013; Bains *et al.*, 2017).

If the expected contribution from the application of CAC technology by sector is considered, the International Energy Agency (IEA) projects that 39.6% of the emission reduction will be in the electricity generation sector based on coal (Anonymous, 2002; Blanco *et al.*, 2018a, b; Al-Douri *et al.*, 2017).

CO₂ capture, transport and storage: CAC technology is a process that consists in the separation of the CO₂ emitted by the industry and sources related to energy, its transport to a place of storage and its isolation from the atmosphere in the long term. CAC technology when applied to industrial processes or power generation plants can reduce CO₂ emissions considerably (the highest target capture rates reach approximately between 85 and 90% (Li *et al.*, 2015; Voldsund *et al.*, 2016), taking into account both economic as techniques referred to as “total capture” systems) which is why it is considered as a GHG mitigation technology.

The three main components or phases that constitute the complete chain of CAC technology are capture, transport and storage, applied to CO₂ sources produced by industrial activities as detailed in Fig. 1. In general, the following are the options or methods applicable to each of the phases of CAC technology.

Capture: In power generation plants, CO₂ capture can be achieved through the following methods: pre-combustion, post-combustion and oxygen-gas combustion.

Transport: Except in the case that the plants are located directly on a geological storage site, the captured and compressed CO₂ must be transported from the collection point to a storage place. Transportation systems include: 1000 km pipelines (mature market), ships and railcars or tank trucks (not large-scale).

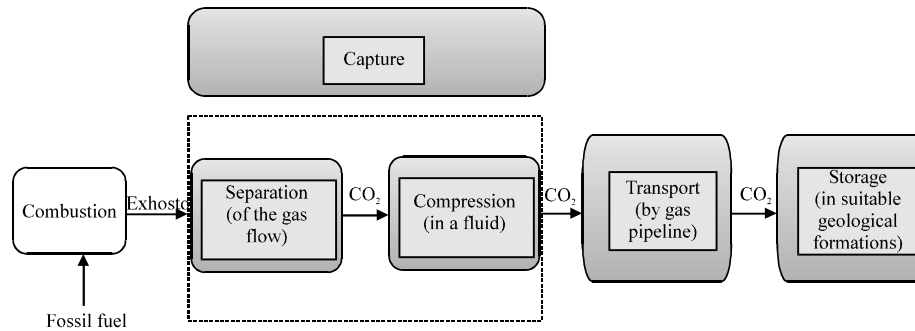


Fig. 1: CSS phases

Storage: The possible technical methods of storage are the following: geological storage, oceanic storage, industrial fixation of CO₂ in inorganic carbonates, improved recovery of hydrocarbons and industrial uses of CO₂. Regarding geological storage, the following three options are available: depleted oil and gas deposits, deep salt formations: marine and terrestrial and the use of CO₂ for the improved recovery of methane in coal layers.

Implementation experiences of CAC: The following list presents the industrial projects that have implemented CAC technology in a range of 1 million tons of CO₂ per year (Voldsund *et al.*, 2016; Blanco *et al.*, 2018a, b; Seifert *et al.*, 2016; Dinca *et al.*, 2018):

- Sleipner project in a sea salt formation in Norway
- Weyburn project for improved oil recovery in Canada
- In Salah project in a gas field in Algeria

Implementation costs: For the year 2007, the IPCC estimated that the application of the CAC to the production of electricity in the conditions prevailing in 2002, would raise the costs of electricity generation between US \$ 0.01 and US \$ 0.05./kWh (US \$/kWh), depending on fuel, specific technology, location and national circumstances (Hombach *et al.*, 2019; Yoo *et al.*, 2018; Schemme *et al.*, 2017), however, it was also noted that the inclusion of the benefits of enhanced oil recovery would reduce the additional electricity production costs incurred by the CAC between US \$ 0.01 and US \$ 0.02./kWh (Nandy *et al.*, 2016; Sanpasertparnich *et al.*, 2010; Zhao *et al.*, 2018).

The IPCC report Anonymous (2007) also indicates that during the next decade, the cost of capture could be reduced between 20 and 30% and new technologies that are still in the research or demonstration phase should be able to achieve greater achievements. The costs of transportation and storage of CO₂ could decrease slowly

as the technology continues to mature and the scale grows (Adenle *et al.*, 2015; Filatova, 2014; Yulandhika and Nugrahanti, 2014). Most studies related to the costs and indicators of CAC technology consider the following aspects for their analysis: Plant size. Installed capacity in MW; type of plant and capture technology. Integrated gasification combined cycle, combined natural gas cycle, Pulverized Carbon (USCPC, SCPC, PC), circulating/post-combustion fluidized bed combustion, pre-combustion and oxi-combustion. State of technology. Demonstrative, commercial in early stage and commercial mature.

Capture costs: Currently there are significant energy costs and reductions associated with the application of CCS technologies available in their current state of development. The analyzes of different studies (DOE/NETL, 2010, IPCC, 2005a, IEA/OECD, 2011, McKinsey Climate Change Initiative, 2008), allow us to estimate that in the case of a pulverized coal plant the capture costs are among the 1.700 and 5.100 USD \$/kW for the pre-combustion method, between 3.200 and 4.600 USD/kW for the post-combustion case and between 1.480 and 5.100 USD/kW for oxy-combustion.

Transportation costs: Referencing the associated transportation costs, it depends on the distance, quantity transported and the massification of the technology. “The cost of transportation by pipeline for a nominal distance of 250 km costs, generally, between USD \$ 1-8 per ton of CO₂ (Elum and Momodu, 2017; Bayramoglu *et al.*, 2018; Rodriguez and Pena-Boquete, 2017).

RESULTS AND DISCUSSION

Generation of thermoelectric energy in Colombia: This study presents the current state of the thermoelectric sector in Colombia including the characteristics of the current thermoelectric plants, emissions, projections and expansion of the sector.

Thermoelectric power plants in Colombia: At the end of 2013, the National Interconnected System (SIN) has a net installed capacity of 14.559 MW distributed between hydroelectric (64%), thermal (31%), lower (4.5%) and cogeneration (0) plants (5%) (Anonymous, 2014).

The thermoelectric plants represent 4.515 MW of installed energy, distributed in natural gas (1.972 MW), coal (997 MW), fuel oil (307 MW), ACPM (917 MW), Jet A1 (46 MW), gas-Jet A1 (276 MW). These plants are located on the Atlantic Coast (Atlantico, Bolivar and Guajira), Norte de Santander, Valle Medio del Magdalena, Cundiboyacense highlands and Valle del Cauca (Lopez *et al.*, 2016; Garcia *et al.*, 2013).

From the above information, it is observed that in Colombia, there is a defined field for carbon management where the few reduction efforts are made by private companies that voluntarily decide to mitigate the effects of CO₂. It should be noted that the generation of energy based on fossil fuels, represents about 31.55%, if the processes of self-generation and cogeneration are taken into account which represents an important space to implement carbon management programs which are in agreement with the reduction and mitigation options established by the IPCC (Gonzalez-Salazar *et al.*, 2014; Devis-Morales *et al.*, 2014; Rodriguez and Pena-Boquete, 2017).

CO₂ emissions in the national thermoelectric sector: The CO₂ emissions for the electricity generation sector have been estimated by the operator and administrator of the XM electrical system. Some of the conclusions that XM has presented during 2013 for the information compiled by the system regarding CO₂ emissions from electricity generation activity in Colombia, include (Ifaro, 2015):

The production of energy has a high component coming from water sources and a very important part of thermal generation comes from natural gas. Of the different indicators defined in the Clean Development Models (CDM), the one corresponding to the carbon dioxide emissions which are the result of the production of an electric power unit (kWh), represents the footprint that is leaving the environment the generation of electric power for a given country. For Colombia, considering the power generation of the plants dispatched centrally by XM, on average, this indicator is 130 g of CO₂/kWh which among all the countries of America which supply electricity through hydrothermal systems is exceeded only for Brazil that has 81 g of CO₂/Wh.

There is evidence of the low polluting impact that the production of electric power is having in the country, data

that identifies Colombia as a country with a world-class electricity sector that enables the export of clean energy to countries in the region.

The impact of climatic variability in Colombia is observed with the occurrence of climatic phenomena of drought (El Nino) or rain phenomena (La Nina) in the production of carbon dioxide. It can be seen that during El Nino events, the indicator has risen to 400 g CO₂/kWh and during the La Nina phenomena it has dropped to 50 g CO₂/kWh.

Notwithstanding the foregoing, it can be observed that the emission of CO₂ that thermoelectric plants in Colombia present, during the periods of time in which their generation is required can not be underestimated, a fact that is reinforced during periods of water scarcity caused by phenomena as El Nino (Guerra *et al.*, 2019).

Sector projections in Colombia: The expansion of generation through the reliability charge allows the development of new projects in the country in such a way that in the future it will be possible to guarantee the energy reliability of the SIN. The expansion in thermoelectric plants for the long term (2014-2020) is constituted by 574 MW of coal-based energy (15.9% of the total expansion in generation) and 88 MW of energy based on liquid fuel (2.4% of the total of expansion in generation).

Carbon capture at a thermoelectric power plant in Colombia: The following is a conceptual analysis of the implementation of a capture and storage system in a thermoelectric plant located in Colombia. This analysis addresses technical aspects, costs and carbon management and management.

CO₂ capture system in a thermoelectric power plant: For the analysis, a case has been selected that meets basic conditions that allow the implementation of a CAC system, that is CO₂ production by the energy generation process and closeness to geological storage.

Of the thermal power plants that are currently in operation, those that operate on a coal basis have been reviewed and are located in the departments of Boyaca, Cundinamarca, Guajira and Norte de Santander.

Given this location, the proximity to possible geological storage sites was reviewed with which the Norte de Santander area was chosen, given that the oil and gas fields Tibu, Petrolea, Rio Zulia, Cerro Gordo and Cerrito are located there. They belong to the Catatumbo oil basin. Some of these fields are in secondary recovery or depletion stage.

Table 2: Basic technical conditions for the implementation of a CO₂ capture system

Technology	Powdered coal
Size of the unit	150 MW
CO ₂ emissions	1,280,000 CO ₂ ton/year
Type of capture	Pos combustion
Capture (%)	90%
Type of transport	Terrestrial pipelines
Distance to storage	80-90 km
Type of storage	Oilfields in exhaustion stage

In summary, the basic technical conditions of the case are summarized in Table 2. The calculation of CO₂ emissions as well as the operating data of the thermoelectric power plant were simulated in a specialized program (Thermoflow 24) which designs the capture system to be implemented. The flow diagram of the CAC system and its main systems for this case, it is expected that the useful life of the CAC system will be at least 30 years.

Based on the results obtained from the simulation of the operation of the plant, a potential CO₂ emission of 1,286,000 tons/year is obtained (Calderon *et al.*, 2016; Normann *et al.*, 2017).

The capture system that has been included in the plant has an efficiency of 90%, therefore, it is possible to capture 1,160,000 tons/year of CO₂.

Cost of implementation of the CAC system: Through the financial module of the simulation program used, it was obtained that the costs of the system put in place are of the order of USD \$ 200,000,000 which corresponds to 1,300 USD \$/kW installed, a figure lower than the one reported in the references consulted in section 2.4.1 of this study for post-combustion CAC systems.

Annual transport and storage costs, according to the sources consulted in study 2.4.1, range from USD 2 to USD 16/tCO₂ which corresponds to a range between USD 2,320,000-18,500,000/year (Wang *et al.*, 2018; Chen *et al.*, 2018).

The costs per ton of CO₂ avoided vary substantially both with the type of production facility and with the type of capture and storage system implemented, however, taking a pulverized coal plant as a reference, these costs are between US \$ 30-71/tonne of avoided CO₂, although, if the capture and storage imply oil recovery these costs are estimated in ranges of 9-44 USD/CO₂ tonned avoided (Sun *et al.*, 2018).

In relation to the costs of implementing a CO₂ capture system through compensation for reforestation, it has been calculated with data from projects carried out and the experience of the researchers that to reduce 1,286,000 tons of CO₂ annually, a thermoelectric plant must invest taking into account that for every 21.6 tons of CO₂, 1 ha of land with temperate forest is required, that is to say for the

annual catch, about 60,000 ha are required. Similarly, it is estimated that if the costs for CO₂ capture services are equal to USD 30/ton, the thermoelectric plant will incur investments close to USD 38 million/year (Wang *et al.*, 2018).

Carbon management and management: In search of CO₂ mitigation options for the electric power generation sector based on fossil fuel, there are different options for carbon reduction or mitigation that can be substitutes or complementary in relation to CO₂ capture. For these options, the following was analyzed (Ogungbenro *et al.*, 2017):

Improvements in energy efficiency

For this option it was found that it has as advantages:

- Lower production costs by consuming less energy per unit produced
- Contributes to compliance with environmental requirements
- Greater generation capacity available which allows the use of the electrical system available for other uses

Increase in the use of solar, wind, biomass, geothermal renewable energy:

For this option it was found that it has the following advantages (Wang *et al.*, 2018): they do not produce CO₂ emissions or other polluting gases into the atmosphere during their operation, so, it helps to reduce the greenhouse effect as it replaces fossil fuel-based power generation systems. The primary energy sources for its operation are considered inexhaustible and/or renewable resources. Disadvantages for this option include; you do not always get the same energy with them, that is they depend on whether there is wind or the amount of Sun, so, sometimes they have difficulties to guarantee the supply and they have to be complemented with another type of energy. Large tracts of land are needed to obtain an appreciable amount of energy.

Change to less carbon intensive fossil fuels: Changes to less intensive fossil fuels are usually achieved by moving from coal to gaseous fuels such as natural gas. Because of its characteristics, natural gas produces less amounts of CO₂ and its transport tends to be less impact than the transport of coal to thermoelectric plants. Its use also improves the operation and efficiency of the generating units (Chen *et al.*, 2018).

Reduction of greenhouse gas emissions other than CO₂:

This option has benefits for the environment, since,

equipment and systems that reduce NO_x, SO_x and MP are implemented which in the country has gained experience in relation to the management of these emissions and has generated national regulations for its control. PM management also contributes to some extent to the control of carbon produced in thermoelectric plants (Chen *et al.*, 2018).

Biological sinks: The improvement of biological sinks is proposed, changing the use of land and forestry or by fertilizing the oceans for this option it was found that it has the following advantages (Calderon *et al.*, 2016; Normann *et al.*, 2017): reduce emissions of CO₂ fluxes and can be reduced by controlling the carbon and nitrogen fluxes. Increase carbon sequestration because it can be sequestered in vegetation and soil through the use of perennial crops and minimum tillage practices or zero tillage. The following were also found as disadvantages: to be able to implement them successfully, there must be a balance between the additional benefits and the possible adverse effects, communication and strengthening of work capacity in communities is also necessary. It is important that there is an adoption of good management practices at the landscape level in a broad sense.

Carbon capture: In general and as presented in this study, the combustion of fossil fuels can be continued using carbon capture systems, taking into account that the cost of implementation in an existing thermoelectric power plant is greater than in the case of building a project new that includes CAC system (Calderon *et al.*, 2016).

Technical and cost implications of CAC systems: It can be seen from the technical analysis that regarding the situation in other countries and reference points, Colombia has technical opportunities as the electricity generating centers are integrated with the oil production sector, a case that has not been achieved so far. By the difference of markets and vision of the actors of these productive chains. This situation is favorable given the distances from the production centers and geological storage centers which for the case described are <100 km, it is presumed that in other parts of the country they do not exceed 300 km of pipeline transport and in some cases can be used for the transport of hydrocarbons.

The results regarding CO₂ emissions in terms of tons of CO₂/year, contribute to the dimensioning of the solutions in which the carbon program to be implemented must be framed.

The calculated implementation costs are observed within the ranges of those found in the references consulted which indicates that the technology to be installed in Colombia will be maintained within these indicators, favoring the inclusion of this technology within the analyzes to be carried out by the thermoelectric plants.

The cost of implementing the CAC system (1.300 USD \$/kW) corresponds to about 75% of the investment costs of a new coal-fired power plant (1.800 USD/kW) and is higher than that of a gas-fired power plant (1.200 USD/kW). The operating costs of the CAC system increase the operating costs of the thermoelectric plant, given that they correspond to new processes that are not part of those established for the current operation.

Similarly, the integration of energy generation processes in relation to the improved recovery of hydrocarbons, achieves results that can provide benefits at different levels of the productive chains in the sense of a decrease in the use of primary resources and therefore, in the reduction of environmental impacts.

Of the programs and systems proposed as part of the carbon management programs for the thermoelectric sector, there are important opportunities to combine and complement technical solutions with those of the biological sink type, achieving greater benefits. It is noteworthy that the capture and storage of carbon is emerging as a safe and effective solution to the challenges imposed by the increase and energy requirements by communities at the global level, allowing the rational use of resources, through management controlled and efficient greenhouse gas emissions.

The CAC systems as a mitigation tool: In Colombia, there are currently no long-term solutions for carbon management in the electric power generation sector based on fossil fuels, the mitigation option is compensation but only for 30% that represents the thermoelectric sector in Colombia, it is estimated that close to 500,000 ha of forest would be necessary, taking into account the medium-term expansion of the sector, it will be necessary to have an additional 250,000 ha which represents large areas of forests and areas to be reforested and investments in rural areas that are difficult to access due to the armed conflict (Gong *et al.*, 2019; Farsangi *et al.*, 2018; Ramli and Munisamy, 2015; Akber *et al.*, 2017).

The use of the CAC will make it possible to maintain Colombia as a country with a world-class electricity sector, opening possibilities for the export of energy with low CO₂ production to other countries, keeping the sector up to date with the world's booming trends, complying

with the required requirements for international investors, all this in order for the Colombian electricity system to provide reliable energy from thermoelectric plants due to the scarcity of water during the summer and when natural phenomena occur that produce drought (Fong-Silva *et al.*, 2017; Martinez *et al.*, 2016; Usman *et al.*, 2018).

Regarding the scope of the evaluation for the implementation of the CAC in the thermoelectric sector of Colombia, it is clarified that the implementation could be developed for those plants that are located near industries that require significant amounts of CO₂ and/or in the vicinity of areas that have the potential and geological characteristics required to achieve the storage of captured CO₂.

Approach of a carbon management program: Based on the results obtained, a program is presented below that contains the carbon management structure to be implemented in the organization of a thermoelectric plant and that can be useful for environmental managers who are faced with this type of challenge: measurement and quantification of emissions. Based on the knowledge of the power generation process, CO₂ emissions must be calculated, both in the main emission train and in all possible emitters, even when the latter are irrelevant with respect to the main source of emission. Establishment of objectives: the objectives of the program should be aimed at the production of energy with low CO₂ emissions in accordance with the guidelines of the agent or owner of the generating plant. Study and selection of available technologies and methods to reduce CO₂ emissions. Review of the guidelines and options established by the IPCC, applicable to the energy sector.

Technical and environmental feasibility of the solutions found. This involves the integration of specialists in issues of power generation, processes and applications of CO₂, gas transport, geological storage and improved production of hydrocarbons.

Financial analysis of the alternative or selected alternatives. According to what has been stated, it is very possible that integral solutions can be found that combine the capture of carbon through technology with reforestation type compensations.

Review of the possibilities of financing the project investments, given their technical and environmental nature by instruments such as the CDM or other organizations or financial entities.

Design of monitoring programs for the capture, transport and storage process. Periodic review of the outlined goals.

CONCLUSION

The main conclusions and recommendations obtained from this analysis are presented below: the technological

development of the carbon capture and storage systems seeks to respond and solve one of the most significant environmental challenges worldwide such as global warming.

The carbon capture and storage systems are in line with the technological development which allows the design of integrating solutions between the sectors of energy generation and hydrocarbon production.

The costs of implementing carbon capture and storage technology, under the current scenarios for developing countries such as Colombia where there is no regulation regarding CO₂ emissions are high, however, it is very possible that the integration with the hydrocarbon sector allows avoided CO₂ costs lower than those presented in this study.

For the environmental management of the organizations of the energy sector in Colombia carbon capture and storage represents a challenge, following global trends it is essential to include the management, capture and control programs of CO₂ emissions, given that each day. It makes more noticeable the need to implement solutions that are already underway at a global level.

It is relevant to develop knowledge about CO₂ storage in geological formations, in order to recognize the possible benefits or affectations to these natural systems.

It is very important to study and develop knowledge about the possible uses and effects of CO₂ in other industries in order to quantify their value, even when they are less than the total amount of emissions by thermoelectric plants.

Due to the above, it is necessary to recognize the life cycle of carbon in order to optimize its use and reduce its impact on the environment.

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