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# Decarbonizing the Environment: Viability Analysis of Carbon Emission Reduction Processes in Thermoelectric Power Plants

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***Abstract*— The uncontrolled emission of $CO_2$ gases into the atmosphere is one of the main causes of global warming. This gas, made up of carbon and oxygen, is produced by the combustion of fossil fuels (coal, natural gas, and petroleum). This paper focuses on the emission of $CO_2$ in electric energy generation coming from thermoelectric power. Even though currently there is a transition effort to renewable sources to reduce emissions of $CO_2$, this type of energy production only accounts for 26,8 % of the total. This transition will take many years to be relevant. It is very important to search for viable alternatives to reduce the emission of $CO_2$ in traditional energy in the meantime. The objective of this paper is to analyze the viability of different methods to reduce $CO_2$ emissions into the atmosphere.**

**Keyworks- CO2 emission, carbon dioxide, CO2 capture, reduction of CO2 emission**

***Resumen*— La emisión descontrolada del gas $CO_2$ a la atmosfera es una de las principales causas del calentamiento global. Este gas, compuesto por carbono y oxígeno, es producido por la combustión de combustibles fósiles (carbón, gas natural y petróleo). En este trabajo nos centraremos en las emisiones producidas por la industria de generación de energía eléctrica proveniente de centrales termoeléctricas. A pesar de que en la actualidad está ocurriendo una transición a las fuentes de energía renovables para disminuir las emisiones de $CO_2$, este tipo de producción de energía solo abarcan el 26,8% del total. Si bien esta transición llevará muchos años en ser relevante. Es importante buscar alternativas viables para disminuir la emisión de $CO_2$ en las fuentes de energías no renovables. El objetivo de este trabajo es analizar la viabilidad de los diferentes métodos para reducir las emisiones de $CO_2$ en la atmosfera.**

**Palabra clave- emisiones de CO2, dióxido de carbono, captura de CO2, reducir de emisiones de CO2**

## I. Introduction

Currently, energy production is mostly dependent on thermoelectric power plants, which allow electric energy to be produced on a large scale. The problem with these plants is that their operation is based on burning fuel to generate steam, which is then used to move electricity-generation turbines. As it is well-known, the burning of fuel generates carbon dioxide, which goes to the atmosphere and becomes the pollutant that is responsible for greenhouse gases emissions and climate change.

One of the main challenges for engineering today is to be able to continue depending on thermal plants but with the least possible impact on the environment. This issue is related with one of the National Academy of Engineering's 'Grand Challenges for Engineering', whose title is 'Develop carbon sequestration methods' [1, p13].

These last years, different methods aimed at the reduction of the amount of $CO_2$ that is released into the atmosphere have been developed, but their application has not been an easy task, and they will possibly require many technical and economic resources to become a reality. As future engineers, our objective in this paper is to analyze the viability of the main methods to reduce $CO_2$ emissions into the atmosphere. To this end, firstly, the problem of $CO_2$ emissions caused by thermal electric energy production and its consequence for our planet will be analyzed. Then, the methods of capturing $CO_2$ that exist to solve this problem and the viability of the different methods of reducing $CO_2$ emissions will be analyzed. Finally, a feasibility analysis in relation to the introduction of these methods in thermoelectric power plants will be made.

## II. Problem Of $CO_2$ Emissions Caused By Thermoelectric Energy Production

In conventional thermoelectric power plants [2, Fig. 1], fossil fuels are burned in a boiler resulting in thermal energy that is used to heat water, which in turn is transformed into a high-pressure steam. Then, the high-pressure steam turns a large turbine that converts the heat energy into mechanical energy. This energy is later transformed into electrical energy by using a generator [3].

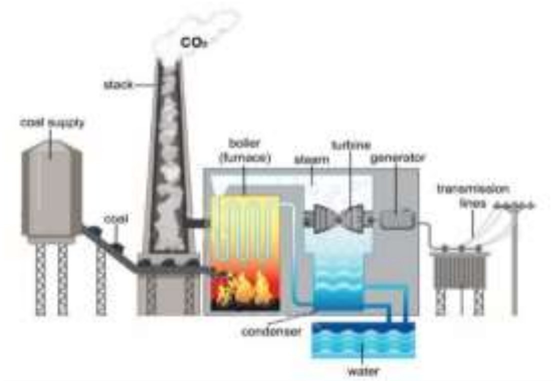


Figure 1: Thermal Plant [2]

During the burning of fossil fuels to produce electrical energy, tons of carbon dioxide are produced every day. Global energy-related carbon dioxide emissions rose by 6% in 2021 to 36.3 billion tons, their highest level ever, according to an *International Energy Agency* (IEA) analysis [4].

Power demand in 2021 was intensified by adverse weather and power market conditions. Spikes in natural gas prices led to more coal being burned despite renewable power generation posting its highest ever growth [4].

More than 40% of the overall growth in global CO2 emissions in 2021 was generated by coal, surpassing an all-time high of 15.3 billon tons. Natural gas exceeded the levels reached in 2019 while oil remained below the levels in the same year [5]. In [4, Fig 2], $CO_2$ emission levels in the period 1900-2021 are shown.

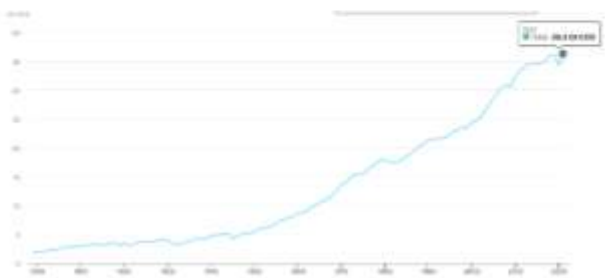

Figure 2: IEA, CO2 emissions from energy combustion and industrial processes, 1900-2021, IEA, Paris [4].

## III. Methods To Reduce $CO_2$ Emissions

To solve this problem there are different methods for capturing and reducing $CO_2$. These methods have a potential application in thermoelectric power plants. The principal methods that will be analyzed here are pre-combustion, post-combustion and oxyfuel combustion.

### *A. Pre- combustion*

The pre-combustion method consists in the transformation of a fuel that can be liquid, solid or gas (containing carbon and hydrogen) into a gas stream to later separate the $CO_2$ from the hydrogen. The hydrogen is used as a fuel to generate a clean combustion (it does not produce CO2 in combustion) and $CO_2$ is captured and stored [5, p19]. The precombustion process is shown in [5, Fig.3]. The first part consists in mixing the primary fuel, the steam, and the air in a reactor for the chemical transformation of the primary fuel into carbon monoxide (CO) and hydrogen ($H_2$). [5, p19]

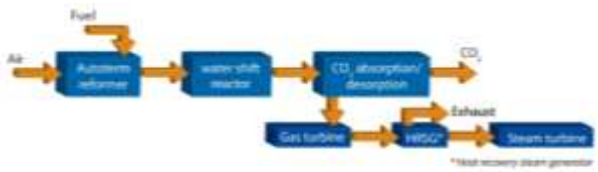


Figure 3: Pre-Combustion Method [5]

This transformation process must be done with high temperature and pressure. The chemical formula that summarizes this reaction is [6, eq. (1)]:

$$C_xH_y + xH_2O \rightarrow xCO + \left(x + \frac{y}{2}\right)H_2 \quad \Delta H + E \qquad (1)$$

This is an endothermic reaction (absorbing heat); therefore, energy must be supplied for the reaction to be completed.

Later, the synthesis gas is cooled in the water-gas reaction (shift) to convert it into hydrogen in the *water exchange reactor*. In this process, the carbon monoxide (CO) reacts with the water, and it is transformed into carbon dioxide ($CO_2$) [5, p19]. The chemical formula that summarizes this reaction is [6, eq. (2)]:

$$CO + H_2O \rightarrow CO_2 + H_2 \quad \Delta H - \frac{41kJ}{mol} \qquad (2)$$

Hydrogen is used as fuel in the turbine, while the $CO_2$ is separated by amines absorption. Amines are chemical compounds that are mixed with water to form an absorbing fluid. The absorption with amines [4, Fig.3] has four steeps [5, p16].

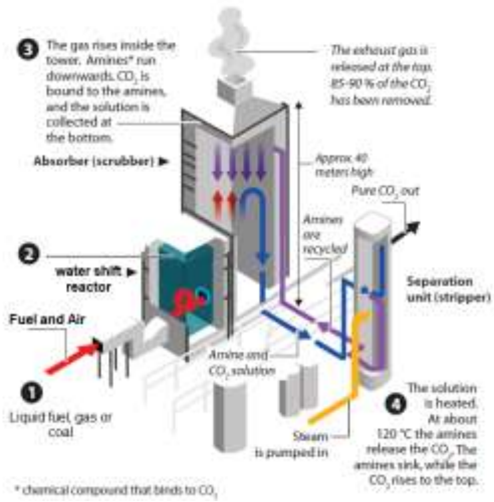


Figure 4: Amines systems absorption of pre-combustion [5]

The gases containing $CO_2$ and $H_2$ pass thorough an absorber tower by which the amines mix with water. Amines absorb $CO_2$ and form a covalent bond. This fluid is transported to another tower called a "stripper", where this fluid is heated to separate the $CO_2$ from the amines. Amines are reinjected into abortion towers to continue capturing $CO_2$ in the cyclic process. The $CO_2$ released by the amines is stored for industrial application [5, p16].

### B. *Post- combustion*

The post-combustion process is based on the capture of $CO_2$ in the exhaust gases when the combustion ends without performing any previous action prior to combustion [4, p16] as shown in [5, Fig. 5].

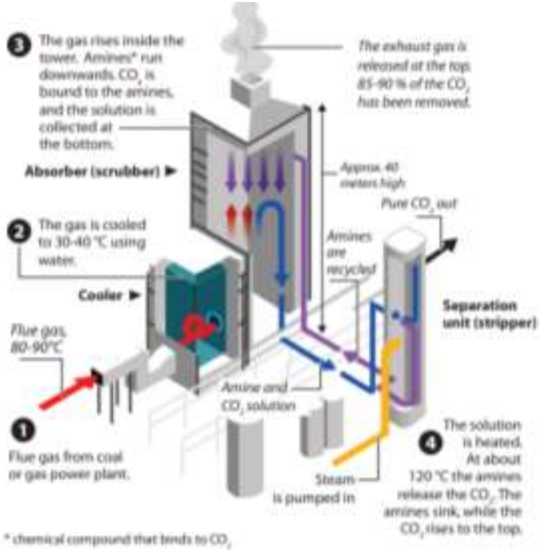


Figure 5: Amine system absorption of post-combustion [5]

For the capture of $CO_2$, the absorption of amines is used, which was detailed in the precombustion method. The main difference in this last method is that the amines system absorption is installed in the chimney outlet of the thermal power plants [5, p16].

This method is the most used due to its versatility. However, it very much depends on the type of fuel used in the power plant because different fuels emit different amounts of $CO_2$. For example, while the exhaust gases from natural gas power plants contain between 3 and 4 per cent of $CO_2$, a power plant using fuel oil or solid coal can quadruple this $CO_2$ emission [5, p16].

Also, the post-combustion method is dependent on the amount of $CO_2$ that needs to be captured. The capture rate is around of 85 percent; however, this rate can increase, but it is highly expensive because it involves an increase in the energy supplied [5, p16].

### C. *Oxyfuel- combustion*

In the oxyfuel process the combustion takes place using pure oxygen instead of air. The exhaust gas consists of water steam and $CO_2$, which is separated by cooling the flue gas so that the water steam condenses into liquid and the $CO_2$ is compressed [5, p20].

This method requires large amounts of oxygen, which is normally extracted from the air. Combustion with pure oxygen generates very high temperatures. Therefore, the combustion chamber technology must be changed to allow recycled $CO_2$ or water steam to be used as inert gas in oxy-fuel projects. In the following simplified illustration [5, Fig 4] the Vattenfall oxyfuel cutting process is shown, in which a separation unit supplies oxygen to the combustion chamber then the particles are separated and finally the water vapor is cooled and condensed, and the CO2 is compressed [5, p20].


Figure 6: Simplified flowchart for an oxy-fuel power plant [5]

## IV. Technical Concepts discussion for the viability analysis

The viability analysis refers to the evaluation of the possibility of implementing a project successfully. In this work, it will be analyzed whether it is viable to implement these methods in thermal power plants and their cost-benefit relationship.

Before moving on to the viability analysis, it is necessary to talk abouts previous technical concepts for clarification. These technical concepts are thermal efficiency and Rankine cycle.

*A.* Thermal Efficiency: thermal efficiency (or thermal performance) is a coefficient that shows the percentage of supplied energy that is converted into produced energy, this is the ratio between input energy and output energy [7, p78].

$$\eta_{ter} = \frac{E_{produced}}{E_{supplied}} = \frac{E_{output}}{E_{input}} \qquad (3)$$

In thermoelectric power plants, the *input energy* is thermal energy generated from the fuels in the boiler and *output energy* is electric energy produced in the turbine. For Example, if one thermoelectric power plant has 35% of thermal efficiency, this means that only 35% of energy supplied (heat energy form burning fuel) is converted into electric energy and the other part (65%) is lost as heat and friction in the industrial equipment. This is so because all these power plants work through of cycle denominated

*Rankine* cycle, which absorbs and releases heat for complete the cycle. The losses heat reduces of thermal efficiency [7, p263].

*B.* Rankine cycle: most of the thermoelectric power plants use the Rankine Cycle for the generation of electric energy. To understand this cycle, [2, Fig. 1] shows a summary flowchart of Ideal Rankine Cycle.

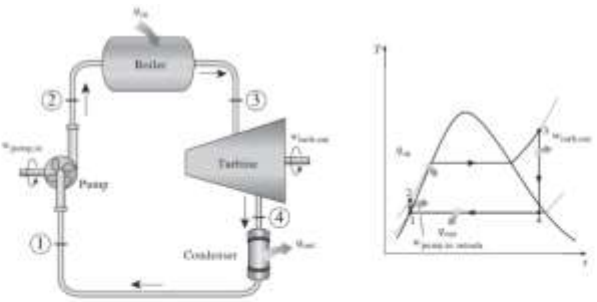


Figure 7: flowchart and graphic of Ideal Rankine Cycle.[7]

The cycle begins when the water is pumped to the boiler, which increases the temperature and pressure of the water, transforming it into steam thorough the heat generated in the burning fuel. The water steam is used in the turbine to move an axis that is connected to the electric generator. In the turbine, the steam water decreases its pressure and temperature and produces mechanical work. Finally, to complete the cycle, the steam is condensed and pumped to start the cycle again [7, p561].

Mechanical work in thermodynamics means the transfer of energy that a system generates. The more work, the more energy efficiency is generated. The formula of work in the turbine is obtain between an energy balance [7, p236]:

$$E_{intput} = E_{output} \quad (4)$$

$$q_{intput} = W_{turbine} + q_{out} \quad (5)$$

$$W_{turbine} = q_{int} - q_{out} \quad (6)$$

In the Ideal Cycle Rankine formula energetic losses due to friction and heat losses of some equipment like water pumps, pipes, condensers, among others are not included. These energetic losses can be included in de formula (4) like $S_{f+h}$:

$$W_{turbine} = q_{intput} - q_{output} - S_{f+h} \quad (7)$$

The work in the turbine is the difference between energy in the form of heat absorbed by steam ($q_{int}$) and the energy in the form of heat after passing through the turbine ($q_{out}$).

In a boiler, all the heat produced from burning fuel is not transferred to water due to losses. Then ($q_{int}$) is:

$$q_{int} = (q_{fuel}).k_{boiler} \quad (8)$$

Where $k_{boiler}$ is a heat transfer coefficient of the boiler.

It is important to clarify that thermoelectric power plants have-much more equipment in their premises than what can be seen in [7, Fig. 7] such as more pumps, condensers, turbines in parallel, superheaters, preheaters, among others. In this paper, the viability analysis will center in the ideal Rankine Cycle due to its simplicity for effective for realize good approximations.

The concepts of efficiency and thermodynamics cycles are necessary to understand that any loss of energy in the equipment (turbine, condensers, pumps) decreases the thermal efficiency in the power plant; therefore, it increases the cost of production because it is necessary to make use of more fuel to produce electric energy.

## V. Viability Analysis of methods

*A. Pre- combustion:* Starting from the constructive analysis of the precombustion system, implementing this system requires a large initial cost due to the installation of the amines system, which has a chemical reactor, cooling tower and absorption towers, among others as parts of its equipment. Also, this needs to use energy for its reactions, which must be extracted from the thermoelectric power plant [5, p16].

First, if a thermoelectric power plant operating without the amines system is analysed, the thermal efficiency is:

$$n_{ter} = \frac{E_{out}}{E_{int}} = \frac{W_{turb}}{q_{int}} = \frac{(q_{int} - q_{out})}{q_{int}} = 1 - \frac{q_{out}}{q_{int}} \quad (9)$$

When the amines system is in operation, it needs to use energy to separate $CO_2$ and $H_2$ from the primary fuel. This energy is extracted from the builder; therefore, according to formula (6), the thermal efficiency decreases because $q_{out}$ decreases. However, this energy loss can be reduced if the hydrogen obtained in the separation for the formula (3) is used as fuel in the boiler so $q_{int}$ increase but this would not compensate for the loss in thermal efficiency.

According to some data, thermoelectric power plants with 38.7% thermal efficiency decreases to 31.2% when this system is implemented. The losses of 7.2% are quite substantial if the following equation is considered:

if a medium thermoelectric power plant can produce 5000 MWh (megawatts) of electric energy annually, it implies a loss of 350MWh per year. This loss of energy could cover the electricity demand for around 200 homes [8, p24].

Having analysed this method, this analysis, should be asked, is it justifiable to install this equipment? If this equipment is installed to obtain an environmental improvement, it can harm the energy user to a greater extent. This is because the price of electric energy could increase due to a decrease in energy supply.

### B. *Post- combustion*

The viability analysis of the post-combustion process begins with the construction details. In this case, the amines system is installed directly at the combustion gases outlet, and it does not require a gas pretreatment system, so its implementation is more versatile compared to the pre-combustion process. In addition, the energy consumption is lower in post-combustion because it only needs energy for the amines system and does not have gas pretreatment. In the viability discussion for this method, it is important to remember formula (9), the more $q_{out}$ decreases, the lower the efficiency.

The decrease in thermal efficiency in the new power plants with this system is around of 7% [5, p17]. This efficiency is close to the pre-combustion method, and maybe this is due to the fact that in the precombustion a part of energy loss is recovered when hydrogen is injected as fuel is recovered in the boiler.

Another factor that is of great importance in the separation of $CO_2$ through post-combustion is the dependence on the level of $CO_2$ in the exhaust gases. For example, a thermoelectric power plant that use natural gas as a primary fuel contains less $CO_2$ in the exhaust gases than a power plant that uses coal. Therefore, in the natural gas thermoelectric plants, it is viable to apply the precombustion method but in coal-fired plants its application can be very complicated and non-viable.

The percentage in the separation of $CO_2$ is around of 85%. However, this percentage can be increased but this implies a higher energy consumption and, therefore, a reduction in thermal efficiency [5, p16].

This method has as a major advantage its versatility to be applied in any type of thermoelectric power plant. The main disadvantage is that the $CO_2$ capture capacity is much lower compared to other methods such as pre-combustion. However, it is currently the method most used. This may be so since the fines for low $CO_2$ emissions in most countries of the world are not applicable or do not represent economic loss, so this method is enough to comply with legal regulations by investing the lowest capital possible.

### C. *Oxyfuel- combustion*

The viability analysis of the Oxy-Fuel Combustion demonstrates that this is the best process for carbon dioxide separation because the end gas of this process is $CO_2$ and water. This process simplifies the capture work with great efficiency and low cost [8, p25].

Although air separation and $CO_2$ compression require extra energy, with an overall loss of energy efficiency of around 12%, the overall electric efficiency in oxy-fuel combustion plants can be higher than that used by a conventional power plant that uses combustion with air. It is for this reason that the efficiency of energy generation in an electric power plant of gas with oxygen combustion and $CO_2$ compression is between 43-48 % [5, p21].

Oxy-fuel combustion technology has the advantage of providing a simple way to capture most of the $CO_2$ without emissions. It can be done by using conventional steam turbines and air separation methods which are already well known. This oxy-combustion technology can be used in any thermal plant, not only in liquid fuel, but also in gas and coal plants, which favors its application in any power generation plant [5, p21].

The disadvantage of this process is that it has a large O2 production requirement, which may be unacceptable energy costs in certain industries [8, p27].

## VI. Conclusion

In this paper, the main methods for capturing $CO_2$ were developed in a simplified way with the aim of understanding it and demonstrating that the greenhouse effect owing to $CO_2$ emission into the atmosphere can be addressed without affecting electric energy production.

In the viability analysis it can be seen that the application of these methods depends on the type of power plant, its size, its production and principally the fuel used. Fortunately, the new thermoelectric power plants use natural gas as fuel, which emits the lowest $CO_2$ amounts and there is a trend to convert all the power plants that used coal or diesel into natural gas plants.

The rate of implementation of these methods in the world can be discouraging since in many countries there is not enough control due to excess $CO_2$ emission into the atmosphere. Also, it is unjustified to apply these methods in countries where the $CO_2$ emission is not relevant for the world. For example, it is not justified to apply these methods in countries such as Brazil, where the total $CO_2$ emission per year (industry and power plants combined) is less than 1% and not to apply these systems in China or the US, whose combined $CO_2$ emission is around 43% per year [9].

Currently, electricity production tends to move to renewable energy sources, which do not produce $CO_2$. However, the dependence on thermoelectric power plants will continue for some decades. The current thermoelectric power plants are used as base power centrals and they differ from renewable sources because they can produce energy on a large scale. However, the main challenge for the future professionals in the energetic area is the continuous development of technology that can allow thermoelectric plants to be used to generate energy with the least possible environmental impact.

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The present manuscript is part of the research activities in the Inglés II lesson at Universidad Tecnológica Nacional, Facultad Regional Paraná. Students are asked to research into a topic so as to shed light on a topic of their interest within the National Academy of Engineering's Grand Challenges or the United Nations' Sustainable Development Goals frameworks. If sources have not been well paraphrased or credited, it might be due to students' developing intercultural communicative competence rather than a conscious intention to plagiarize a text. Should the reader have any questions regarding this work, please contact Graciela Yugdar Tófalo, Senior Lecturer, at gyugdar@frp.utn.edu.ar