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**DRP-CCDRM**

# INTERNATIONAL MASTER PROGRAM IN RENEWABLE ENERGY AND GREEN HYDROGEN

**SPECIALITY: Bioenergy/Biofuels and Green Hydrogen Technology**

# MASTER THESIS

**Subject/Topic:**

**INDUSTRIAL DECARBONIZATION AND REFINING WITH GREEN HYDROGEN TO PRODUCE SNG: CASE STUDY OF A POWER PLANT LOCATED IN GORUBANDA, NIAMEY, NIGER**

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by:

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WASCAL West African Science Service Centre on Climate Change and Adapted Land Use
Federal Ministry of Education and Research

## DEDICATION

This master's thesis is dedicated to **Doctor Abdoulkadri Ayouba Mahamane**, a great mentor and inspiration throughout my academic career.

Your consistent dedication to the pursuit of knowledge, as well as your great mentoring, have played critical roles in defining my academic and professional development. Your enthusiasm for education and dedication to the development of young minds has served as a constant source of inspiration for me. Your exceptional leadership and dedication to excellence have instilled in me the values of perseverance, integrity, and continuous learning. I appreciate every minute that you spent coaching me, patiently answering my questions, and encouraging me to try new things. Your knowledge, insight, and encouragement have helped to shape the path of my research and the quality of my work.

This thesis is evidence of the essential things I learned under your guidance. I dedicate this effort to you, Doctor Abdoulkadri Ayouba Mahamane, with great pride and appreciation. Thank you for being a source of light in my academic career and inspiring in me an appetite for knowledge that will drive me forward.

With sincere admiration and thanks,

**CHAIBOU HAROUNA Habibou**

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## Declaration

I, CHAIBOU HAROUNA Habibou, hereby certify that the research work provided in this Master's thesis is wholly my original work unless otherwise noted. This thesis has not been submitted for any other academic degree or qualification, in part or whole.

All sources of material and ideas used in this thesis have been properly acknowledged, whether they are published or unpublished works, electronic or personal correspondence. Other people's contributions to the research and writing of this thesis have been properly cited and referenced.

Rostock, 15 August 2023 CHAIBOU HAROUNA Habibou

# ABSTRACT

Global warming and climate change are two of today's most serious environmental issues, with greenhouse gas emissions being the primary cause. As a result of the increased concentration of carbon dioxide in the atmosphere, more reflected sunlight was captured, producing serious acute and chronic environmental problems. The concentration of carbon dioxide in the atmosphere reached 421 ppm in 2022, up from 280 in the 1800s, due to rising carbon dioxide emissions from the Industrial Revolution. Carbon dioxide emissions into the atmosphere can be reduced by employing low-carbon energy technologies, such as carbon capture storage, and utilization technologies. It has been reported that applying carbon capture, utilization, and storage can capture up to 95% of the carbon dioxide emitted in running power plants (Mukherjee *et al.*, 2019). Furthermore, renewable energy sources are making their way into the energy system. However, since renewable energy sources are intermittent, storage is a major issue. To meet energy demand while mitigating climate change, renewable energy technologies must be combined with carbon capture and utilization to produce synthetic natural gas.

In this thesis, an economic analysis of a carbon capture and methanation project was performed. The project aims to implement this carbon capture and methanation technology in a power plant in Gorubanda/Niamey. A life cycle analysis was also performed to evaluate the project's environmental implications using OpenLCA software. Furthermore, carbon capture via adsorption employing Aspen Adsorption software was proposed for reducing both, the cost of investment and the environmental impacts of the project. The economic analysis results showed that the project is economically feasible with a return on investment of **13%**, a payback period of **9.4** years, and a synthetic natural gas cost of **0.32 €/MWh.** The life cycle analysis findings indicated that the marine aquatic ecosystem is the most affected. Further findings showed that the adsorption process has the potential to replace the considered absorption process in economic analysis. Overall, the study's findings provide a substantial contribution to the field of sustainable energy and carbon emissions reduction.

**Keywords:** Climate change; carbon capture utilization, and storage; renewable energy storage; synthetic natural gas; sustainability.

## Résumé

Le réchauffement climatique et le changement climatique sont deux des problèmes environnementaux les plus graves d'aujourd'hui. Les émissions de gaz à effet de serre étant la principale cause. En raison de la concentration accrue de dioxyde de carbone dans l'atmosphère, davantage de lumière solaire réfléchie a été capturée, ce qui a entraîné de graves problèmes environnementaux aigus et chroniques. La concentration de dioxyde de carbone dans l'atmosphère a atteint 421 ppm en 2022, contre 280 dans les années 1800, en raison de l'augmentation des émissions de dioxyde de carbone résultant de la révolution industrielle. Les émissions de dioxyde de carbone dans l'atmosphère peuvent être réduites en utilisant des technologies énergétiques à faible émission de carbone, telles que les technologies du captage du dioxyde de carbone et de stockage. Il a été rapporté que l'application de la capture, de l'utilisation et du stockage du carbone peut capturer jusqu'à 95 % du dioxyde de carbone émis dans les centrales électriques en fonctionnement (Mukherjee *et al.*, 2019). De plus, les sources d'énergie renouvelables font leur entrée dans le système énergétique. Cependant, les énergies renouvelables étant intermittentes, le stockage est un enjeu majeur. Pour répondre à la demande énergétique tout en atténuant le changement climatique, les technologies d'énergie renouvelable doivent être combinées avec la technologie de capture et l'utilisation du dioxyde de carbone pour produire du gaz naturel synthétique.

Dans cette thèse, une analyse économique d'un projet de captage et de méthanisation du dioxyde de carbone a été réalisée. Le projet vise à mettre en œuvre cette technologie de captage et de méthanisation du dioxyde de carbone dans une centrale électrique à Gurobanda/Niamey. Une analyse du cycle de vie a également été réalisée pour évaluer les implications environnementales du projet à l'aide du logiciel OpenLCA. En outre, la capture du carbone par adsorption à l'aide d'un logiciel Aspen Adsorption a été proposée pour réduire à la fois le coût d'investissement et les impacts environnementaux du projet. Les résultats de l'analyse économique ont montré que le projet est économiquement faisable avec un retour sur investissement de **13 %**, une période de récupération d'investissement initial de **9,4 ans** et un coût du gaz nature synthétique de **0,32 €/MWh**. Les résultats de l'analyse du cycle de vie ont indiqué que l'écosystème aquatique marin est le plus touché. D'autres découvertes ont montré que le processus d'adsorption a le potentiel de remplacer le processus d'absorption considéré dans l'analyse économique. Dans l'ensemble, les

conclusions de l'étude apportent une contribution substantielle dans le domaine de l'énergie durable et de la réduction des émissions de dioxyde de carbone.

**Mots-clés :** Changement climatique ; capture, utilisation et stockage du dioxyde de carbone ; stockage d'énergie renouvelable ; gaz naturel synthétique ; durabilité environnementale.

# Acronyms and Abbreviations

## °

°C
degree Celcius....1

## A

AC
Acidification Potential....39
ACAPEX
Annualized Capital Expenditure....23

## C

CAPEX
Capital Expenditure....18
CC
Carbon Capture....9
Climate Change....39
CCUS
Carbon Capture Utilization and Storage....1
CH4
Methane....1
CHP
Combined Heat and Power Plant....15
CO2
Carbon dioxide....1
CO2eq
CO2 equivalent....2
CRF
Capital Recovery Factor....25

## E

ECL-CCC
External Cooling Loop Cryogenic Carbon Capture....14
EU
European Union....1

**F**

FC
Fuel Consumption....25
FE
Freshwater Ecotoxicity....39
FU
Functional Unit....34

**G**

GHG
Greenhouse gas....1

**H**

HT
Human Toxicity....39

**I**

i
interest rate....25
IGCC
Integrated Gasification Combined Cycle Power Plant....16

**K**

K
Kelvin....36

**L**

LC
Levelized Cost....23
LCA
Life Cycle Assessment....3
LCI
Life Cycle Inventory....23

**M**

MDEA
Methyl Diethanol Amine....36

**N**



**O**



**P**



**R**



**S**

## List of tables

## List of figures

# Table of contents

Table of contents

# Chapter 1: **Introduction**

Over time, variations in temperature and weather patterns are referred to as climate change. These variations could have been artificial or natural. Nevertheless, human endeavors have been generating these shifts fueling climate change throughout the end of the nineteenth century. The primary activity performed by humans that emits harmful greenhouse gases directly into the atmosphere is the consumption of fossil fuels including natural gas and coal, see Figure 1. The main considered gases that cause climate change include carbon dioxide ($CO_2$) and methane ($CH_4$). The continual consumption of fossil fuels is a hindrance to minimizing the phenomenon of global warming through decreasing emissions of greenhouse gases (Mukherjee *et al.*, 2015). Carbon dioxide emitted by fossil fuel combustion makes up sixty-five percent of the total amount of greenhouse gases(Bains, Psarras, and, Wilcox, 2017). The increased amount of greenhouse gases (GHGs) in the nearest (troposphere) atmosphere increases the earth's global temperature by trapping heat from the sun and the earth. The aforementioned phenomenon is a significant factor contributing to climate change. The contribution of consuming fossil fuels to climate change is obvious, as they emit greenhouse gases, mainly $CO_2$, into the atmosphere once burnt. Global net-zero greenhouse gas (GHG) emissions must be achieved to meet the Paris Agreement's climate target of keeping the global average temperature well below 2°C and reducing temperature increases to 1.5°C (Bataille *et al.*, 2018).

Despite understanding that the consumption of fossil fuels contributes to climate change and has several negative environmental consequences, the vast majority of countries' energy systems, both developed and developing, rely on fossil fuels (Martins *et al.*, 2019). Furthermore, fossil fuels are currently the primary sources of energy used in the transportation, industrial, and electrical energy generation sectors, as well as practically all other sectors where energy needs to be supplied (Zheng, 2011). To decrease or eliminate the emissions of carbon dioxide ($CO_2$) caused by the consumption of fossil fuels, which could contribute to meeting the Paris Agreement's objective of decreasing greenhouse gas emissions in the atmosphere, low-carbon energy technologies such as renewable energy sources (RES) and carbon capture, utilization, and storage (CCUS) must be implemented on a wide scale (Nogalska, Zukowska and Garcia-Valls, 2017). As a result, numerous European Union (EU) countries, including Norway, Germany, and Denmark, were considering renewable energy options. After a study to determine whether a 100% renewable European power

system is achievable by 2050, it was found that a 100% renewable power system will still require a large flexible zero-carbon storage capacity to balance variable renewable energy generation (Zappa, Junginger and van den Broek, 2019). To tackle this, the world has begun to emphasize carbon capture and utilization technologies together with renewable energy. CCUS technologies enable the integration of renewable energies in an energy system through storage and continuous utilization of fossil fuels as there are no emissions.

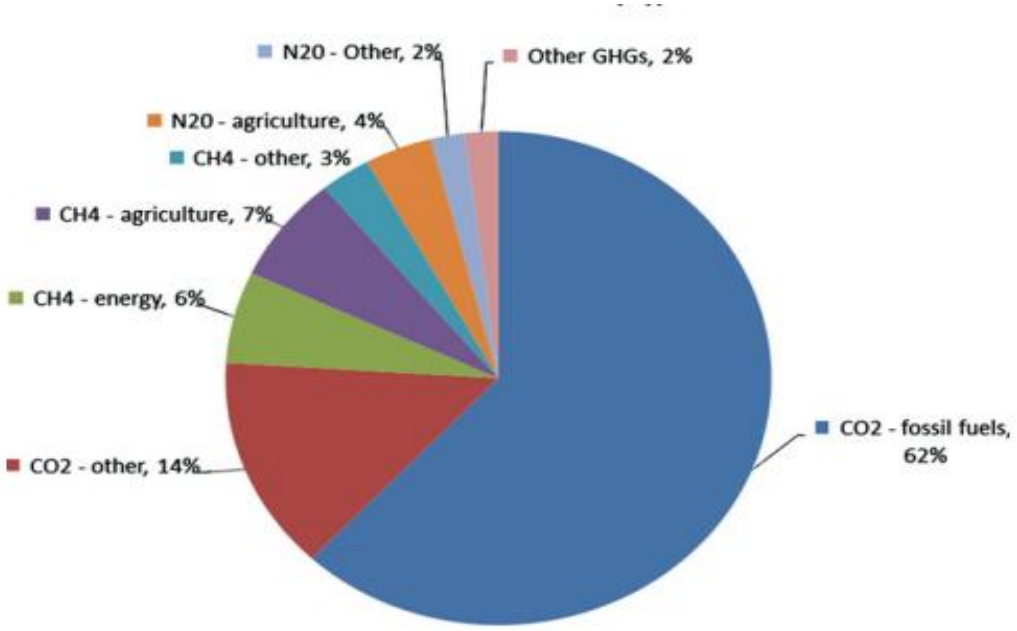



Figure 1: Global anthropogenic GHG emissions by type and source (Höök and Tang, 2013)

Carbon capture and utilization is the best technology to halt emissions of $CO_2$ coming from burning fossil fuels or any carbon-based energy source. It consists of separating $CO_2$ from industrial and energy-related sources and transporting it to a storage location for other applications or long-term isolation from the atmosphere (Wennersten, Sun, and Li, 2015). CCU has the technical potential to serve as a carbon source for chemical production decoupling the production of a chemical such as methanol and ethanol from fossil fuels, reducing GHG annual emissions by up to 3.5 Gt $CO_2$-eq in 2030 (Kätelhön *et al.*, 2019). In addition, it was found that an energy system consisting of fossil fuels, hydrogen, bio-fuels and renewable energy sources could be a good initiative for energy transition and combating climate change (Kalkuhl, Edenhofer and Lessmann, 2015). In this present work, an economic feasibility study and carbon capture simulation were conducted for the implementation of a carbon capture and methanation (with green hydrogen) project in a power

plant located in Gorubanda/Niamey, and a life cycle assessment was also conducted to analyze the environmental impacts of the project.

## 1.1 Problem Statement

The greenhouse effect refers to the ability of gases such as carbon dioxide and methane to effectively trap the planet's reemitted thermal radiations. The greenhouse effect is a necessary component for life on Earth to exist. However, trapping much of these radiations warms the planet as well, resulting in environmental damage. Human activities are increasing the concentration of carbon dioxide and other gases in the atmosphere, warming the earth by 1-5$^{o}$C (Wuebbles and Jain, 2001). Many studies have established that anthropogenic climate change is caused by the world's use of fossil fuels. Also, (Gustavsson *et al.*, 2017) have proven that high harvest levels and efficient utilization of forest biomass provide more climate benefits than limiting harvest and leaving biomass residues containing carbon compounds that can be naturally combusted or degraded. Furthermore, the combustion of fossil fuels like coal, petroleum, and natural gas is a major cause of air pollution, affecting the physical and mental health of people, particularly children, who are the most sensitive (Perera and Nadeau, 2022). Nevertheless, another major concern identified was the decreasing supply of fossil fuels. The anthropogenic climate change problem and the fossil fuels energy crisis are two intertwined challenges that require a comprehensive solution (Höök and Tang, 2013). Changes in fossil fuels utilization pathways and investments in carbon-free energy production technologies are essential for the observed global warming to be kept below 2$^{o}$C (Johnsson, Kjärstad and Rootzén, 2019).

Energy is critical to any country's economic and social development. Population expansion and increasing urbanization also have a significant impact on energy demand. Figure 2 depicts how global energy demand rises in tandem with population growth. The sector of electricity generation is the most important among the various sectors of energy consumption because of the rapid increase in electrical energy demand in both developed and developing countries, which is also tied to population expansion (Figure 3). According to (Warsame, 2022) after conducting a study of the effects of urbanization on energy demand, it was discovered that urbanization reduces energy consumption while economic and population expansion raise energy consumption. In 2011, the worldwide energy consumption was predicted to be around 550 exajoules, which was primarily met by fossil fuels. Greenhouse gas emissions are another element that may raise energy demand

as a result of the potential integration of carbon management technologies into energy production systems for climate change mitigation (Siirola, 2014).

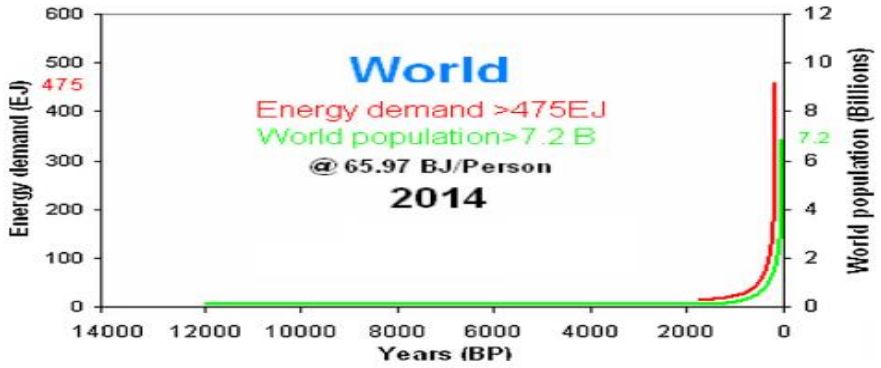



Figure 2: Energy demand and population growth (Abas, Kalair, and Khan, 2015)

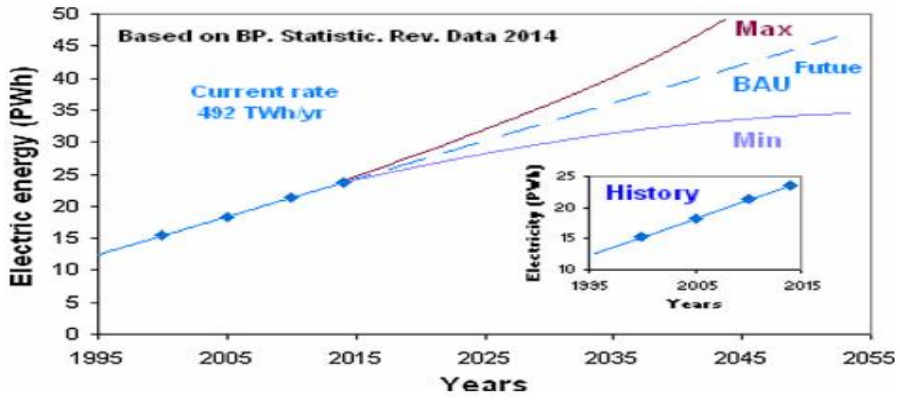



Figure 3: Worldwide accumulative electric energy demand over time (Abas, Kalair and Khan, 2015)

## 1.2 Research Questions

The purpose of this study is to investigate the economic analysis and life cycle assessment (LCA) of a carbon capture and methanation project together with a simulation of a carbon capture system. Several research questions were addressed to reach this goal**.**

- What will be the economic costs and benefits of implementing the project in a power plant in Niamey?
- Will the analysis provide insight into the important elements determining the project's economic viability, taking regional and sectoral differences into account?

- What will be the project's environmental performance, including its influence on greenhouse gas emissions, resource consumption, and overall carbon footprint reduction?

By addressing these research questions, the study aimed to provide significant insights into the project's economic and environmental aspects.

## 1.3 Research Hypothesis

The primary goal of this study is to investigate the economic analysis and life cycle assessment (LCA) of a carbon capture and methanation project using numerous research hypotheses. It is assumed that implementing a carbon capture and methanation project at this power plant will result in a net economic advantage after accounting for implementation costs, operational expenses, and the value of the produced methane. According to the study, factors such as feedstock availability and energy prices will have an impact on the project's economic viability. Furthermore, it is anticipated that the project will result in a reduction of the overall carbon footprint, as determined by a full LCA, as well as lower environmental consequences, such as greenhouse gas emissions and consumption of resources. This study intends to contribute to a better understanding of the economic and environmental ramifications of the carbon capture and methanation project by exploring these research hypotheses.

## 1.4 Research Objectives

The goal of this work is to examine the economic analysis and life cycle assessment (LCA) of a carbon capture and methanation project, with the research objectives that follow:

i. To evaluate the economic costs and benefits of implementing this carbon capture and methanation project in a power plant located in Gurubanda/Niamey and analyze the primary factors influencing the project's economic viability.

ii. Through a full life cycle assessment, analyze the overall carbon footprint reduction achieved by implementing the carbon capture and methanation project and quantify the environmental implications of the project's various stages, including greenhouse gas emissions and consumption of resources.

**iii.** Assess the potential co-benefits of project implementation, such as reduced air pollution and increased energy security, and make a simulation of a carbon capture system for incorporating uncertainty and fluctuation in crucial variables such as feedstock availability and energy costs into the project.

# Chapter 2: Literature Review

This chapter contains a review of the literature on various carbon capture systems and procedures for the separation of $CO_2$ from flue gas. A literature review on green hydrogen applications and the decarbonization of certain types of power production plants, as well as the method of methanation of collected carbon dioxide with green hydrogen, has also been conducted.

## 2.1 Carbon Capture Technologies

Carbon capture technologies are currently categorized into four categories: post-combustion, oxy-fuel combustion, pre-combustion, and chemical looping cycle. The parameters to consider while selecting carbon capture technology are the concentration of $CO_2$ in the flue gas, the operating condition of the flue gas, and the pressure of the gas stream.

### 2.1.1 Oxy-fuel Combustion $CO_2$ Capture Technology

Oxy-fuel combustion is one of the promising carbon capture technologies used to capture industrial $CO_2$ (Carrasco-Maldonado *et al.*, 2016). In oxy-fuel combustion, the fuel is burned in pure oxygen rather than in air (Buhre *et al.*, 2005). In the absence of nitrogen (N2), the concentration of $CO_2$ in the flue gas is higher as a result of combustion in an oxygen-only atmosphere. Given that there is no nitrogen in the flue gas, using this method to capture $CO_2$ may reduce NOx emissions into the atmosphere. It may also make the separation of $CO_2$ from the flue gas easier. The produced gas in the oxyfuel combustion method can be recycled back into the boiler to control the temperature. Due to the recycling of the flue gas, it then consists primarily of CO2, allowing $CO_2$ to be stored without being stripped from the flue gas (Buhre *et al.*, 2005). Techno-economic assessments of oxy-fuel combustion technology have proved that it is a cost-effective technology, and life cycle analysis has proved that it is an emissions-reducing technology (Gerbelová, Van Der Spek and Schakel, 2017). Nevertheless, in comparison to the others, the technology is still not widely in application (Chen, Yong and Ghoniem, 2012).

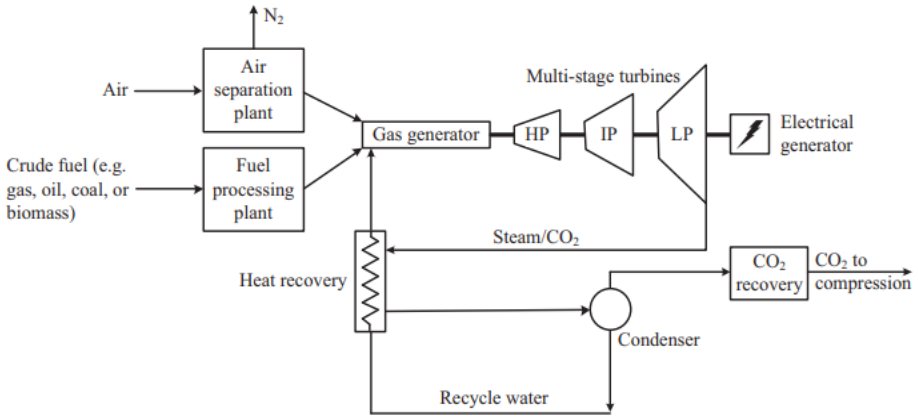



Figure 4: Steam turbine-based oxy-fuel power generation system (Yin and Yan, 2016).

### 2.1.2 Post-combustion $CO_2$ Capture Technology

Post-combustion technology is the most current technology used to reduce Carbon dioxide ($CO_2$) (that contributes to global warming and must be minimized (Mukherjee *et al.*, 2019)) emissions. $CO_2$ is caught in post-combustion technology at the end of a fuel's combustion in the air. The primary goal of this technology is to separate and store $CO_2$ from flue gas (Bailey and Feron, 2005). The difficulty with this methodology is the low $CO_2$ concentration in the flue gas, which is caused by the dilution of the oxidizing agent (oxygen) by nitrogen from the air. Figure 4 depicts a hypothetical power plant operating in post-combustion mode.

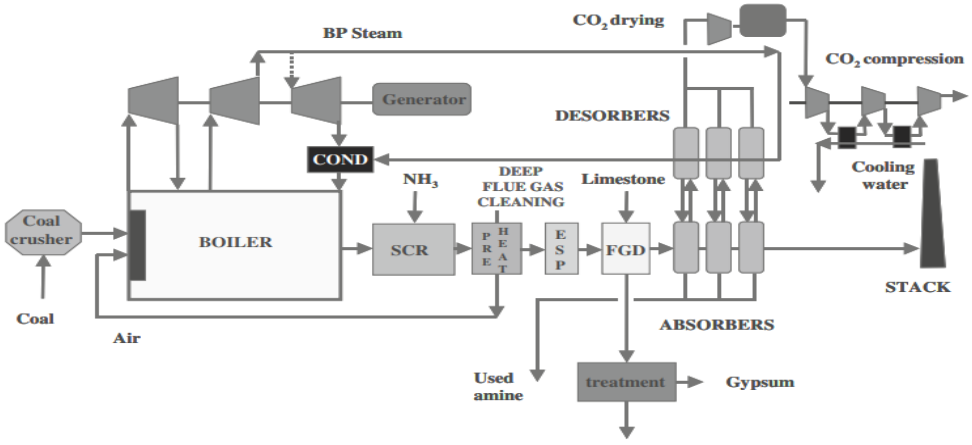



Figure 5: Example of post-combustion technology (Kanniche *et al.*, 2010)

### 2.1.3 Pre-combustion $CO_2$ Capture Technology

Post-combustion technology is the most scaled-up of the carbon capture methods. However, post-combustion technology has two major issues: low $CO_2$ content in the flue gas, which affects

separation costs, and NOx emissions due to the presence of nitrogen in the oxidizing agent (air) (Theo *et al.*, 2016). Pre-combustion is the technology that can be used to capture $CO_2$ before the combustion of fuel (van Selow *et al.*, 2009). The oxidizing element is not diluted with nitrogen. One of the difficulties in dealing with this technology is the need for practically pure oxygen.

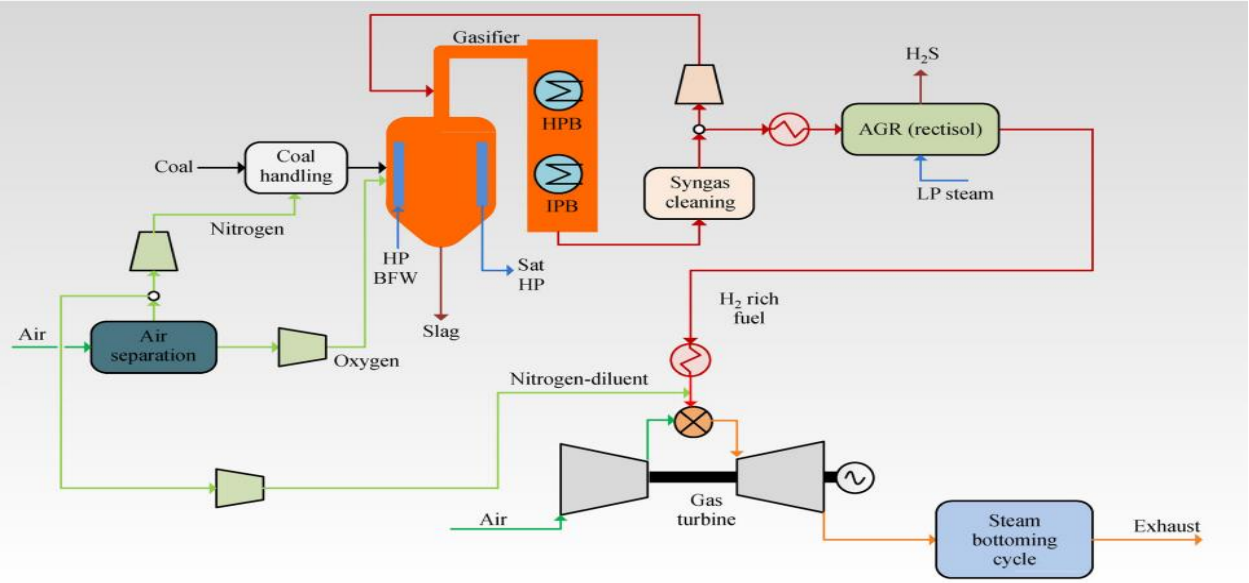



Figure 6: Process flow diagram of pre-combustion technology (Roussanaly *et al.*, 2020)

### 2.1.4 **Chemical Looping Cycle**

Solid compounds termed oxygen carriers are utilized as oxidizing agents in chemical looping technology. In the fuel reactor, oxygen carriers oxidize the fuel. After being reduced by the fuel, oxygen carriers are returned to the air reactor to be regenerated (figure 8).

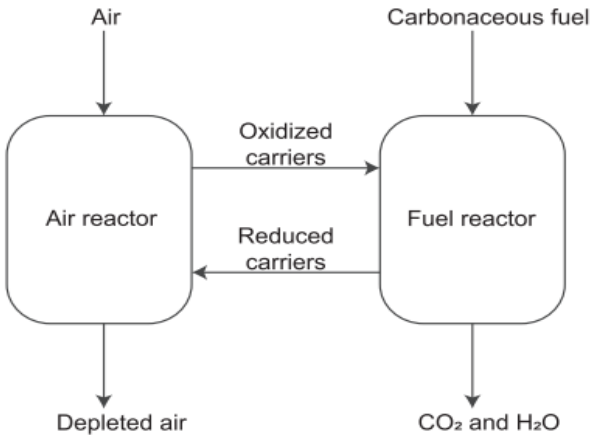



Figure 7: Schematic illustration of chemical looping combustion (Saqline, Chua and Liu, 2021)

## 2.2 Carbon Capture Processes

For the separation of $CO_2$ from exhaust flow gases, the processes have often been integrated with the four specified technologies. They are divided into four categories: absorption, adsorption, membrane separation, and cryogenic separation.

### 2.2.1 Absorption

The absorption process is a high-capacity technology for removing $CO_2$ from flue gas. This process is typically used in conjunction with post-combustion technology for $CO_2$ capture and separation from stream gas utilizing amines as solvents (Sreedhar *et al.*, 2017). Due to the fact that the captured stream gas may come from a variety of sources, the choice of carbon capture (CC) technology is crucial. Absorption technology is divided into three categories: chemical absorption, physical absorption, and hybrid physical-chemical absorption. According to the techno-economic analysis of the three different absorption processes, chemical absorption has the best performance at low $CO_2$ concentrations (30.4%), hybrid physical-chemical absorption is the most cost-effective at medium $CO_2$ concentrations (30.4%-59.3%), and physical absorption is the most economical at high $CO_2$ concentrations (>59.3%) (Zhang *et al.*, 2020). Furthermore, because of the use of solvents, this approach has several limitations, such as corrosion, solvent degradation, and solvent regeneration ('Feasibility Study of Carbon Capture and Storage Process to Implement in Maritime Industry.', 2022).

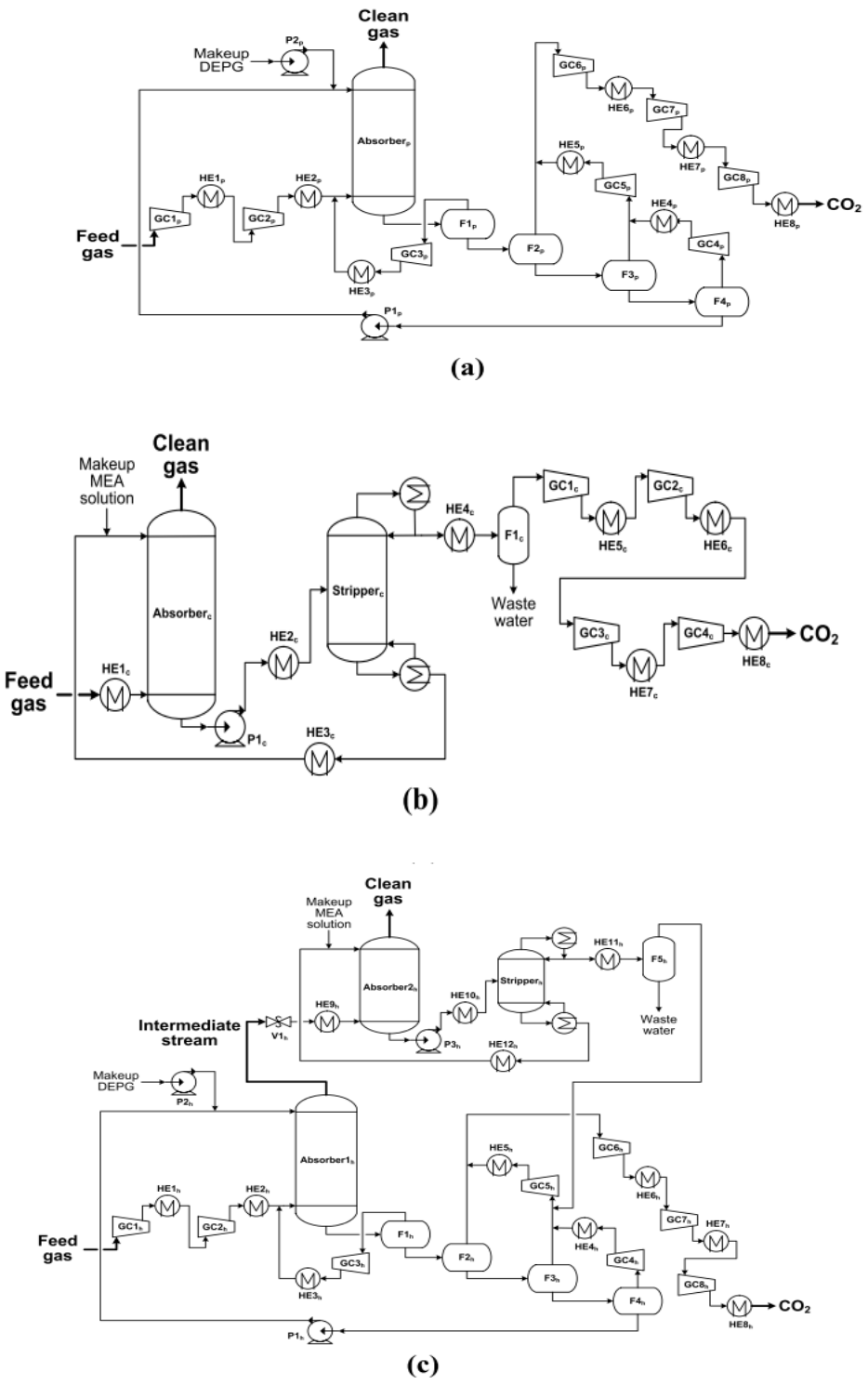



Figure 8:(a) physical absorption process, (b) chemical absorption process, (c) hybrid physical-chemical absorption (Zhang *et al.*, 2020).

### 2.2.2 **Adsorption**

Adsorption, in general, is a physical phenomenon that involves or consists of the separation of a material from one phase, followed by its accumulation or concentration at the surface of another phase. Adsorption is a cyclic process in carbon capture technology that alternates between adsorption and desorption modes of operation. Adsorption sorbents are categorized into three types based on their working temperature: low-temperature sorbents (200$^{o}$C), intermediate-temperature sorbents (200$^{o}$C-400$^{o}$C), and high-temperature sorbents (>400$^{o}$C). Because of the potential chemical interactions, the two final groups of sorbents are not suitable for the post-combustion procedure (Wilcox *et al.*, 2014). The adsorption method is made up of four (4) processes Figure 9 (a).

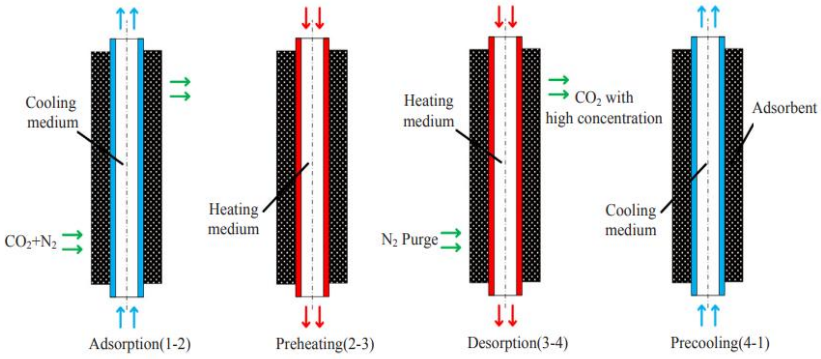
Process 1-2: Adsorption of $CO_2$ in a reactor with a cooling medium occurs. The cooling medium removes the heat produced by the adsorption reaction.

Process 2-3: The step in which a reactor with a heating medium begins to be heated for $CO_2$ desorption to occur.

Process 3-4: The desorption process begins at this point.

Process 4-1: The phase of desorption

The thermodynamics of the several processes are illustrated in Figure 9 (b).




(a)

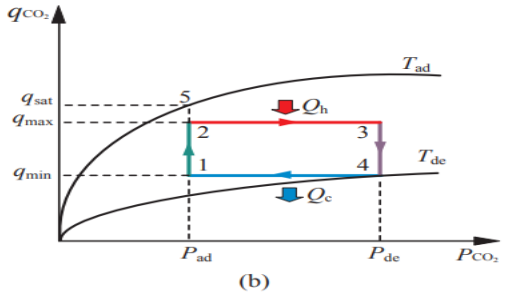



Figure 9: (a) four adsorption steps, (b) adsorption isothermal diagram(Jiang, Roskilly, and Wang, 2018).

### 2.2.3 **Membrane Separation Technology**

Membrane separation is another approach for separating $CO_2$ from collected gas streams by utilizing a selective membrane as a filter that permeates the desirable components while retaining the unwanted ones (Figure 10).

Gas flow permeation under unit pressure difference across unit membrane area, through unit membrane thickness (mol s-1 m-2 Pa-1) is known as permeability, and membrane selectivity is defined as the ratio of permeabilities of distinct gas molecules entering the same membrane. Some of the criteria that define a gas's selectivity are its molecular size, affinity to membrane material, and molecular weight (Ji and Zhao, 2017).

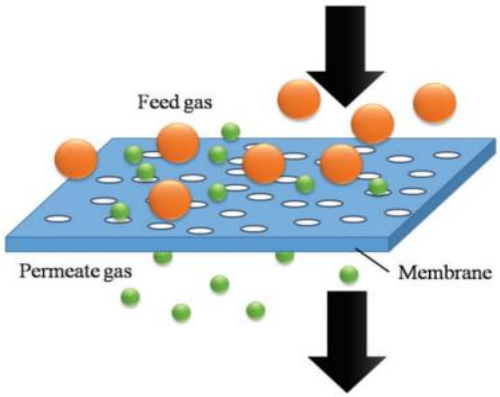



Figure 10: Schematic of membrane for binary gas mixtures (Ji and Zhao, 2017).

### 2.2.4 **Cryogenic Separation**

Carbon capture and storage technologies have provided a solution to reduce carbon dioxide industrial emissions for economic growth, air pollution reduction, and global warming (Hoeger, Burt and Baxter, 2021). Among the several processes used to extract $CO_2$ from streaming gas, cryogenic carbon capture was shown to be the best in terms of $CO_2$ recovery rate and $CO_2$ purity level, even though it is not widely employed, making it more expensive. The cryogenic $CO_2$ separation is a low-temperature (below 120K) $CO_2$ separation (from flue gas) process that relies on phase change. It is also based on the difference in boiling temperatures and de-sublimation properties of the gas molecules (Font-Palma, Cann and Udemu, 2021). The main cryogenic processes are cryogenic distillation, external cooling loop and cryo-cell process.

#### 2.2.4.1 Cryogenic Distillation

Cryogenic distillation is a $CO_2$ separation process based on the boiling temperatures of carbon dioxide and other gas molecules. Cryogenic distillation separates $CO_2$ from flue gas at very low temperatures and high pressure. $CO_2$ was obtained at extremely high pressure, reducing the cost of compression. However, for a non-$CO_2$-concentrated stream, this process is not economically or energetically practical. Initially, raw gas is compressed using a compression system and then cooled using a heat exchanger before being liquefied in a liquefier. The liquid stream was sent to the distillation tower, where it was separated into two parts: top products and bottom products. The bottom product is a rich $CO_2$ stream that flows after the reboiler at the bottom of the distillation tower has boiled it Figure 11.

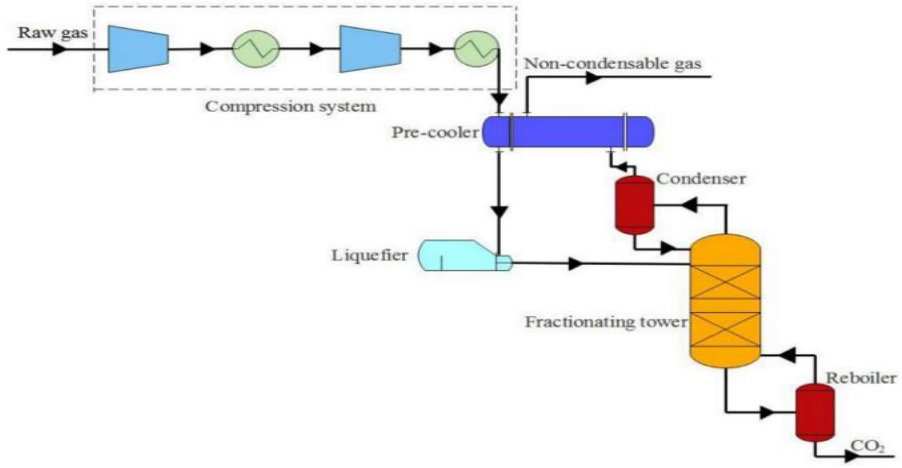



Figure 11: Example of a diagram of cryogenic distillation (Liu *et al.*, 2019)

### 2.2.4.2 **External Cooling Loop Cryogenic Carbon Capture**

External cooling loop cryogenic carbon capture (ECL-CCC) is a process that involves drying, cooling, and compressing of flue gas to a temperature above the $CO_2$ sublimation point. The flue gas is cooled using an external refrigerant loop in this process. Mostly, the process could be powered by cold waste industrial energy. This process is currently being utilized to capture up to one ton of $CO_2$ each day (Frankman *et al.*, 2021). The ECL-CCC cools a provided flue gas to 175 degrees Celsius, de-sublimating $CO_2$ particles. If the flue gas can be chilled to less than -140°C, it can reach a $CO_2$ recovery rate of 90% or even higher(Xu and Lin, 2017). The flue gas enters the heater for cooling, and the cooled gas is further chilled and de-sublimated. Finally, the de-sublimated $CO_2$ is obtained using a solids filter see Figure 12.

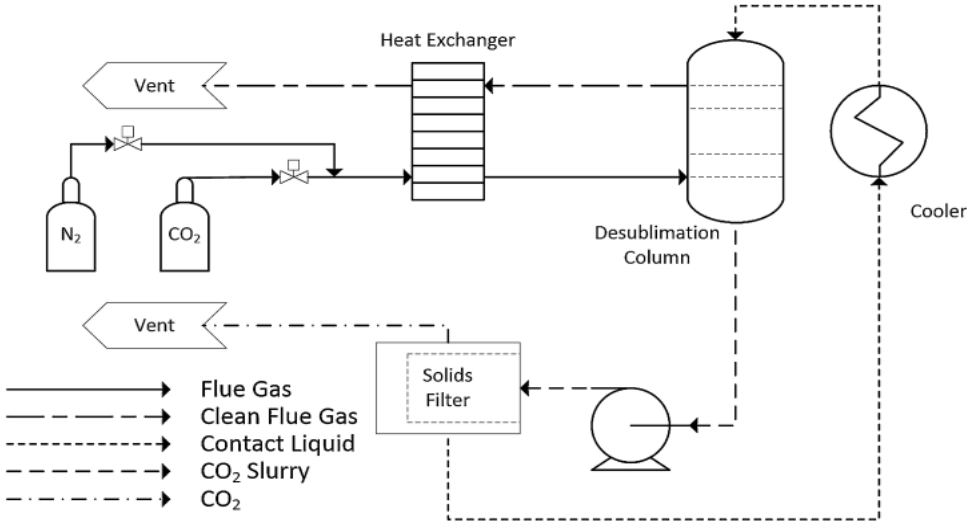



Figure 12: Simplified diagram of ECL-CCC technology (Jensen *et al.*, 2015)

### 2.2.4.3 **Cryo-cell process**

The cryo-cell technique is fundamentally identical to the external cooling loop approach. The initial stage in cryo-cell is to dehydrate the flue gas, followed by cooling it through a heat exchanger until it gets condensed. The produced liquid then undergoes a Joule Thomson expansion, resulting in a three-phase mixture separated by a three-phase separator known as a cryo-cell chamber.

## 2.2.5 **Comparison of $CO_2$ separation processes**

In Table 1, the $CO_2$ separation processes are compared in terms of advantages and disadvantages.

Table 1: Comparison of the different $CO_2$ separation processes

| Process | Advantage(s) | Drawback |
|---|---|---|
| **Physical absorption** | • $CO_2$ can be removed at low temperatures<br>•low toxicity<br>•lower vapor pressure<br>•Solvent less corrosive | •High energy demand |
| **Chemical absorption** | •most mature and commercialized<br>•Can be used with current industrial set-ups | •Good absorbent efficiency required<br>•Improvement required for the overall process<br>•low $CO_2$ capture capacity<br>•Equipment corrosion<br>•Solvent degradation<br>•high energy demand for regeneration<br>•large equipment |
| **Membrane separation** | •Increase in membrane stability | •low selectivity<br>•low product purity<br>•compression required for enough driving force |
| **Cryogenic separation** | •Simple and well-established<br>•Possibility of having high $CO_2$ purity<br>•Moderate pressure required | •Operating Cost very high |
| **Adsorption** | •Energy efficient<br>•Ease of material regeneration<br>•Much of adsorbent available | •Work required to improve stability and performance of the adsorbent material<br>•low selectivity<br>•May be affected by high water contain<br>•not suitable for post-combustion |

## 2.3 Green Hydrogen Applications

Some of the drivers of global warming are greenhouse gas emissions from the use of fossil fuel energy. As a result, the demand for green energy to combat climate change is growing day to day. Many studies have been conducted on the generation of green energy in different ways. Green hydrogen was discovered to be the most environmentally friendly and sustainable form of energy (Basheer and Ali, 2019). Green hydrogen is a clean form of energy that is produced from renewable sources such as sun, wind, hydropower, biomass, and so on. It is used in stationary applications such as combined heat and power plants (CHP) and fuel cell electric generators for energy storage and generation (Widera, 2020). There are currently two means for extracting hydrogen energy: fuel cells and internal combustion engines.

### 2.3.1 **Mobility application of hydrogen**

Following extensive scientific investigation, green hydrogen was identified as a possible alternative fuel to replace traditional fuels (such as oil) in transportation sectors such as shipping to reduce greenhouse gas emissions (Atilhan *et al.*, 2021). It could be used to create alternative fuels, such as **SNG**, for transportation by utilizing carbon dioxide.

Today, hydrogen is utilized as a fuel in land transportation such as cars and buses, maritime transportation such as ships, and aeronautic mobility such as manned light aircraft, unmanned aerial vehicles, and unmanned underwater vehicles. Honda, Toyota, Hyundai, and BMW have all expressed interest in hydrogen vehicles. Toyota, for example, introduced the "MIRAI" in 2014 for 7.23 million yen (about 50,000 euros) (Mansilla *et al.*, 2018).

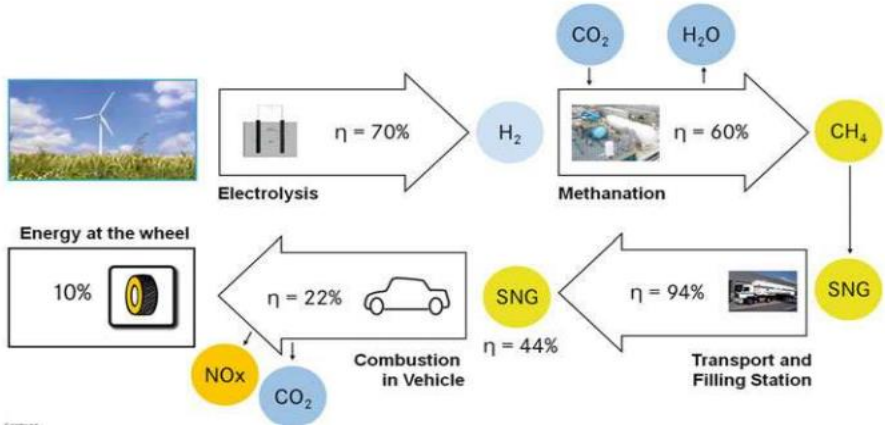



Figure 13: Methane gas production and utilization (Perspectives, no date)

### 2.3.2 **Stationary application of hydrogen**

In general, hydrogen stationary application refers to the use of hydrogen to create power or co-generate heat and electricity on one side and chemical synthesis such as ammonia, **SNG** on the other. Fuel cell devices are used to transform the chemical energy contained in hydrogen molecules into electrical energy for the generation of electricity or combined heat and power (Dönitz, 1998). Carbon dioxide from industrial sectors caused by the combustion of fossil fuels may be utilized to synthesize methanol for climate change mitigation in chemical hydrogen-based synthesis.

## 2.4 **Decarbonization of power generation plants**

The energy sector is the most influential among the sectors driving global political, economic, and social development. Environmental and climate problems are growing in tandem with energy

demand. Among the various energy consumption sectors, the power generation sector was determined to be the largest, accounting for 40% of total yearly $CO_2$ emissions (Bany Ata *et al.*, 2021).

### 2.4.1 Integrated gasification combined cycle (IGCC) power plant decarbonization

Gasification, in general, is the process of turning liquid or solid carbon-based materials into gases for use in power production or as chemical feedstock. An integrated gasification combined cycle is a system that produces syngas by partially oxidizing a given carbon-based fuel and then combining it with steam to produce hydrogen for power generation. The use of both steam and gas to generate electricity is referred to as a combined cycle. $CO_2$ emissions from industry should be restricted or minimized in light of global warming and rising energy demand. Carbon capture and utilization was identified as a viable technique for this purpose. There are currently four carbon capture technologies: post-combustion CC, pre-combustion CC, oxyfuel combustion CC, and chemical looping cycle CC. Carbon capture technology is usually identified based on the operating conditions of a plant.

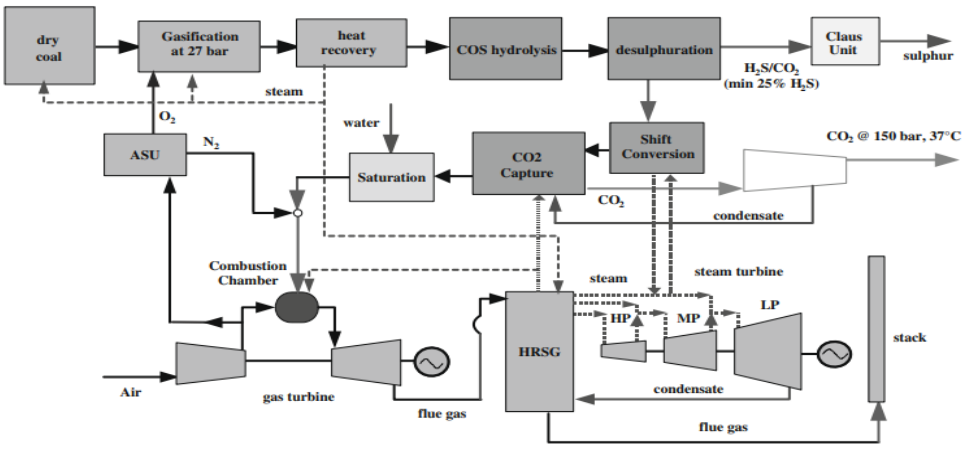



Figure 14: Example of IGCC with carbon capture (Kanniche *et al.*, 2010)

### 2.4.2 Conventional combustion of pulverized coal (PC) power plant decarbonization.

PC is another system mode for generating electricity. Coal is utilized in the system to power the facility through the combustion process, which emits $CO_2$. $CO_2$ emissions must be regulated to mitigate climate change. When compared to IGCC, a pulverized coal power plant system is more adaptable. It can be decarbonized using both post-combustion technology and oxy-combustion technology (Kanniche *et al.*, 2010). According to research, the deployment of carbon capture

technology may improve ecosystem integrity and human health while increasing resource use (Tang and You, 2018). Based on a study conducted by (Zhai, Ou and Rubin, 2015), Partial carbon capture is achievable for approximately 60 gigatons of existing coal-fired capacity, and the cost is highly dependent on unit characteristics and fuel costs.

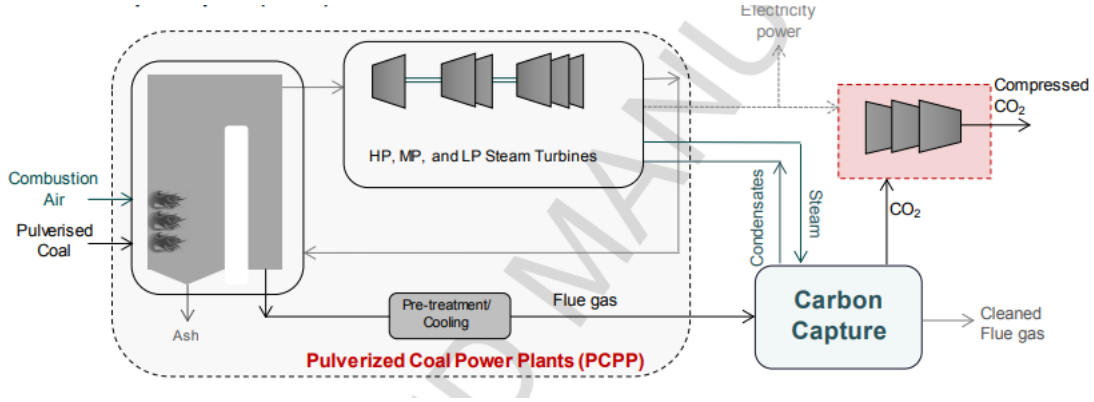



Figure 15: Summary of operation condition of Pulverized coal power plant with carbon capture (Sharifzadeh and Shah, 2019).

### 2.4.3 Natural gas combined cycle power plant decarbonization

Decarbonization technologies for natural gas combined cycle (NGCC) power plants include oxyfuel combustion and pre-combustion carbon capture. In the current system, natural gas is utilized as a fuel to operate a power plant, either by burning the fuel in an oxygen atmosphere or by partially oxidizing the fuel to syngas and then passing it through a shift reactor to make hydrogen. Furthermore, some writers identified the natural gas water-gas shift reaction as a process that may improve the efficiency of gas turbine cycles as a function of temperature, pressure, steam/methane ratio, and natural gas chemical composition (Lozza and Chiesa, 2002). In addition, a new integrated system for NGCC plant decarbonization that involves reusing waste heat generated during the $CO_2$ capture process was investigated and compared to the conventional NGCC power plant decarbonization system. The power output and energy efficiency of the new integrated system were determined to be 19.4 MW and 73.6% greater, respectively, than those of the conventional system. The integrated system takes only 2.6% additional investment to generate more than 3.1 € per MWh (Hu *et al.*, 2018).

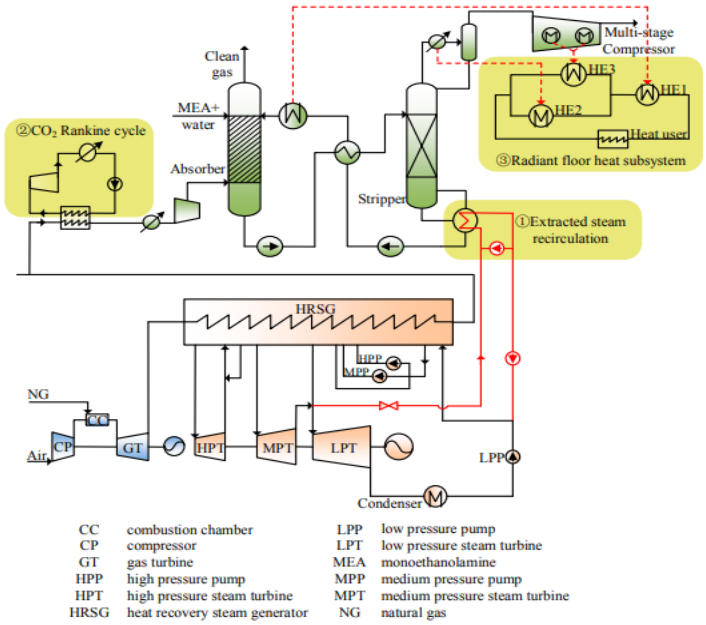



Figure 16: Integrated system for NGCC power plant decarbonisation (Hu *et al.*, 2018)

## 2.5 Methanation of an industrial captured $CO_2$ with green hydrogen

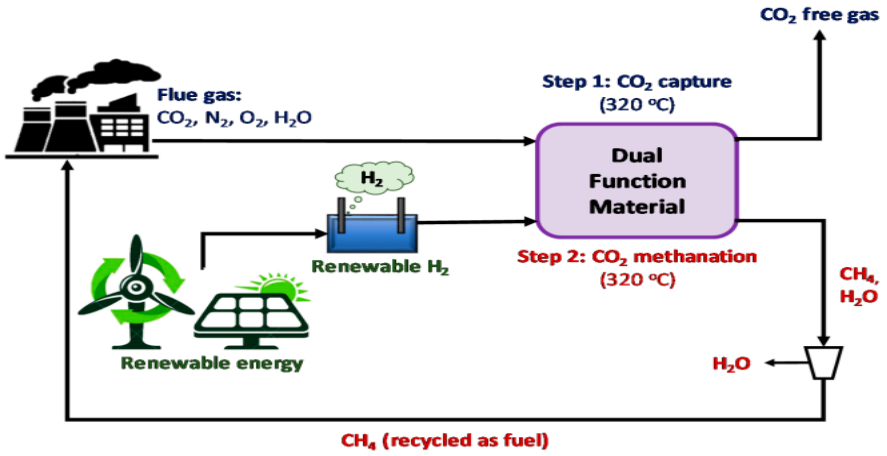
The methanation of collected industrial $CO_2$ with green hydrogen is a viable method for both utilizing hydrogen energy when hydrogen utilization infrastructure is lacking and transferring hydrogen to different locations of need in order to meet the energy demand. The methanation process, on the other hand, necessitates the creation of effective adsorbents and catalysts as stated by (Meylan, Piguet and Erkman, 2017). Surpluses of renewable energy should be employed as much as feasible in the methanation process, with biogenic and atmospheric $CO_2$ being the most desired sources for combating climate change. In other circumstances, industrial fossil-based $CO_2$ is also convenient.

According to research, a cyclic decarbonization-carbonization cycle can be achieved by utilizing a single dual-functional material via adsorption and methanation (Zheng, Farrauto, and Chau Nguyen, 2016). The dual functional material is made up of a nano-dispersed CaO that acts as a $CO_2$ adsorbent and a Ru metal supported on a y-$Al_2O_3$ (5%Ru, 10% $CaO/Al_2O_3$). However, as compared to CaO-based sorbents, carbonated Ni/CaO catal sorbents were found to be entirely regenerated after converting $CO_2$ into methane during the methanation process (Jo *et al.*, 2020). The activation energy of $CO_2$ methanation was discovered to be 66.1 kJ/g per mole of methane.

The reaction orders for hydrogen, $CO_2$, and the product ($CH_4$) were 0.88, 0.34, and zero, respectively (Duyar *et al.*, 2015).

CO2 hydrogenation, on the other hand, was done apart from its capture site. The chemical process that is taking place is known as the Sabatier reaction, which is depicted in equation (1) below. The reaction is exothermic, with an operating temperature of approximately 250-400ºC. According to an investigation carried out by (Castellani *et al.*, 2017), the operating pressure range was discovered to be 2-20 bar, with high operating pressure corresponding to a high CH4 percentage in the outlet gaseous mixture: 64.75% at 8 bar and 97.24% at 20 bar.

$$CO2 + 4H2 \rightarrow CH4 + 2H2O \qquad \Delta H = -164\ kJ/mol \qquad (1)$$

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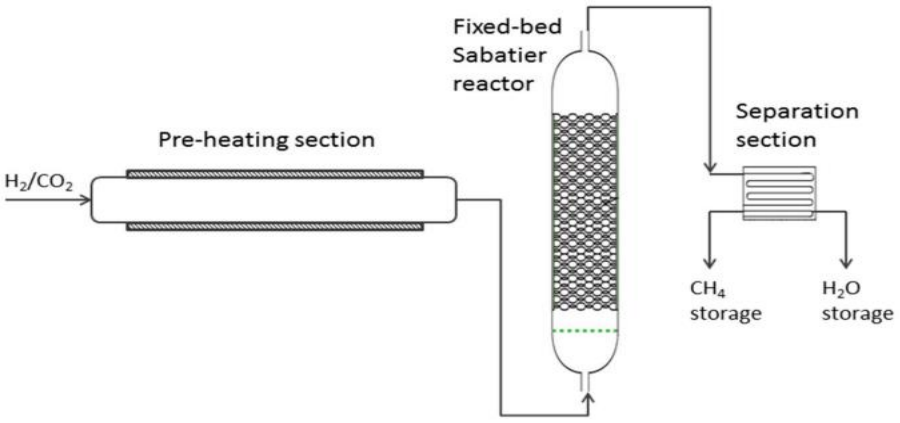



b)

Figure 17: a) Summary of the dual function-material concept (Tsiotsias *et al.*, 2020), b) Schematic of $CO_2$ methanation process (Castellani *et al.*, 2017)

# Chapter 3: Materials and Methods

In this work, a feasibility study of decarbonizing a specific power-producing plant located in Gorubanda in Niamey was conducted through economic analysis, life cycle assessment, and a simulation of a carbon capture system. One of the absorption processes was used to absorb $CO_2$ from exhaust gas generated by combustion in the power plant. The post-combustion $CO_2$ capture technology was chosen based on the fuel utilized by the plant and the operating conditions of the plant (combustion process for power generation).

## 3.1 Materials

The main focus of this thesis was on process simulation and analysis. A combination of software tools and a spreadsheet (Excel) were used as materials to conduct the research. The materials employed are as follows:

- **Excel for the economic** analysis of the project and some calculations.
- **OpenLCA software** for life cycle analysis of the project.
- **Aspen Adsorption software** for simulating $CO_2$ capture system via adsorption phenomena.
- **QGIS software** for mapping the study area.

## 3.2 Methods

### 3.2.1 Economic analysis

Economic assessment is a special aspect of analyzing the possibility of any technology being economically applicable. Costs for both operations and initial investments of the overall project were assessed in this work. According to the ratio factors suggested by Peter and Timmerhaus (Chauvy *et al.*, 2020) for fluid processing plants, the total capital investment (CAPEX) was calculated using the methodology below, together with the capital investment (x) of the equipment .

$$CAPEX = TDC + TIC \qquad (2)$$

Where TDC is the total direct cost and TIC the total indirect cost of goods, summarized in

Table 2 and RF is the ratio factor for direct, indirect, and working capital.

Table 2: Total capital investment (TCI) estimation (Chauvy et al., 2020)

| Type | Item (i) | Ratio Factor | Cost (Euro) |
|---|---|---|---|
| **Direct cost** | Purchased equipment(delivered) | 1.00 | X |
| | Purchased equipment installation | 0.47 | X*0.47 |
| | piping | 0.36 | X*0.36 |
| | Instrumentations and controls | 0.68 | X*0.68 |
| | Electrical systems | 0.11 | X*0.11 |
| | Buildings (including services) | 0.18 | X*0.18 |
| | Yard improvements | 0.10 | X*0.10 |
| | Service facilities | 0.70 | X*0.70 |
| **Total direct cost** | | | Y=X*3.6 |
| **Indirect cost** | Engineering and supervision | 0.33 | Y*0.33 |
| | Construction expenses | 0.41 | Y*0.41 |
| | Legal expenses | 0.04 | Y*0.04 |
| | Contractor's fee | 0.22 | Y*0.22 |
| | contingency | 0.44 | Y*0.44 |
| | Working capital | 0.89 | Y*0.89 |
| **Total indirect cost** | | | Z=Y*2.33 |
| **Total capital investment (CAPEX)** | | | =Y+Z |

The main process equipment cost is supposed as X and, the TDC and TIC are considered as Y and Z respectively.

The operating cost was estimated using Table 3. The yearly amount required for items such as catalyst, solvent, green hydrogen, water and energy was calculated followed by cost estimation.

Table 3: Operating cost estimation(Becker, Penev and Braun, 2019; Zhang *et al.*, 2019; Chauvy *et al.*, 2020)

| type | Item (j) | Cost |
|---|---|---|
| **FOPEX** | Operating labor | 5 labors/shift, 3 shift/day |
| | Supervisory & clerical labor | 20% Operating labor |
| | Maintenance & repairs | 3% CAPEX |
| | Operating supplies | 15% M&R |
| | Catalyst | 90€/kg |
| | Solvent | 1€/kg |
| **VOPEX** | hydrogen | 2.17€/kg |
| | Cooling Water | 0.025€/ton |
| | Energy consumption | 9.3€/kWh |
| **TOPEX** | | = FOPEX + VOPEX |

### 3.2.2 **Life Cycle Assessment**

LCA is the best method for examining how a process, product, or activity may affect the environment. LCA has had a remarkable increase in use over the last ten years. In parallel with this development, the ISO standardization process was launched, structuring the LCA process and providing practitioner recommendations (Pehnt and Henkel, 2009). An LCA is completed in four steps:

- Defining the goal and scope of the study

The goal definition must describe "the intended application of the study and the reasons for carrying out the study". On this basis, the objective to be studied, its functional unit, reference flow, system boundaries, objectives, and potential uses of the study must be stated within the scope.

- Stage of the life cycle inventory (LCI)

LCI entails compiling and quantifying the system's inputs and outputs. The collected data can be further classified as inflows (energy inputs, raw material inputs, ancillary inputs, and other physical inputs) and outflows (products, co-products, waste, emissions to air, discharges to water, and so on). Where LCI data from measurements or the literature is unavailable, generic data from LCI databases must be used. The data's representativeness can differ between potential databases (for example, ecoinvent and GaBi professional).

- Impact analysis of the life cycle

In this step, the system's inputs and outputs are categorized and divided into environmental effect categories, and category indicator results are calculated.

- The interpretation of the results

The results must be summarized and presented as the foundation for conclusions and suggestions in the last stage. Limitations must be discovered. Sensitivity analysis can be an effective method for this.

### 3.2.3 **Aspen Adsorption simulation**

The simulation of $CO_2$ capture with Aspen Adsorption software was made in three steps with **silicate** based adsorbent material on a single bed.

- Creation of the simulation model

After launching Aspen Adsorption, a new simulation model was created. The components used to build up the model are gas feed and product, valves, adsorption bed and cycle organizer.

- Specification on some parameters

Specifications on feed gas, feed valve, adsorption column, and product valve and gas product were carried out. The specifications were mainly on temperature, pressure, feed property and composition, feed flowrate, bed height and diameter, time taken for each step of the three etc.

- Running simulation

After the specifications, the simulation was executed by running the established model. The software has calculated and simulated the behavior of the adsorption process based on the specifications made. The system was controlled by the cycle organizer.

# Chapter 4: Case study of power plant located in Gorubanda

The Gorubanda diesel-based power plant, located 5km south of Niamey with four 20 MW diesel turbines was built by Sinohydro, which started construction in April 2013. The construction of lines and substations was carried out by the Chinese company TBEA. This plant was built with the aim of improving the power supply of Niamey and reducing dependence on the interconnection with Nigeria.

In addition, with four MAN 18V48/60TS engines already in operation on-site, the installation of another of the same kind has increased the power plant's total capacity by 20 MW, bringing it to more than 100 MW. "After this expansion, the Gurobanda power plant will provide more than 45% of Niger's power generation capacity ''Saab stated''(Chad, 2022). Despite that, Niger remains one of Africa's countries with the lowest electrification rate.

The work presented here aims to create an additional energy generation capacity of the Gorubanda power plant to promote the economic and social development of Niger. As impact, this project may be involved in making the power plant ''green'', reduce $CO_2$ emissions and help to integrate renewable energy into Niger's energy system.

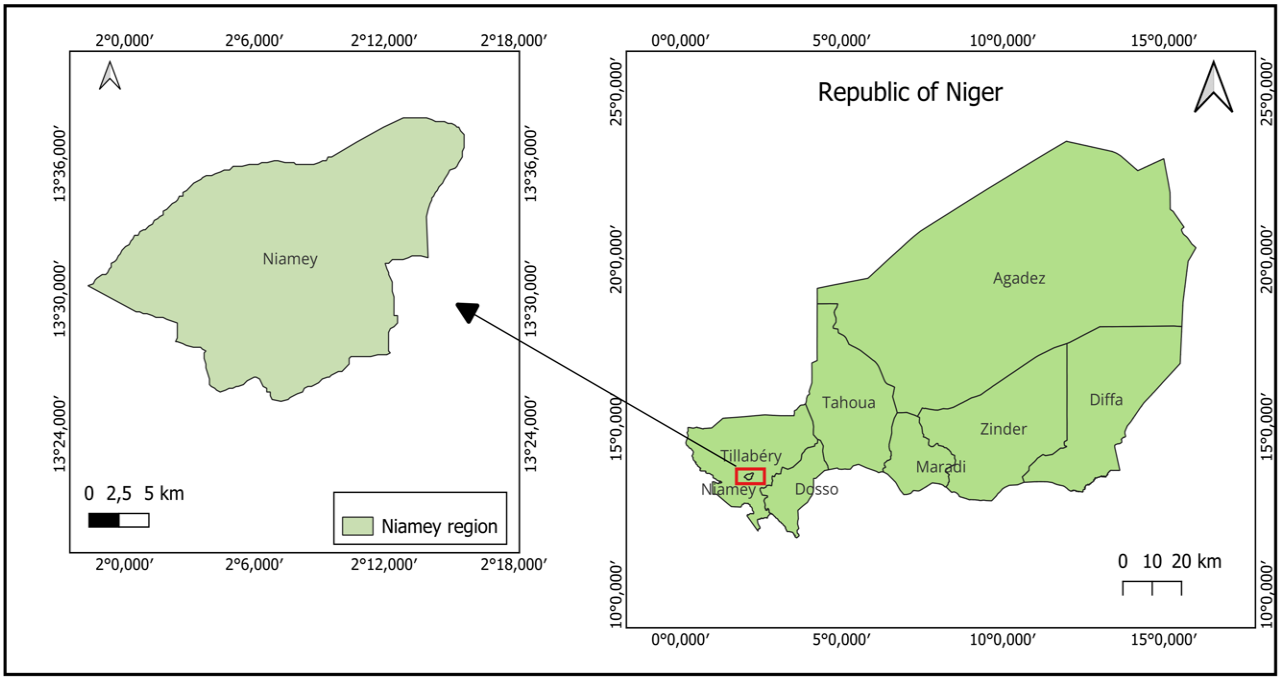



Figure 18: Map of the study area

## 4.1 Economic Evaluation of the Project

In the economic evaluation of the present project, the following has been determined:

- Total CAPEX and OPEX of the project
- Levelized cost of the product (LC) and net present value (NPV)
- Return on investment, payback period and sensitivity analysis

The methodology used to calculate the CAPEX and OPEX which were used to calculate the remaining parameters was shown in chapter 3. The cost of the main equipment (Table 4) for $CO_2$ capturing, methanation and gas upgrading was estimated to be around **28.14M€** and taken reference from a similar project (Chauvy *et al.*, 2020). The annualized CAPEX is calculated by multiplying the CAPEX with the capital recovery factor (CRF) which was calculated the using equation below.

$$CRF = \frac{i(i+1)^n}{(i+1)^n - 1} \qquad (3)$$

Where, n=number of years and i = interest rate.

Table 4: Main equipment of the process

| Main equipment | $CO_2$ capture | $CO_2$ methanation | Gas upgrading |
|---|---|---|---|
| **Columns(absorber/stripper)** | ✓ | - | - |
| **Reactor** | - | ✓ | - |
| **Compressors** | ✓ | ✓ | ✓ |
| **Turbine** | - | ✓ | - |
| **Heat exchangers (Heaters/coolers)** | ✓ | ✓ | ✓ |
| **Flash tanks** | ✓ | ✓ | - |
| **Membrane** | - | - | ✓ |

For estimating the amount of $CO_2$ that the plant can generate, it is important to know the fuel consumption rate in liters per hour or the specific fuel consumption rate in liters per kilowatt-hour (l/kWh). It was assumed in this work that the fuel consumption rate is at 0.28 l/kWh (The assumption was based on diesel generators used in the power plant). Also, it has to be mentioned

that diesel fuel contains approximately 2640 grams of carbon per liter. The combustion process of diesel fuel releases about 2.66 kg of $CO_2$ for every kilogram of carbon burned.

**Hourly fuel consumption calculation:**

$$\mathrm{FC} = \frac{power\ ouput}{specific\ consumption\ rate} \quad (4)$$

$$= \frac{100}{0.28}$$

$$\boldsymbol{FC = 357.14 L/h}$$

**Carbon content in the fuel calculation:**

$$\mathrm{CC} = \frac{FC * CCD}{1000} \quad (5)$$

$$= \frac{357.14 * 2640}{1000}$$

$$\boldsymbol{CC = 943.99 kg/h}$$

**CO2 emissions calculation:**

$$\mathrm{CO2e} = Carbon\ content * CO2\ emission\ factor \quad (6)$$

$$= 943.99 * 2.66$$

$$\boldsymbol{CO2e = 2511.26 kg/h}$$

Therefore, this power plant running on diesel fuel with a capacity of 100MW can generate **2511.26kg/h or 2.51 metric tons/hour of $CO_2$**.

### 4.1.1 CAPEX and OPEX Estimation

The capital expenditure of the project was estimated using Table 2 in Chapter 3 and the total equipment cost presented in this chapter.

Table 5: CAPEX Calculation

| Items | DC (€) | IC (€) | CAPEX (€) |
|---|---|---|---|
| **Total equipment cost** | 28,140,000 | - | 28,140,000 |
| **Purchased equipment** | 13,225,800 | - | 13,225,800 |
| **Installation** | | | |

| Items | DC (€) | IC (€) | CAPEX (€) |
|---|---|---|---|
| **piping** | 10,130,400 | - | 10,130,400 |
| **Instrumentations and controls** | 19,135,200 | - | 19,135,200 |
| **Electrical systems** | 3,095,400 | - | 3,095,400 |
| **Buildings (including services)** | 5,065,200 | - | 5,065,200 |
| **Yard improvements** | 2,814,000 | - | 2,814,000 |
| **Service facilities** | 19,698,000 | - | 19,698,000 |
| **Engineering and supervision** | - | 33,430,320 | 33,430,320 |
| **Construction expenses** | - | 41,534,640 | 41,534,640 |
| **Legal expenses** | - | 4,052,160 | 4,052,160 |
| **Contractor's fee** | - | 22,286,880 | 22,286,880 |
| **contingency** | - | 44,573,760 | 44,573,760 |
| **Working capital** | - | 90,160,560 | 90,160,560 |
| **Total Cost** | 101,304,000 | 236,038,320 | 337,342,320 |

Based on the capital expenditure records, the calculation of the annualized CAPEX was then proceeded using a discounted cash flow analysis. This analysis incorporates the time value of money by discounting future cash flows to their present value based on an appropriate interest rate. The aim of performing this calculation was to obtain a more accurate representation of the annualized CAPEX, factoring in the opportunity cost of investing in this project. This provided valuable insights for financial planning and decision making. The lifetime of the main equipment was assumed to be 25 years and the interest rate was 8% (Zhang *et al.*, 2019). Using equation 3, the calculation of CRF was done as follows:

$$= \frac{0.08(1+0.08)^{25}}{(1+0.08)^{25}-1}$$

$$\boldsymbol{CRF = 0.093}$$

$$ACAPEX = 337342320 * 0.093$$

$$\boldsymbol{ACAPEX = 31372835.76}\ €$$

To calculate the total operating cost, the yearly amount of $CO_2$ to be collected from the plant needs to be known. For that, two assumptions were supposed to be made. First, it was assumed that the plant works **8 hours** per day (this is the standard time of a production shift in Niger) and second, it works **365 days** per year. From that, one can conclude that the plant works **2920** hours per year. As mentioned earlier in this chapter, this plant can generate 2.51 tons/hour. Taking into account the assumptions, the plant generates about **7329.2 tons** of $CO_2$ per year.

After knowing the amount of $CO_2$ to be generated yearly, the amount of hydrogen needed per year needs to be calculated. From the balanced equation (1), it can be seen that four (4) moles of hydrogen are required to react with one mole of $CO_2$ to produce one mole of methane.

To calculate the amount of hydrogen needed, one needs to convert the mass of $CO_2$ to moles using the molar mass of $CO_2$ (44.01g/mol) and then use the stoichiometric ratio.

**Given:**

Mass of $CO_2$=7329.2 tons=7329.2 *1000kg=7329200kg

Molar mass of $CO_2$=44.01g/mol

Molar mass of $H_2$=2.02g/mol

**Step 1: Conversion of mass of $CO_2$ to moles**

$$n(CO2) = \frac{m(CO2)}{M(CO2)} \qquad (7)$$

$$= \frac{7329200}{0.044}$$

$$\boldsymbol{n(CO2) = 166572727.3\ moles}$$

**Step 2: Calculation of moles of hydrogen**

$$\frac{n(GreenH2)}{4} = \frac{n(CO2)}{1} \qquad (8)$$

$$= 4 * \mathrm{n(CO2)}$$

$$\mathbf{n(GreenH2) = 666290909.1\ moles}$$

**Step 3: Conversation of moles of hydrogen to tons**

$$m(GreenH2)/year = n(H2) * M(H2) * 10\text{^}(-6) \quad (9)$$
$$= 666290909.1 * 2.02 * 10^{-6}$$
$$\boldsymbol{m(GreenH2)/year = 1,345.90\ tons}$$

The yearly cost of green hydrogen needed was calculated as follows:

$$Cost(GreenH2)/year = m(GreenH2)/year * Cost(GreenH2) \quad (10)$$
$$= 1345.90 * 2170$$
$$\boldsymbol{Cost(GreenH2)/year = 2,920,603}\ €$$

For calculating the cost of catalyst, the daily captured $CO_2$ needs to be known. As mentioned, the plant generates 2.51 tons/hour which means it generates 20.08tons/day as it works eight (8) hours per day.

Knowing the loading of the catalyst (5%) together with daily mass of $CO_2$ captured, the mass of the catalyst needed daily can be estimated.

$$m(Catalyst) = m(CO2)/day * L \quad (11)$$
$$= 20.08 * 0.05$$
$$\boldsymbol{m(Catalyst) = 1\ ton}$$

According to Table 2, the price of the catalyst is 90€/kg, which means 90000€/ton. In this work, the catalyst has been changed once per year. The cost of the total catalyst needed was multiplied by two (2) to have the yearly cost of the catalyst.

$$Cost(catalyst)/year = m(catalyst)/ton * Cost(catalyst) * 2 \quad (12)$$
$$= 1 * 90000 * 2$$
$$\boldsymbol{Cost(catalyst)/year = 180,000}€$$

The daily amount of solvent required is calculated using the following formula.

$$m(solvent) = \frac{daily\ mass\ of\ CO2}{Concentration\ or\ mole\ fraction\ of\ CO2} \quad (13)$$
$$= \frac{20.08}{0.12}$$
$$\boldsymbol{m(solvent) = 167.33\ tons/day}$$

Solvent also was considered to be changed once per year.

$$\text{Cost(solvent)/year} = \text{m(solvent)} * \text{Cost(solvent)/ton} * 2 \quad (14)$$
$$= 167.33 * 1000 * 2$$
$$\boldsymbol{Cost(solvent)/year = 334,660€}$$

According to (Li *et al.*, 2016), 2.4 kg of water is required for the process of capturing one ton of $CO_2$. In this work, only the cost of water required for $CO_2$ capture is considered. The produced water was continuously used for the remaining needs.

$$\text{m(Water)} = \text{m(CO2)/day} * 2.4 \quad (15)$$
$$= 20.08 * 2.4$$
$$\boldsymbol{m(Water) = 48.19\ kg}$$

$$Cost(water) = \frac{m(Water) * Cost(Water)/ton}{1000} \quad (16)$$
$$= \frac{48.19 * 0.025}{1000}$$

$$\mathbf{Cost(Water) = 1.2010^{-3}€}$$

(Chauvy *et al.*, 2020) observed that a total amount of energy of around 0.05MW is required for the methanation of 9.09 tons of $CO_2$ per hour. Taking that as a reference, the hourly amount of energy needed in this thesis was evaluated as follows:

$$E(energy\ required) = \frac{0.05 * m(CO2)/hour}{9.09} \quad (17)$$
$$E(energy\ required) = \frac{0.05 * 2.51}{9.09}$$

$$\boldsymbol{E(energy\ required) = 0.014MW/h}$$

$$Cost(ER)/year = Energy\ required * Cost(energy) * 8h * 365days \quad (18)$$
$$Cost(energy\ required) = 0.014 * 9300 * 8 * 365$$
$$\boldsymbol{Cost(energy\ required)/year = 380184\ €}$$

Table 6: Summary of total annualized OPEX

| FOPEX | Cost (€) |
|---|---|
| **Operating labor** | 22,824 |
| **Supervisory & clerical labor** | 4,564.8 |
| **Maintenance & repairs** | 941,185.07 |
| **Operating supplies** | 141,177.76 |
| **Catalyst** | 180,000 |
| **Solvent** | 334,660 |
| **VOPEX** | |
| **Hydrogen** | 2,920,603 |
| **Cooling water** | 0.00120 |
| **Energy consumption** | 380,184 |
| **TOPEX** | 4925,198.63 |

### 4.1.2 **Levelized Cost of the Produced SNG**

The cost of the methane gas produced per ton and megawatt-hour has been evaluated taking into account the operating and fixed expenses using the following formulas:

$$\text{Levelized cost of CH4(LC)} = \frac{ACAPEX + annual(OPEX)}{mass(methane\ produced)/year} \quad (19)$$

$$= \frac{31372835.76 + 4925198.63}{7329.2}$$

$$\boldsymbol{LC(CH4) = 4,952.52\ €/ton}$$

To convert tons into megawatt-hours, following conversions have to be done:

1 ton is equal to 1000kg, 1kg of methane is equal to 5.55 MJ and 1 MWh is equal to 3.6 MJ. Therefore, the levelized cost of methane per MWh is calculated as follows:

$$LC(CH4)/MWh = (LC(CH4)/ton * 3.6)/(1000 * 55.5) \quad (20)$$

$$= (4952{,}52 * 3.6)/55500$$

$$\boldsymbol{LC(CH4) = 0.32€/MWh}$$

### 4.1.3 Calculation of Net Present Value, Return on Investment and Payback Period

A comprehensive financial analysis of the project has been performed, including the calculation of key financial metrics such as net present value, return on investment, and payback period. By evaluating these metrics, it was gained into the project's profitability, investment efficiency, and time required to recoup the initial investment. This analysis provided a robust financial assessment, helping in making decisions and determining the project's financial viability. Below are given the different formulas for the calculations and a table summarizing the results obtained using Excel.

Net present value is the difference between the present value of your cash inflows and the present value of your cash outflows over a particular period. Similar to the accounting rate of return (ARR), it is used in investment planning and capital budgeting to quantify the profitability of projects or investments. Essentially, one can determine whether a certain investment is worthwhile by looking at all of the money one can expect to make from it and translating those returns into the current dollar value. The main advantage of NPV is that it takes into account the temporal value of money (TVM), converting future cash flows into the worth of today's dollars. Because inflation can diminish purchasing power, net present value (NPV) is a far more useful estimate of your project's potential profitability. Furthermore, net present value formulae provide a single, clear number that managers may compare against the initial investment to determine project or investment success. Overall, a positive NPV shows that the estimated earnings from a project or investment, when discounted for their present value, surpass the anticipated costs in today's currency. An investment with a positive NPV is assumed to be lucrative. A negative NPV investment will result in a net loss.

$$\boldsymbol{Net\ Present\ Value} = \sum_{n=1}^{25} \frac{Cash\ flows}{(i+1)^n} - initial\ investment \qquad (21)$$

Return on investment (ROI) is a performance metric that is used to assess the efficiency or profitability of an investment or to compare the efficiency of several projects. ROI attempts to directly assess the amount of return on a certain investment about the cost of the investment. An ROI calculation is sometimes used in conjunction with other methodologies to provide a business case for a specific proposition. The overall ROI for an organization is used to assess how successfully a business is handled. If a company has immediate goals, such as increasing market

revenue share, developing infrastructure, or positioning itself for sale, a return on investment may be judged in terms of accomplishing one or more of these goals rather than immediate profit or cost savings. A higher ROI denotes a more profitable investment. One can devote more time and effort to similar investments. If the return on investment is insufficient to cover its costs, it may be time to try a new strategy or invest in a different area of your organization.

$$\boldsymbol{Return\ on\ \ investment} = \frac{net\ present\ value}{initial\ investment} * 100 \qquad (22)$$

The payback period is the amount of time required to repay the cost of an investment. Simply described, it is the amount of time it takes for an investment to reach its breakeven point. People and organizations invest money to be paid back, which is why the payback period is so critical. In principle, the shorter the payback period of an investment, the more appealing it becomes. The payback period can be calculated for anyone by dividing the initial investment by the average cash flows. The quickest feasible payback period is the optimum. Repaying or recovering the initial cost of a project or investment should be completed as soon as possible.

$$\boldsymbol{Payback\ Period} = \frac{initial\ investment}{annual\ cash\ flow} \qquad (23)$$

Table 7: Summary of Net Present Value, Return on Investment, and Payback Period values.

| **Net present value (€)** | **Return on investment (%)** | **Payback Period (Years)** |
|---|---|---|
| **45205609.76** | 13 | 9.4 |

## 4.2 Life Cycle Analysis of the Project

It was committed in this work to carry out a complete Life Cycle Assessment (LCA) of the project by the methodology to get a comprehensive understanding of its environmental implications and guide sustainable decision-making.

### 4.2.1 Goal and Scope Definition

**Study's goal**

This work seeks to examine the life cycle environmental impact of SNG production utilising a combined carbon capture technology and methanation reaction, as shown in Figure 19 (Askestad *et al.*, 2021; Federici *et al.*, 2022), in order to identify the main environmental problems and provide methods to improve its environmental performance. With regards to the purpose of the study, the LCA was conducted as a ‘’cradle to gate’’ LCA.

a)

b)

Figure 19: a) Carbon capture unit b) Methanation unit

**Functional Unit**

A functional unit defines the quantifiable reference unit for which environmental impacts are evaluated and enables meaningful comparisons between alternative solutions. As the primary purpose of the process is to produce SNG, the functional unit, FU, is 7329.2 tons (calculated in the economic analysis part) of methane produced every year. Even though $Nm^3$ /h of methane produced is the more frequent unit in industrial practice, the produced SNG can be easily expressed in this unit.

**System description**

As shown in Figure 20, synthetic natural gas (SNG) production is made in two main steps: $CO_2$ capture from the flue gas followed by the methanation of the $CO_2$ with green hydrogen.

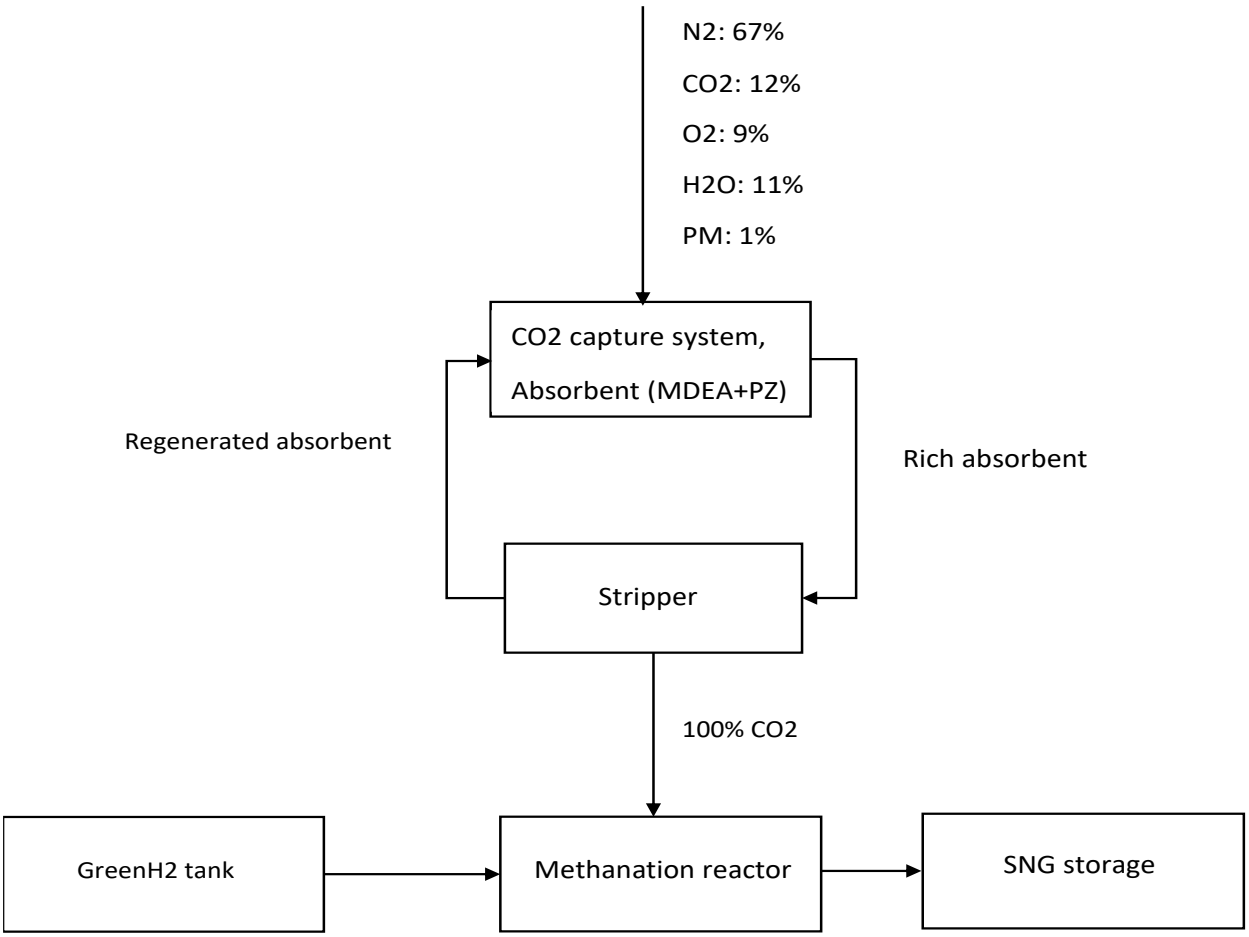



Figure 20: System boundary

The first step consists of a post-combustion carbon capture technology. This technology involves absorbing $CO_2$ from flue gas with a liquid solvent, usually an amine-based solution. The system is made up of two main units: An absorber where $CO_2$ is absorbed by an amine solution and a stripper where the solvent is regenerated.

After the flue gas is captured from the power plant, it is directed to an absorption column where it comes into contact with an amine solution. The amine solution consists of methyl diethanolamine (MDEA) together with piperazine (PZ). As the flue gas flows through the absorption column, the amine solution captures the $CO_2$ by a chemical reaction forming a stable complex. The Absorption process removes a large portion of $CO_2$ from the flue gas stream.

The $CO_2$-rich amine solution, referred to as the "lean" solution, is then separated from the flue gas. $CO_2$ is released from the amine solution via a process known as desorption or regeneration, which

requires raising the temperature of the solution. The heat enables the $CO_2$ to separate from the amine solution, allowing it to be collected and processed further. The depleted $CO_2$ amine solution is referred to as the "rich" solution, and it can be recycled back to the absorption column for further $CO_2$ capture.

Following separation, the captured $CO_2$ is typically compressed and transported directly to the methanation reactor, where it is mixed with green hydrogen to produce SNG.

The Sabatier process, also known as methanation, is carried out in a packed reactor at atmospheric pressure and 398 K. A nickel-based catalyst is used to convert the hydrogen (Considered as green hydrogen produced using solar power) and carbon dioxide to methane. The methanation reaction is exothermic, which means it generates heat, and it is often carried out at high temperatures and pressures to increase the reaction rate.

The reactor is built of steel and is filled with catalysts and glass spheres. It is encircled by a ceramic jacket in which electrical resistance is fixed to heat and control the reactor and feed. To avoid heat loss and for security, the system is insulated with stone wool. The gases are cooled after passing through the reactor, and the liquid phase is separated before the reaction products are analyzed.

Following methanation, the generated gas comprising methane, as well as certain residual gases and contaminants, is upgraded using the membrane separation process to remove any remaining $CO_2$, water, and other impurities.

Table 8: Composition of diesel exhaust gas (Reşitoɨlu, Altinişik and Keskin, 2015) .

| **Component** | **Mole fraction (%)** |
|---|---|
| **$N_2$** | 67 |
| **$CO_2$** | 12 |
| **$H_2O$** | 11 |
| **$O_2$** | 9 |
| **$SO_2$** | 1 |
| **NOx** | |
| **CO** | |
| **HC** | |

### 4.2.2 **Life Cycle Inventory**

This study used the post-combustion carbon capture technology together with the absorption process to separate $CO_2$ from the captured flue gas to produce a synthetic natural gas using green hydrogen through the Sabatier reaction.

About the processes involved, the following inputs are required:

**Flue gas and absorbent (solvent):** In post-combustion applications, flue gas is a primary input for the carbon capture process. It is produced in the power plant during the burning of diesel fuel. Carbon dioxide ($CO_2$), as well as other pollutants and impurities, are present in the flue gas. An absorbent is critical in absorbing $CO_2$ from an exhaust gas. As absorbents, methyl diethanolamine (MDEA) and piperazine (PZ) were utilized in this study. The mix absorbent, which may be regenerated later, comes into contact with $CO_2$ to form a stable complex.

**Water and green hydrogen:** Water was used in this work for cooling, chemical dilution, and as a medium for steam generation in the processes. Green hydrogen was required for the methanation of the captured $CO_2$.

**Catalyst and energy:** In the methanation process, a catalyst is used to speed up the reaction between $CO_2$ and green hydrogen. A nickel-based catalyst ($Ni/MgAl_2O_4$) was employed. This catalyst aided in the acceleration of the Sabatier reaction, which promoted the conversion of $CO_2$ and green hydrogen into SNG. Various procedures in the carbon capture and methanation process require energy input. This includes energy used to power pumps, compressors, reactors, and other process equipment. Heating, cooling, and maintaining process conditions all demand energy.

The quantity of the different inputs was calculated by the capacity of the plant to deliver $CO_2$ and the chosen working hours of the plant. Some of the input's quantities such as water and energy required were references from a similar project.

Table 9: Inventory data for producing 7329.2 tons of SNG per year.

| Inventory | Identification | Unit | Quantity |
|---|---|---|---|
| **Material inputs** | $CO_2$ | t | 7329.2 |
| | Green$H_2$ | t | 1345.90 |
| | Water | t | 0.048 |

| Inventory | Identification | Unit | Quantity |
|---|---|---|---|
| | Absorbent | t | 334.66 |
| | Catalyst | t | 2 |
| | Flue gas | $m^3$ | 50897222.22 |
| **Energy inputs** | Electricity | MW | 0.014 |
| **Outputs** | $CH_4$ | t | 7329.2 |
| | $H_2O$ | t | 5996618.183 |
| **By-product** | $H_2O$ (after $CO_2$ separation) | t | 4665.57 |
| | $O_2$ | t | 3817.29 |
| **Emission to the air** | $N_2$ | t | 28417.61 |
| | $SO_2$ | | |
| | NOx | t | 424.14 |
| | CO | | |
| | HC | | |
| Waste generation | MDEA+PZ | t | 334.66 |
| | $Ni/MgAl_2O_4$ | t | 2 |

### 4.2.3 **Environmental Impacts Evaluation**

Because the study was conducted in the context of climate change and the project is about green product synthesis, a methodology including climate-related indicators (Environmental Footprint method) was chosen. The environmental footprint method, also known as ecological footprint analysis, is a tool for assessing and measuring the environmental impact of human activities. It provides a complete framework for quantifying the number of natural resources utilized and waste generated by people, organizations, or entire populations. The technique considers a variety of parameters, including energy consumption, water usage, land occupation, greenhouse gas emissions, and waste creation. As a result, the following collection of indicators was investigated in this work: CC—Climate change, AC—Acidification potential, OD—Ozone depletion potential, FE—Freshwater eutrophication potential, POP—Photochemical ozone generation potential, MRD—Mineral resource depletion, and HT—Human toxicity.

## 4.3 Simulation of $CO_2$ capture using Aspen Adsorption Software

Due to its lower energy consumption and less reliance on chemical processes, the adsorption process is currently considered more cost-effective and less pollutant than the absorption approach for carbon capture.

The adsorption method for carbon capture involves the selective binding of $CO_2$ molecules to a solid adsorbent material, commonly activated carbon or molecular sieves. This physical adsorption technique requires little energy input, primarily in the form of pressure swing or temperature swing operations to regenerate the adsorbent and release the collected $CO_2$. The absorption process, on the other hand, relies on chemical reactions between $CO_2$ and a liquid solvent, such as amines, to capture and extract the $CO_2$. Significant energy inputs are required for solvent regeneration in this chemical absorption reaction, including heating, cooling, and compression phases. When compared to adsorption, the energy needs for absorption are often higher, adding to higher operational expenses. In addition, the absorption process necessitates the handling, storage, and disposal of chemicals, including amine solvents, which might result in significant operational and maintenance expenditures.

These factors highlight the reasons why in this work it was found important to integrate the Adsorption simulation using aspen adsorption, in the project. The simulation was done with the purpose of replacing the considered carbon capture unit in case it requires more energy input and presents very high pollution.

The simulation was done in a three-step cycle monitored by a cycle organizer on a single bed (This is an ideal way to simulate the adsorption process in Aspen Adsorption software). The first step was **adsorption** followed by **heating** for desorption and then **cooling**, for the bed to restart the adsorption. The process was an adiabatic adsorption of $CO_2$ on a single bed of **Silicate** based adsorbent.

Table 10: Feed properties

| Property | Value |
|---|---|
| **Flowrate(kmol/s)** | **8e-7** |
| **Pressure(bar)** | **10** |
| **Temperature(K)** | **298** |
| **Composition (molar fraction)** | |
| **$N_2$** | **67%** |
| **$CO_2$** | **12%** |

Table 11: Summary of the three-step cycle configuration

| | ADSORPTION | HEATING | COOLING |
|---|---|---|---|
| B4 | Completely opened | closed | Opened |
| B5 | Opened with a constant flow rate | Opened | Closed |
| Duration**(**mn**)** | 60 | 80 | 60 |

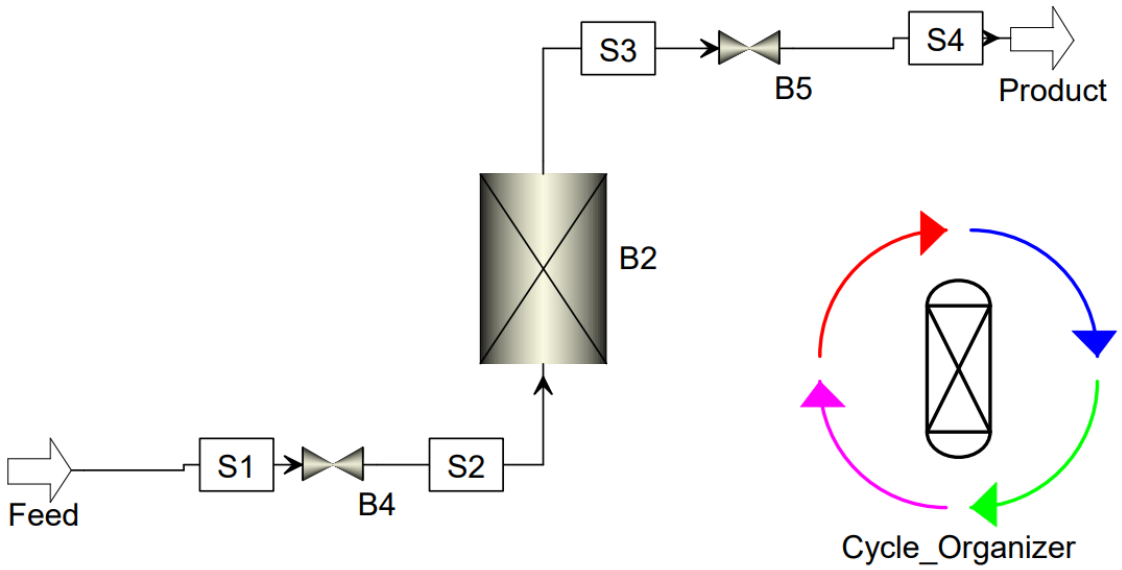



Figure 21: Process flowsheet of the three-step cycle simulation on a single bed.

# Chapter 5: Results and Discussion

## 5.1 Economic analysis

The capital expenditure was estimated using the main equipment of the process taking into account the cost of transportation, installation and all the related fixed cost. Annualized capital expenditure was also estimated for further calculations. In addition, operational expenditure was also calculated taking into account all the day to day required input cost. Later, the levelized cost of the produced **SNG** was estimated based on the calculated ACAPEX and OPEX. Furthermore, the net present value, return on investment and payback period were also evaluated using the initial investment and the expected cash flow. The overall economic analysis result is summarized in Table 12 below.

In the total initial investment of the project, it could be observed that the capital expenditure (CAPEX) is very high compared to operational expenditure (OPEX). This is because the cost of transportation of the main equipment from Germany (as they were considered to be bought there) to Niger is integrated in the ration factor of each unit. The OPEX is also very high comparing to that one (**1.71 M€**/year) found by (Chauvy *et al.*, 2021), just because of cost of green hydrogen **2.9 M€/year** is considered in the operating cost. Apart from green hydrogen, all the remaining required inputs were found cheap. In addition, the annualized capital expenditure (ACAPEX) may be seen as very high, which is because of the considered interest rate of 8%. In this work, after the first investment, the OPEX is included in the discounted cash inflow. This means that the cash inflow is discounted in such a way that the operating cost is being taken from it.

The levelized cost of the produced SNG, was very cheap compared to the one found by (Peters *et al.*, 2019)(about 3.6 M€/ton) after making an economic analysis of the power to gas route in Germany. This fact is also understandable because the cost of SNG in Germany cannot be the same in Africa (Niger). A positive net present value found in this study means that the discounted cash inflow for 25 years (lifetime of the project) is much greater than the initial investment of the project. The ROI of 13% represents the return on investment expressed as a percentage of the initial investment. A greater ROI signifies a better return on investment in comparison to the initial investment. The present ROI indicates that the project is likely to generate 13% of the initial investment each year. The obtained result on the payback period indicates that it may take 9.4 years to generate cash inflow that recoup the initial investment.

Table 12: Result of economic analysis.

| Variable(s) | Value(s) |
|---|---|
| **CAPEX** | 337342320€ |
| **ACAPEX** | 31372835.76€ |
| **OPEX** | 4925198.63€ |
| **LC(CH4)** | 4952.52€/ton |
| **NPV** | 45205609.76€ |
| **ROI** | 13% |
| **PP** | 9.4 years |

## 5.2 Life cycle assessment

After conducting an LCA using OpenLCA software with a focus on some specified impact categories, the results shown in Table 14 were achieved. For further understanding, the result was plotted in Excel, given Figure 22. The different impact categories are described in Table 13 below.

Table 13: Impact categories description

| Impact category | description |
|---|---|
| **Abiotic depletion** | This category assesses non-renewable resource depletion. |
| **Abiotic depletion (fossil fuels)** | It focuses on the depletion of fossil fuel resources in particular. |
| **Acidification** | Acidification is the process of increasing the acidity of the environment. |
| **Eutrophication** | Eutrophication is the excessive development of algae or other plants caused by elevated nutrient levels in water bodies. |
| **Fresh water aquatic ecotoxicity** | The harmful impact on freshwater ecosystems is assessed in this category. |

| | |
|---|---|
| **Global Warming Potential (GWP100a)** | The global warming potential (GWP) quantifies the impact of greenhouse gas emissions to climate change. |
| **Human Toxicity** | The toxic impact on human health is assessed in this category. |
| **Marine Aquatic Ecotoxicity** | This term refers to the harmful influence on marine aquatic ecosystems. |
| **Ozone Layer Depletion Potential (ODP)** | Ozone layer depletion potential (ODP) assesses a substance's ability to degrade the ozone layer. |
| **Photochemical Oxidation** | Evaluates the generation of smog or other oxidants in the atmosphere. |
| **Terrestrial Ecotoxicity** | The harmful impact on terrestrial ecosystems is assessed in this category. |

The result obtained for the abiotic depletion suggests a relatively low impact on non-renewable resources. This may be due to the non-utilization of many minerals in the different processes involved. However, further analysis would be required to determine the significance of this depletion. For the specified depletion of fossil fuel, the impact appears to be relatively significant. This is probably due to the use of energy from fossil fuel resources for heating, cooling and the regeneration of absorbent. It may be commented that, for the non-renewable resources' depletion, the depletion of some non-renewable resources is lesser than the depletion of fossil fuel resources.

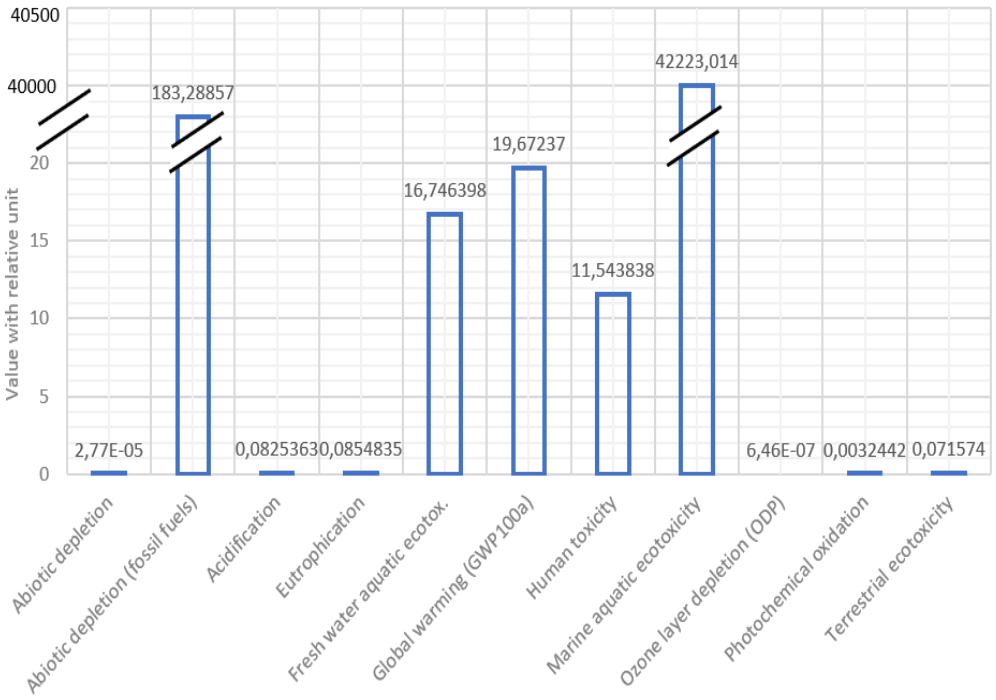
The result obtained on acidification and eutrophication indicates respectively a moderate impact on environmental acidification and eutrophication, suggesting that there may be an increase in nutrient levels in the water body leading to potential ecological disturbances. This result may be probably due to the utilization of green hydrogen considered to be produced from biomass which contains sulfuric and phosphoric compounds. The observed impact on freshwater ecotoxicity, marine aquatic ecotoxicity and terrestrial ecotoxicity may be probably due to the toxic chemical generation from the absorption process. The modest influence on photochemical oxidation obtained shows that it makes only a minor contribution to the formation of smog or other oxidants in the

atmosphere. Human toxicity impact observed is related to environmental acidification, fossil fuel depletion, and photochemical oxidation.

The moderate global warming potential impact obtained may be due to the utilization of electricity from fossil sources. As well, the low impact on ozone layer depletion indicates a low number of substances coming out of the process that may deplete the ozone layer.

Table 14: Environmental impacts of SNG production per year.

| Impact category | Reference unit | Result |
|---|---|---|
| Abiotic depletion | kg Sb eq | 2.771E-05 |
| Abiotic depletion (fossil fuels) | MJ | 183.28857 |
| Acidification | kg SO2 eq | 0.0825363 |
| Eutrophication | kg PO4--- eq | 0.0854835 |
| Fresh water aquatic ecotox. | kg 1,4-DB eq | 16.746398 |
| Global warming (GWP100a) | kg CO2 eq | 19.67237 |
| Human toxicity | kg 1,4-DB eq | 11.543838 |
| Marine aquatic ecotoxicity | kg 1,4-DB eq | 42223.014 |
| Ozone layer depletion (ODP) | kg CFC-11 eq | 6.459E-07 |
| Photochemical oxidation | kg C2H4 eq | 0.0032442 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 0.071574 |




AD: kg Sb eq
AD(FF): MJ
A: kg SO2 eq
E: kg PO4 eq
FWA: kg 1,4-DB eq
GWP: kg CO2 eq
HT: kg 1,4-DB eq
MAE: kg 1,4-DB eq
OLD: kg CFC-11 eq
PO: kg C2H4 eq
TE: kg 1,4-DB eq

Figure 22: Values of impact categories; NB: Please consider comma as dot.

## 5.3 Carbon capture Simulation

After settling all the parameters in the adsorption software, different specifications were made for the different steps in the cycle organizer in order to control the cycle. The simulation was run after putting all the inputs and making all the specifications to make a maximum of three cycles. Later on, two analyses were made together with a sensitivity analysis. Analysis of the adsorption bed performances Figure 23 and analysis of the composition of outlet stream Figure 24.

Analyzing the breakthrough curve, it is possible to conclude that, the adsorption bed is capable of performing a continuous adsorption procedure for $CO_2$ capture. This means that as the $CO_2$-containing gas stream passes over the bed material, the $CO_2$ molecules are preferentially captured and retained. The bed can continuously adsorb $CO_2$ over an extended period of time without requiring frequent regeneration or replacement of the adsorbent material. This continuous adsorption process enables the efficient and continuous removal of $CO_2$ from the gas stream, making the adsorption bed a viable solution for carbon capture and storage applications or other $CO_2$ removal operations.

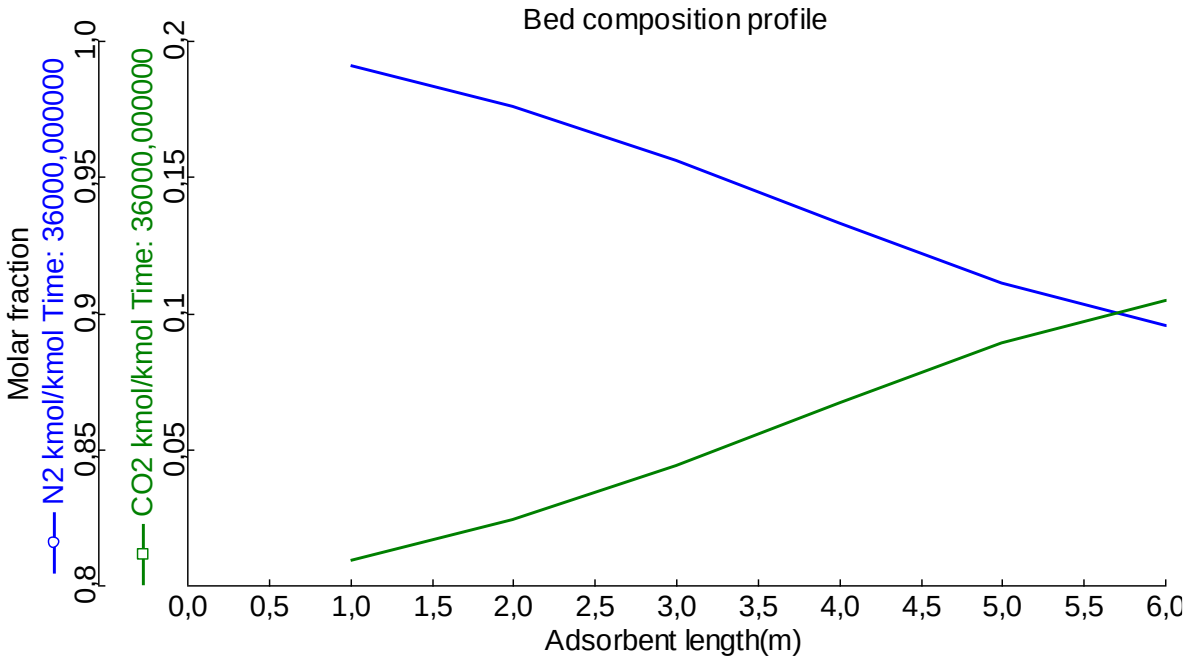



Figure 23: Breakthrough curve

In Figure 24, is shown the outlet stream composition of the first step (adsorption) of the cycle. Due to the effective adsorption process occurring within the bed, the mole fraction of $CO_2$ in the outlet stream gas is unusually low. The adsorption bed material selectively absorbs and holds $CO_2$ molecules as the gas stream passes through it, effectively eliminating them from the gas phase. Because of this excellent adsorption mechanism, only a tiny quantity of $CO_2$ molecules remains in the outflow stream. The bed maximizes separation efficiency through the continuous adsorption process by selectively adsorbing $CO_2$ while allowing other gases to pass through relatively unimpeded. This selectivity reduces the concentration of $CO_2$ in the outflow stream significantly, resulting in a very small mole fraction.

Unlike the relatively small mole fraction of $CO_2$ in the outflow stream, the mole fraction of the remaining gas components increases continuously. This phenomenon results from selective $CO_2$ adsorption within the bed, resulting in a relative enrichment of non-$CO_2$ gases in the exit stream. As the $CO_2$ molecules are selectively captured and retained by the adsorption bed, the gas stream that exits the bed contains a higher proportion of non-$CO_2$ components. While the $CO_2$ is successfully removed by the bed, the remaining gases flow through relatively un-adsorbed. This causes a progressive accumulation of non-$CO_2$ gases, resulting in a rising mole fraction in the exit stream.

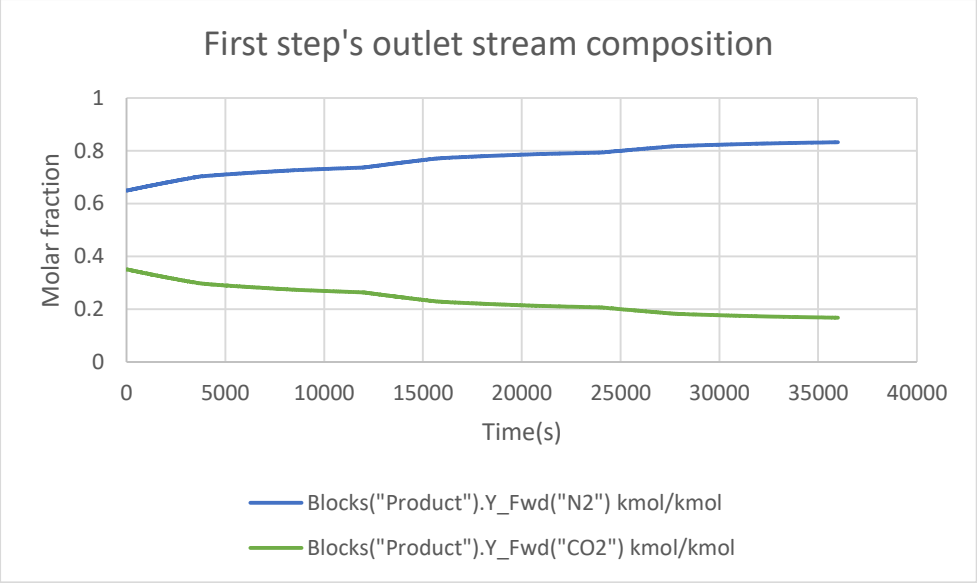



Figure 24: Mole fractions of the components in the product stream

A sensitivity analysis was also made to see the effect of varying some parameters such as **flue gas temperature**, adsorption **bed height** and the **flue gas flow rate**. The initial temperature, flow rate of flue gas and bed height were respectively as follows: 298K, 8e-7kmol/s and 0.6m.

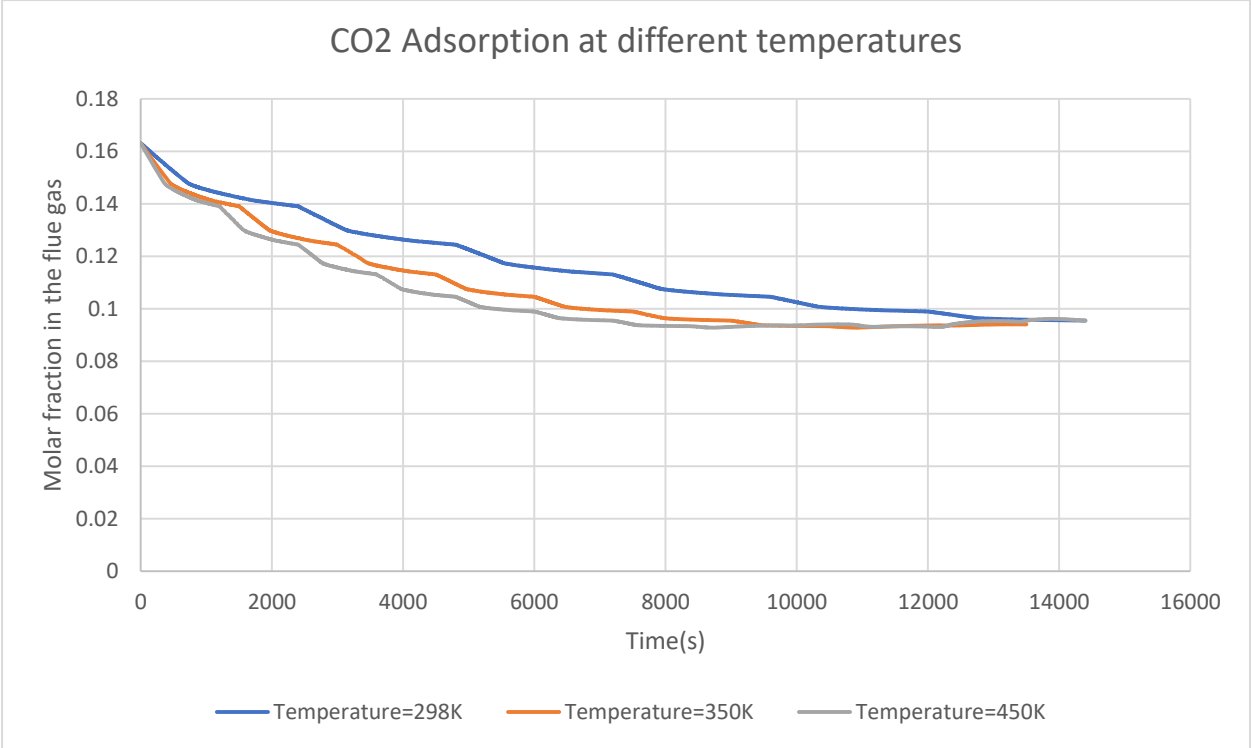



Figure 25:$CO_2$ breakthrough curve at different temperatures

Figure 25 shows the $CO_2$ adsorption from the flue gas at three different temperatures. It may be observed that, increasing flue gas temperature results in an increase in $CO_2$ adsorption at a short time **as the molar fraction of $CO_2$ decreases in the flue gas**. Adsorption of $CO_2$ contained in a flue gas at high temperatures has the advantage of reducing time to reach the maximum of adsorption. With a temperature of 450K and 350K, the maximum adsorption is reached at about 9500 seconds while with a temperature of 298K, the maximum adsorption is reached at around 12400 seconds. Higher temperatures increase the kinetic energy of molecules, which can speed up adsorption. When a rapid adsorption process is needed, this can be advantageous. It is crucial to remember, however, that extremely high temperatures might cause desorption or thermal breakdown of the adsorbate, which can reduce overall adsorption effectiveness.

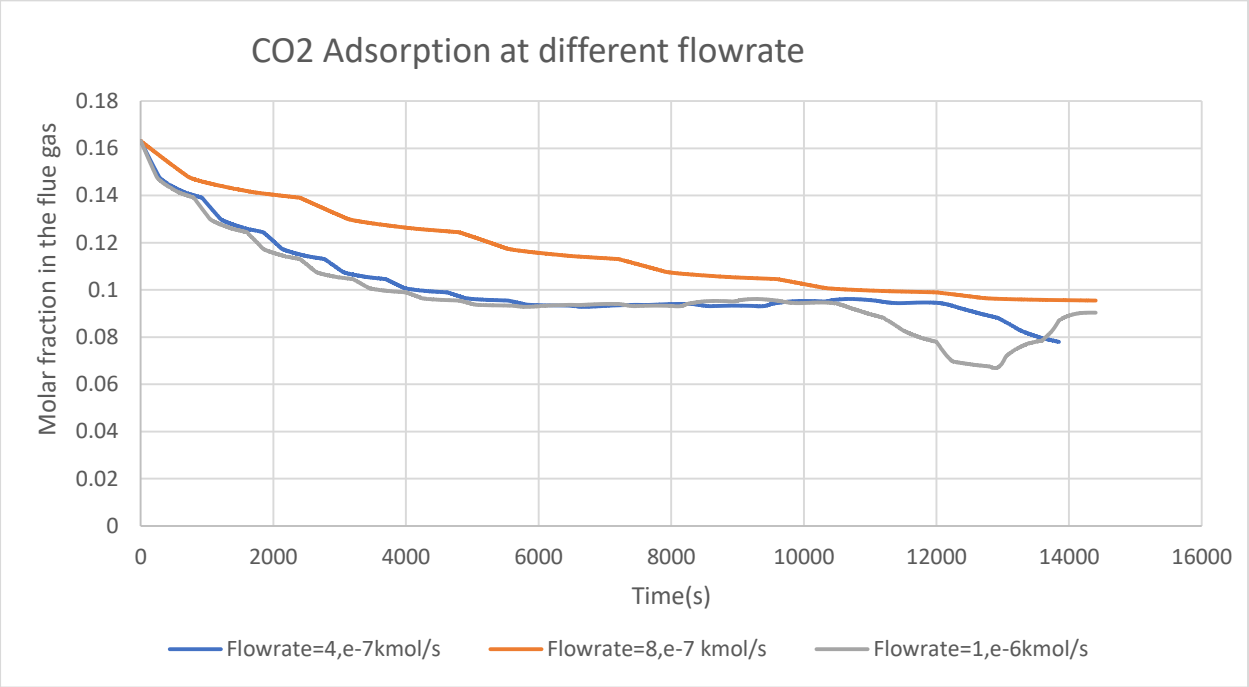



Figure 26: Adsorption at three different flue gas flow rates

The flow rate of flue gas is also another parameter to consider. Figure 26 demonstrates the adsorption of $CO_2$ at three different flue gas flow rates. In the considered figure, the two graphs corresponding to the adsorption of $CO_2$ from the flue gas at 4e-7kmol/s and 1e-6kmol/s are decreasing. This means that, there is more $CO_2$ adsorption at a flow rate of 4e-7 kmol/s and 1e-6 kmol/s compared to the remaining considered flow rate. In conclusion, at a temperature of 298K and an adsorption bed height of 0.6m (remember in this case, temperature and bed height were kept

constant), the flow rates of 4e-7kmol/s and 1e-6kmol/s are more suitable for an effective rapid $CO_2$ in adsorption.

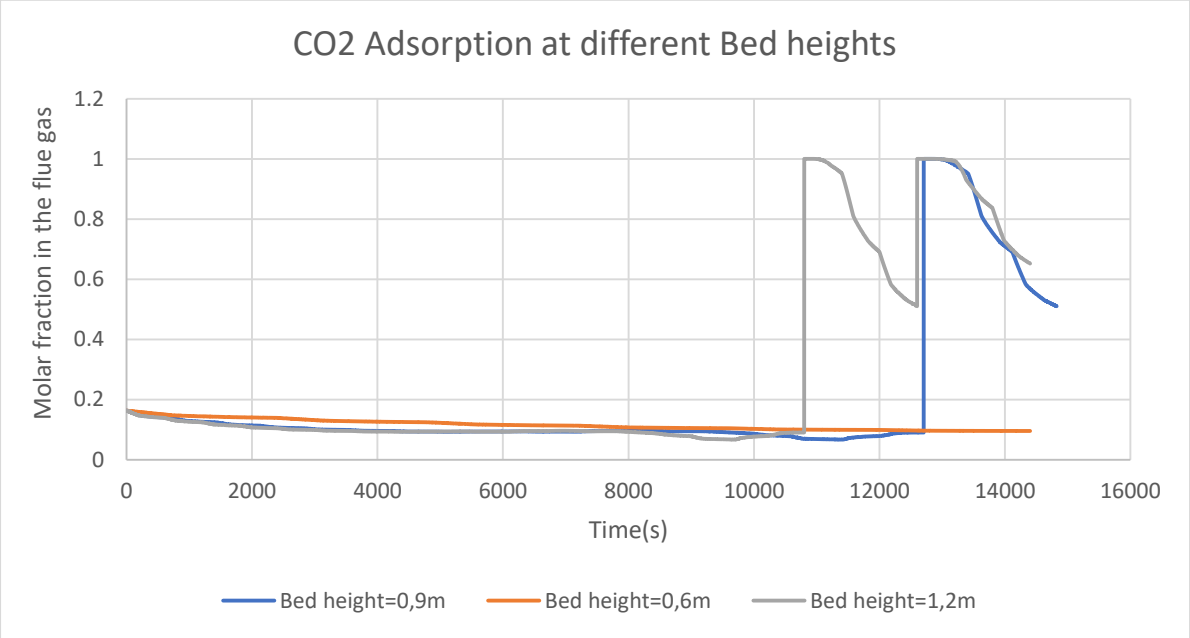



Figure 27: CO2 Adsorption at three different bed heights

Figure 27 represents the $CO_2$ adsorption phenomenon at three different heights of the adsorption bed. It may be understood from the figure that, the height of the adsorption bed does not impact in general, the adsorption process for a short time process. However, when the flue gas takes more time in the adsorption column, it may be seen on the figure that, at a bed height of 0.9 meter and 1.2 meter, a sudden high rate of $CO_2$ adsorption takes place from time to time.

(Maksimov, 2021) has found that decreasing the flow rate of input increases the time taken to achieve the maximum adsorption, increasing temperature decreases the time taken to reach the maximum value of adsorption and increasing the bed height increases also the time taken to achieve the maximum adsorption. As well, in this work, it was found that, increasing temperature reduces the time taken for maximum adsorption. However, an increase in flow rate does not have any relation with adsorption time, and the bed height variation also does not have effect on adsorption time. The similarity observed here is due to the fact that the temperature is more related to the reaction not generally to the input, adsorbent and adsorption column characteristics. It is common that, increasing temperature augments the reaction rate. The differences noticed may be due to the difference in adsorbate and adsorbent used in both cases.

# Chapter 6: **Conclusion**

This study aimed to investigate the economic feasibility and an LCA of a case study of a carbon capture and methanation project. The results indicate that, the project is economically feasible with a return on investment of 13%, a payback period of 9.4 years and a synthetic natural gas cost of 0.32 €/MWh. Further findings show that, the most significant environmental impact is the marine aquatic ecotoxicity, which is due to the chemical's generation every year after the absorption process.

In addition, the study had also the goal of conducting a carbon capture simulation with Aspen Adsorption software for reducing the environmental impacts coming out of the project's system and, for reducing as well the cost of initial investment, and the cost of some of the inputs. The adsorption process simulation findings show that, it is successful at producing continuous $CO_2$ adsorption while keeping a very low mole fraction of $CO_2$ in the outflow stream. Because of the bed's selective adsorption characteristics, $CO_2$ molecules can be efficiently removed from the gas phase, resulting in a highly pure exit stream. The flue gas temperature has the effect of reducing the adsorption time taken to reach the maximum value when it is increased.

The findings of this study contribute significantly to the field of sustainable energy and carbon emissions reduction. It shows that applying measures such as $CO_2$ emission reduction and green energy production for the energy transition in the **Gorubanda's power plant**, are economically viable while having a lower environmental impact. These findings show that investment in these technologies can result in major environmental advantages as well as the generation of renewable energy. Furthermore, the research reveals that substituting the typical absorption method with an adsorption process can result in lower initial investment costs and reduce the project's environmental impact. The findings provide realistic answers for power plants and industries looking to embrace more sustainable practices and contribute to global climate change mitigation efforts. $CO_2$ capture is a critical step towards lowering greenhouse gas levels in the atmosphere. The current study concludes that a large amount of $CO_2$, particularly 7329.2 metric tonnes, is captured annually. This indicates that efforts to reduce carbon emissions and combat climate change are being made, which also supports the hypothesis that, the project will drive the reduction of $CO_2$ emissions. As the cost of energy required in this project is among the highest cost

within the operating expenses, it may have an impact on the levelized cost of SNG produced. This is supporting the hypothesis “energy price will have an impact on the project’s economic viability”.

It is crucial to note, however, that the findings of this study also show the potential for further developments in the field of adsorption processes. There is a definite need for continued research and development activities focused on improving sorbent materials to obtain greater adsorption capabilities. To overcome existing limits and enable more efficient and cost-effective adsorption processes, novel sorbent materials should be investigated.

Furthermore, achieving high product purity remains a critical goal in many industrial applications. Finally, more research should be done to create and optimize catalysts with greater selectivity and efficiency in target component separation. Creating catalysts that are suited to individual adsorption systems would surely lead to higher product quality and lower operational costs.

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