

# Life cycle assessment of a post-combustion CO<sub>2</sub> capture unit through chemical absorption

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## ABSTRACT

This study evaluates the environmental impact of carbon capture technology in the context of reducing industrial CO<sub>2</sub> emissions within Eco-Industrial Parks (EIP). The primary focus is on the post-combustion absorption process, which uses solvents like monoethanolamine (MOA) to capture CO<sub>2</sub> before it is released into the atmosphere. The captured CO<sub>2</sub> is either stored or utilized to prevent further contribution to climate change. The study employs a Life Cycle Assessment (LCA) methodology to compare the environmental impacts of two scenarios: one with CO<sub>2</sub> capture and the other with the direct release of CO<sub>2</sub> into the atmosphere. The LCA considers inputs, outputs, energy requirements, and materials needed for the CO<sub>2</sub> absorption process. The functional unit of the assessment is 1000 tons of CO<sub>2</sub>, to standardize comparisons between both scenarios. Results show that the CO<sub>2</sub> absorption process significantly reduces the impact on climate change, capturing over 80% of the CO<sub>2</sub> from the stream. In terms of climate change, the absorption process has a much lower environmental impact than releasing CO<sub>2</sub> into the atmosphere. However, other ecological impacts, such as resource use and ecotoxicity, are higher in the absorption process due to the materials required and the solvents used. In conclusion, while the CO<sub>2</sub> absorption process offers clear climate benefits, it introduces additional environmental challenges. Future studies should explore alternative carbon capture technologies and extend the scope to include CO<sub>2</sub> storage impacts and a broader range of LCA tools for more detailed assessments.

**Keywords:** Life Cycle Analysis, Carbon Dioxide Capture, Absorption, Decarbonization

## INTRODUCTION

Human activities are acknowledged to have an impact on the environment ever since the pre-industrial era. This influence on the climate, referred to as climate change, is mainly caused by the burning of fossil fuel [1]. Indeed, large amounts of carbon dioxide (CO<sub>2</sub>) and other greenhouse gases are released in the atmosphere and act as traps for the sun's heat radiating from the surface of our planet.

Industrial activities are a major factor in climate change, given the amount of greenhouse gases released into the Earth's atmosphere from fossil fuel burning and from the energy required for industrial processes. In an attempt to reduce the environmental impact of the industry on climate change, many technologies are studied and considered.

This study focuses on one of these technologies –

carbon capture. Carbon capture refers to the process of trapping CO<sub>2</sub> particles before or after the combustion of fossil fuels. Next, the carbon is used or stored in order for it not to reach the atmosphere, where it would be trapped and have a serious impact on climate change, as mentioned previously. This whole process is referred to as Carbon Capture, Utilization and Storage (CCUS). Carbon capture is declined into multiple technologies. This study focuses only on amine absorption, which is described in the next part.

In this study, the process of carbon capture is seen as part of a bigger project aiming at reducing the CO<sub>2</sub> emissions of the industry referred as an Eco-Industrial Park (EIP). Indeed, the process is studied in the context of an EIP in order to determine whether setting it up is more or less valuable in terms of ecological impact than the current situation consisting on releasing the greenhouse gases into the atmosphere.

To properly conduct this study, it was necessary to consider various factors of ecological impacts. Indeed, carbon absorption through an amine lowers the amount of CO<sub>2</sub> released in the atmosphere but on the other hand, the use of amine as a solvent comes with its share of degradation. For instance, the release of amine in the atmosphere is known to have several impacts such as on human health for instance.

Therefore, it was necessary to involve many different criteria in order to compare the ecological impact of a carbon capture and the ecological impact of the release of industry-produced greenhouse gases. To do so, the Life Cycle Analysis (LCA) method was chosen to assess the environmental impacts of both scenarios. This paper aims at presenting a methodology applicable to any technology in order to determine its environmental impact in the context of an EIP. After explaining the methodology, a case study will be made on post-combustion carbon absorption.

## POST-COMBUSTION ABSORPTION PROCESS DESCRIPTION

CO<sub>2</sub> absorption refers to the process in which a

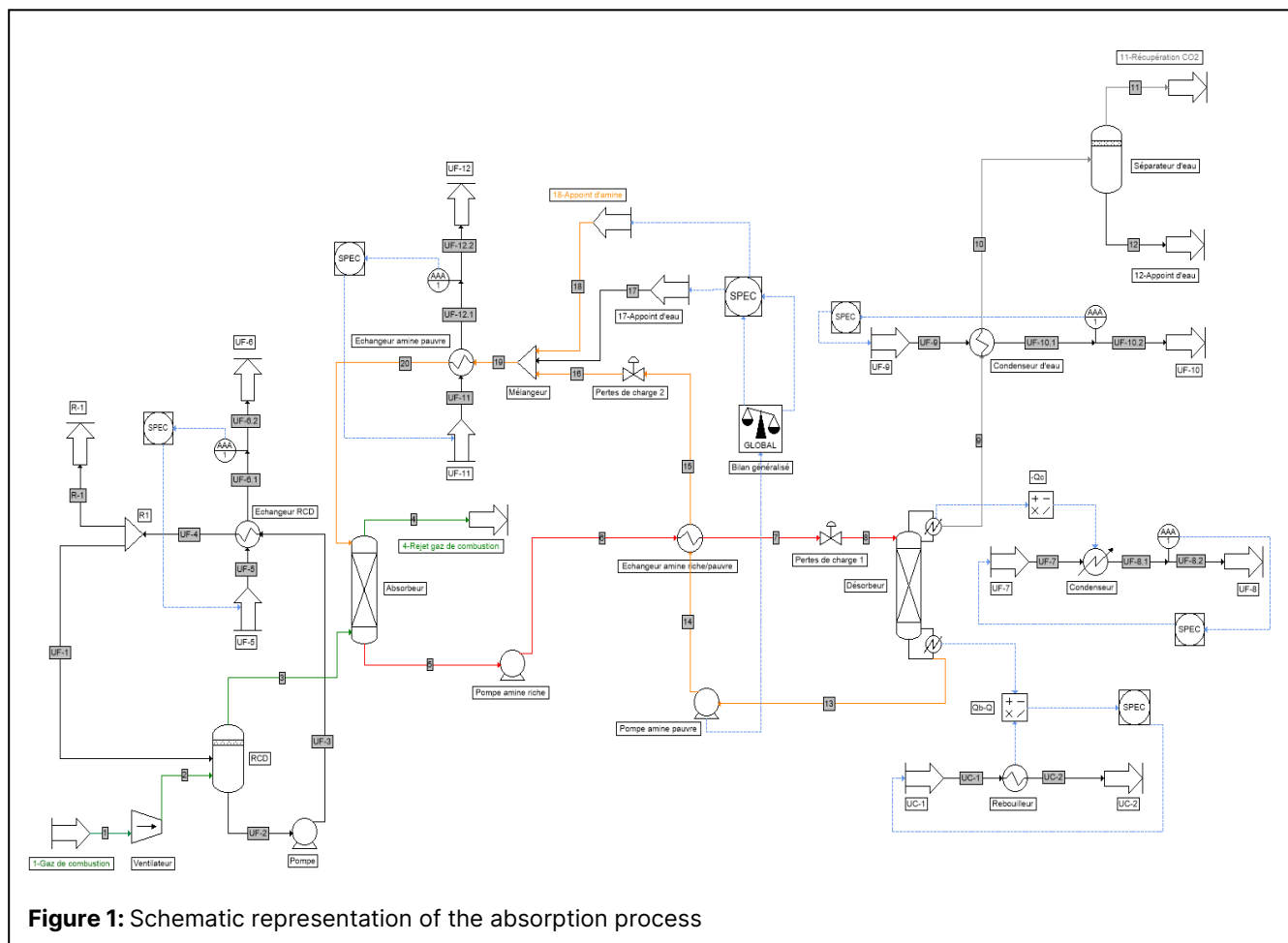
liquid solvent absorbs the CO<sub>2</sub> contained in a gas stream. In order to capture and separate CO<sub>2</sub> from the stream gas, the process of absorption requires solvents with high CO<sub>2</sub> binding capacity [2]. A recurrent solvent used for this purpose is a monoethanolamine (MOA) aqueous solution, given its high reactivity with CO<sub>2</sub> and its low price for production [3].

In this study, the absorption process was simulated with the Fives ProSim® software. The process is part of the software database and is set to treat 3073 tons of stream gas per hour (Figure 1).

## GOAL AND SCOPE OF THE LIFE CYCLE ASSESSMENT

Having clearly defined the CO<sub>2</sub> absorption process in the previous part of this study, this next part is intended to thoroughly define the goal and the scope of the LCA. This exercise is crucial in the LCA methodology as it ensures that the LCA has been performed consistently.

This LCA is conducted in order to quantify the environmental impact of a CO<sub>2</sub> absorption process including the design stage of the process. Ultimately, the goal is to define whether this process has an environmental benefit



**Figure 1:** Schematic representation of the absorption process

over the gases release in the atmosphere.

In order to compare the impact of the CO<sub>2</sub> absorption process to the release of the CO<sub>2</sub> in the atmosphere, a functional unit is to be defined. The functional unit refers to any quantifiable unit in which the process' footprint is measured. Choosing a functional unit enables objective comparisons across all the elements considered. The functional unit selected for this study is 1000 tons of CO<sub>2</sub> collected at the outlet of the plant and treated or released in the atmosphere. In the context of the absorption process, the functional unit refers to the amount of CO<sub>2</sub> contained in the treated stream, whereas in the context of the release in the atmosphere, the functional unit refers to the amount of CO<sub>2</sub> contained in the released stream.

The scope defines the stages of the life of the CO<sub>2</sub> absorption process considered for the LCA. The usual scope would be cradle-to-grave because it covers every stage of the life of the process. However, this study does not include the last stage of the life of the process – waste disposal. Indeed, the disposal of the outputs of the process are considered, but not the disposal of the raw materials used to build the process in itself. The scope can then be referred to as cradle-to-use [4].

## LIFE CYCLE INVENTORY

The life cycle inventory for the CO<sub>2</sub> absorption process consists of the input and output streams, the materials needed to build the process and the energy required to run the process.

### Streams and energy requirements

In order to get an accurate representation of the input required to run the process and the outputs generated, a simulation of the CO<sub>2</sub> absorption process was run on Fives ProSim®. The block diagram featured in Figure 2 shows the results of this simulation.

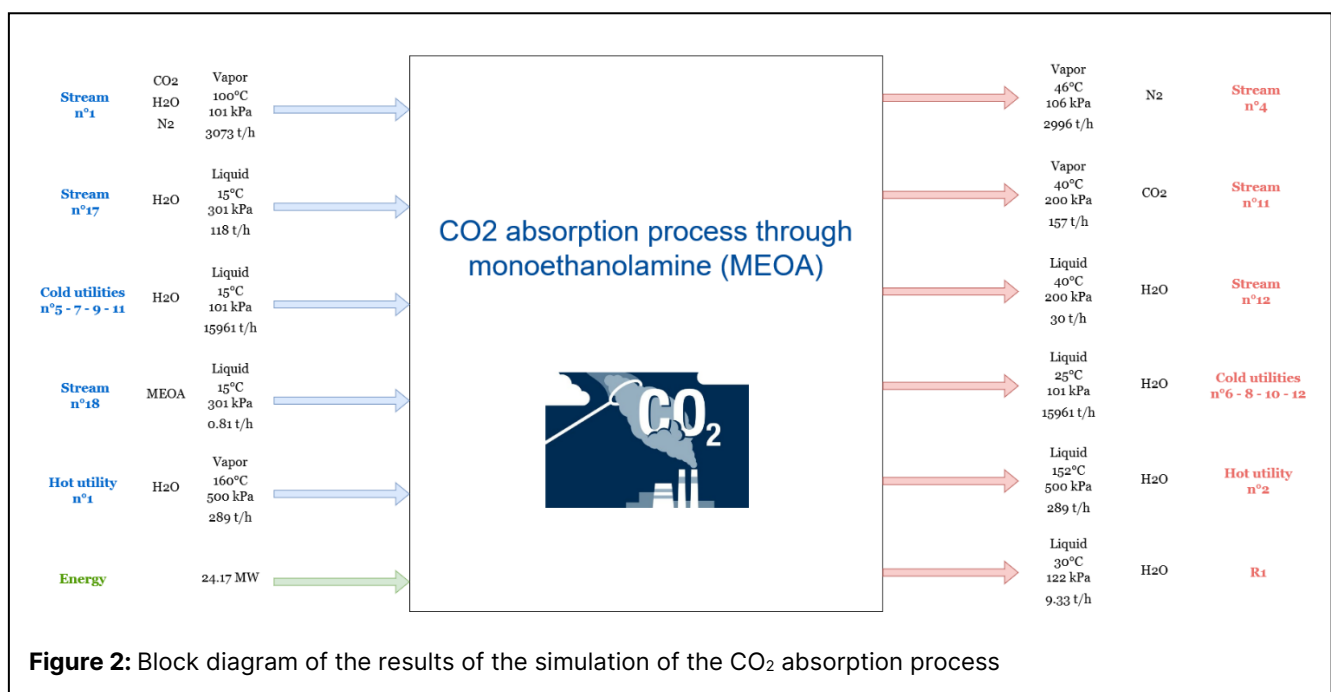
This simulation provided values on the input and output streams as well as the energy requirements of the CO<sub>2</sub> absorption process. However, not every stream has to be considered for the LCA. Some hypotheses were made in order to conduct the LCA.

### Assumptions

First, the nitrogen contained in the input stream n°1 and the output stream n°4 are not considered because the amount in both streams is equal, meaning the amount of nitrogen entering the process is equal to the amount exiting the process. Only a trace is exiting the process through R-1 stream, which was considered in the LCA. Moreover, whether stream gas is treated through the CO<sub>2</sub> absorption process or released into the atmosphere, the amount of nitrogen released in the atmosphere is *in fine* the same.

Next, the utility streams were not considered either in the LCA because it can be considered as recycled. Indeed, the output and input streams carry the same amount.

Lastly, streams n°1 and n°11 are not considered for the LCA. The input stream n°1 is not considered in the LCA, as the purpose of the CO<sub>2</sub> absorption process is to treat said stream by separating the CO<sub>2</sub> from the other gases. The output stream n°11 is not considered either because it is the final product of the CO<sub>2</sub> absorption process, meaning the stream that contains the CO<sub>2</sub>



separated for the other gases. This stream will then undergo a separate process, which does not fall into the scope of this study.

## Materials for process design

In order to get a rough idea of which materials were required to build the installation of the CO<sub>2</sub> absorption process, a Large Language Model was used. This tool provided an estimation of the amount of materials needed for each part of the process, as well as the amount of CO<sub>2</sub> treated by the process before the installation requires being replaced. The amount of materials was then brought back to 1000 tons of CO<sub>2</sub> to match the functional unit of the LCA. The final results used for the LCA are given in Table 1.

**Table 1:** Materials needed to build the process for 1000T of CO<sub>2</sub> treated

Building materials	Amount needed (Ton)
Stainless steel	0.1683
Nickel-based alloy	0.0700
Packing materials	0.0333
Sealing materials	0.0050

## RESULTS AND ANALYSES

The LCA was executed with the SimaPro® software. Figures 3 and 4 show the impacts of respectively the CO<sub>2</sub> absorption process and the release of stream gas in the atmosphere. The method Environmental Footprint was used in the software in order to obtain these two diagrams.

Impacts of both strategies to deal with CO<sub>2</sub> can be compared when considering the *Climate Change* category. Indeed, the impact of the release of stream gas is around 28kPt when the impact of the CO<sub>2</sub> absorption process is around 6.5kPt, meaning more than 4 times lesser than the direct release. 1 Pt is equivalent to the mean annual impact of a European inhabitant for the considered category. This is easily explained by the fact that more than 80% of the CO<sub>2</sub> contained in the stream gas is captured when going through the process.

However, the other categories have a greater impact when the stream gas is undergoing the CO<sub>2</sub> absorption process than when it is directly released. The analysis of the stream gas by SimaPro® can be discussed, as it appears that the stream gas, composed of 1000 tons of CO<sub>2</sub> and 728 tons of water, only impacts the *Climate Change and Water Use* categories.

The LCA was conducted using SimaPro® software. Figures 3 and 4 illustrate the environmental impact of CO<sub>2</sub> absorption and direct emissions, respectively, using the Environmental Footprint method.

Additionally, the energy required for the absorption process contributes to its environmental footprint. Future

work should explore optimizing energy consumption to further reduce negative impacts. Another aspect to consider is solvent management. Amine-based solvents degrade over time, leading to waste generation. Implementing solvent regeneration techniques could enhance sustainability. Furthermore, alternative solvents with lower environmental impacts should be investigated.

## Integration in an optimization model

This study has been integrated into a previous optimization study (Boix et al., 2024) carried out to model and design the best exchanges of steam in an eco-industrial park. A set of companies operates processes that require vapor, electricity, and water. The objective is to determine the optimal configuration of exchanges between these companies that minimizes both cost and carbon emissions. The decision variables in the mathematical model include all inter-company flows (their existence and physical properties) as well as the sizing of necessary equipment.

A multi-objective optimization approach is applied to an Eco-Industrial Park (EIP) incorporating new facilities to assess their impact on greenhouse gas (GHG) emissions. These facilities include:

- An optimal steam network
- A Hybrid Power System (HPS)
- A CO<sub>2</sub> capture unit as modelled in the previous paragraph.

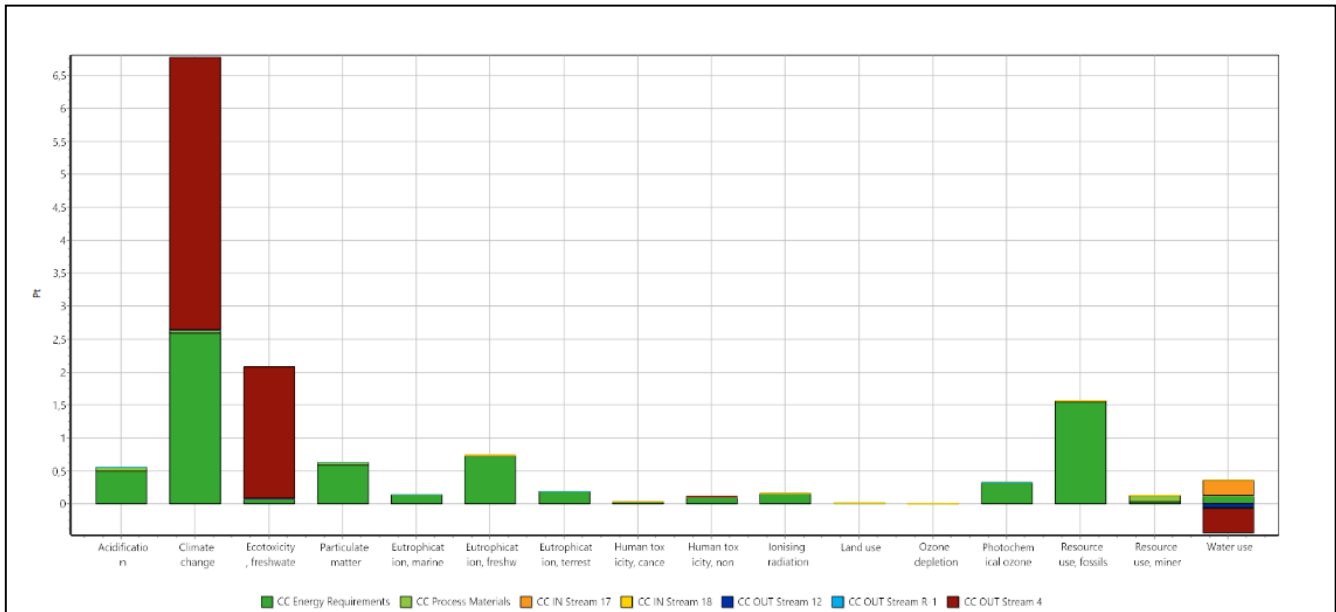
These elements are integrated into the optimization model, which is formulated as a multiperiod Mixed Integer Linear Programming (MILP) approach based on [5, 6]. The study by [7] on Yeosu Industrial Park is used as a case study to demonstrate the applicability of an optimization approach for a steam exchange network in a real industrial complex. The study identifies 15 industries, categorized into two groups: producing companies and consuming companies.

Producing industries generate steam, while consuming industries rely on external steam sources. Each industry has specific steam requirements, varying in type and quantity. The types of steam include:

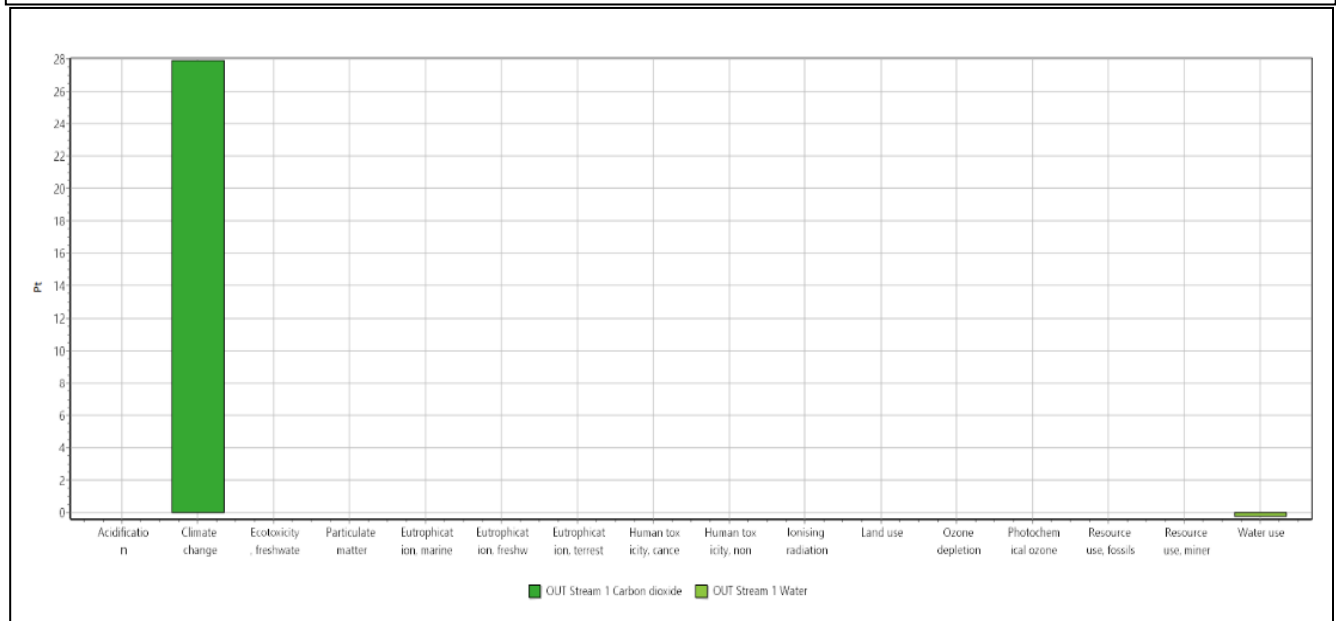
- Very High-Pressure Steam (THP)
- High-Pressure Steam (HP)
- Medium-Pressure Steam (MP)
- Low-Pressure Steam (BP)

Since demand fluctuates throughout the year, it is divided into four periods based on seasons:

- t1: Spring (April to June)
- t2: Summer (July to September)



**Figure 3:** Diagram of the impacts of the CO<sub>2</sub> absorption process across different categories



**Figure 4:** Diagram of the impacts of the release of stream gas across different categories

t3: Autumn (October to December)

- t4: Winter (January to March)

The first step in the optimization process involves defining the flue gas to be treated. Several simplifying assumptions are made:

1. The flue gas stream is considered a binary mixture comprising 14% CO<sub>2</sub> and 86% N<sub>2</sub>.
2. The greenhouse gas (GHG) emissions from boilers consist solely of CO<sub>2</sub>.

3. The flue gas temperature is assumed to be reduced to 25°C.

Using these assumptions, the model calculates the flue gas flow rate to be treated based on the GHG emissions generated by the boilers. This approach provides a structured framework for optimizing industrial symbiosis while integrating cost-efficient and environmentally friendly strategies. According to Table 2, it can be observed that the integration of such a unit in an eco-industrial park can lead to a decrease of GHG emissions of

more than 60% with a little increase of the cost of approximately 0.4%. The total annual cost refers to the operating cost and also the investment linked to the CO<sub>2</sub> capture unit, it includes OPEX and CAPEX.

**Table 2:** Results of the integration of the carbon capture unit in the eco-industrial park

	Without CO <sub>2</sub> capture	With CO <sub>2</sub> capture
Total annual cost (G\$/yr)	1899	1906
Total GHG emissions (TCO <sub>2eq</sub> /yr)	10416	3304

An attention must be paid to the modeling of new processes to be integrated into optimization model and especially with environmental impacts. We suggest that each new technology brick must be carefully modeled in order to quantify environmental impacts before being integrated into an optimization model.

## CONCLUSION AND PERSPECTIVES

Using SimaPro® software, this study demonstrated that CO<sub>2</sub> absorption significantly reduces climate change impact compared to direct emissions. Within an EIP, implementing CO<sub>2</sub> capture could enhance sustainability efforts. However, increased impacts on ecotoxicity and resource consumption warrant further consideration.

Future research directions include:

- Exploring alternative carbon capture technologies such as adsorption or membrane separation.
- Assessing the environmental impact of CO<sub>2</sub> storage.
- Extending the LCA scope to include CO<sub>2</sub> sequestration.
- Evaluating different LCA tools for a more comprehensive impact assessment.
- Investigating process improvements to enhance efficiency and sustainability.
- Studying economic feasibility to determine the long-term viability of CO<sub>2</sub> capture solutions.
- Investigating policy incentives and industrial cooperation strategies to improve the adoption of carbon capture technologies.

By addressing these considerations, future studies can contribute to the development of more sustainable industrial practices, ultimately mitigating climate change while minimizing adverse environmental effects.

## ACKNOWLEDGEMENTS

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