

Accounting for Dynamics in Ranking CO₂ Emissions Mitigation Strategies

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The characteristic topic of the past decade research in the fields of chemical and energy industries can be identified in the continuous investigation of technological strategies aimed at the mitigation of CO₂ emissions in order to meet the UE net-zero target by 2050. The solutions proposed so far cover a very wide range of applications and involve different aspects of the industrial sector, such as chemical-to-molecule, energy optimization, logistics etc. Therefore, in order to provide a more clear overview and to implement effective decision tools for the future selection of the most suitable technology according to the specific application, several classifications were conceived from a comparative perspective. The most established ones take into account the way CO₂ is captured, the way CO₂ is used or also the specific industrial domain where the carbon recovery is carried out. However, due to the very spread nature of the various methodologies, it appears very difficult to find any classification able to include all of them. Furthermore, when comparing the effectiveness of different technologies, it should be accounted for the fact that not all of them have currently achieved the same level of development and deployment. The purpose of this research work is then to find one or more common aspects among the different CO₂ emissions mitigation strategies and to classify the available options based on that. Since the carbon dioxide accumulation in the atmosphere results from the gap between positive and negative CO₂ contributions over time, a new possible classification based on dynamic response function was explored. In order to uniquely characterize the dynamic impact of the selected approach, the removal magnitude and the CO₂ release delay were identified as the two parameters to be used as criteria for the various categories. Therefore, their respective values for each available technology were quantified and then employed to reclassify all of them accordingly. This new classification showed that the most effective way to mitigate carbon emissions is to convert CO₂ into long lasting products while powering the process with renewable energy. Therefore, transforming the process to a negative emission process. For a future perspective, the new categories thus obtained could be considered as a starting point to build decision tools to effectively assess the impact over time of CO₂ removal approaches and make more reliable predictions in terms of long-term emissions.

1. Introduction

Due to the growing concerns about climate change in recent years and the pressing need to meet UE net zero target, the mitigation of anthropogenic carbon dioxide emissions has gained global attention. Many environmental innovations, from CO₂ capture to CO₂ conversion into useful products and from energy consumption optimisation to relying on renewable energies are the key towards greener processes. Regarding this wide diversity, a classification of these methods is needed to guide chemical engineers, through influence of each one when designing a sustainable process. This classification should cover all these approaches with divergent paths. Many reviews and classifications are found in literature regarding CO₂ management techniques, reflecting the diverse approaches and applications for capturing, using, and mitigating CO₂ emissions; however, none can be used as a powerful tool that gives an overview on all strategies and helps to select the most appropriate one in a certain application or process. Numerous flaws and restrictions such as the intersection between categories or the missing of certain features, lead to a misleading or incomplete view of overall CO₂ emission reduction strategies. In addition, the CO₂ cycle and its dynamic behaviour is not explored in any of the classifications mentioned, failing to reflect the real impact of each method.

Various reviews categorized these strategies according to different criteria such as the method used to reduce a carbon emission like different carbon capture or utilization techniques, or depending on the current development stage or maturity of each method. Other interesting classifications divide them according to their adaptability for each industrial sector, or the phase of their implementation in the process. All these divisions are illustrated in Figure 1 and further detailed below.

Starting with the carbon capture and storage (CCS), a method that relies on capturing CO₂ emissions at the source and storing them underground or in other secure locations such as deep ocean reservoirs to prevent them from entering the atmosphere, it was divided in numerous subcategories. First, with respect to the nature of the processing technique whether it is industrial or natural (Quang et al., 2023), or regarding the source of the CO₂ captured, air for direct air capture or flue gas for indirect capture indirect (Pires et al., 2019) and finally based on the capturing technique (precombustion, post-process, oxycombustion methods, direct air capture (DAC) and chemical looping combustion (CLC)) (Kheiririk et al., 2021), (Wilberforce et al., 2021).

Strategies are also classified depending on CO₂ utilization strategies in accordance to the nature of utilization (direct or conversion into valuable product) or the type of product obtained (fuel, biofuel, chemicals and application in thermodynamic processes) (Osman Ahmad et al., 2020).

Another common classification in literature is to split the CO₂ mitigation strategies based on the sector where it is applied. CO₂ management is also specific for every industry such as iron and steel, cement, chemical and petrochemical industries, and petroleum refineries, where each have specific approaches tailored to their unique emission profiles (Kuramochi et al., 2012). Even though this classification provides a framework for understanding the wide range of strategies available for managing CO₂ emissions across various sectors and applications, however it is not englobing all possible applications for instance transportation.

Concerning the classification exploring side management where different strategies are implemented, it includes supply-side, demand-side, and end-of-pipe solutions (Manan et al., 2017). Supply-side strategies focus on reducing emissions at the source by modifying inputs or production processes, such as using low-carbon fuels, increasing energy efficiency, or incorporating renewable energy. These approaches aim to lower the carbon intensity of industrial activities from the start. Demand-side strategies concentrate on reducing CO₂ emissions by changing consumption patterns. This involves improving product efficiency, minimizing waste, and promoting low-carbon products. The goal is to decrease the demand for carbon-intensive goods and services. End-of-pipe solutions address emissions after they have been produced, typically through carbon capture and storage (CCS) technologies. These methods capture CO₂ from flue gases for either permanent storage or repurposing.

Finally, classifications can be established on the current status of CCS development and the type of mitigation strategy employed. This approach divides strategies into those that are commercially viable and in widespread use, those that are still in the demonstration phase, and those that remain in the research and development stage (Bui et al., 2018). However, these classifications, while useful in organizing different approaches, do not serve as direct tools for estimating the efficiency of CO₂ mitigation within the process industry. The efficiency of mitigation efforts depends on specific factors such as the technology used, the scale of implementation, and the unique conditions of each industrial process. Therefore, they provide a conceptual framework for understanding the landscape of CO₂ management strategies, but they must be complemented by detailed, process-specific analyses to accurately assess mitigation efficiency in the process industry.

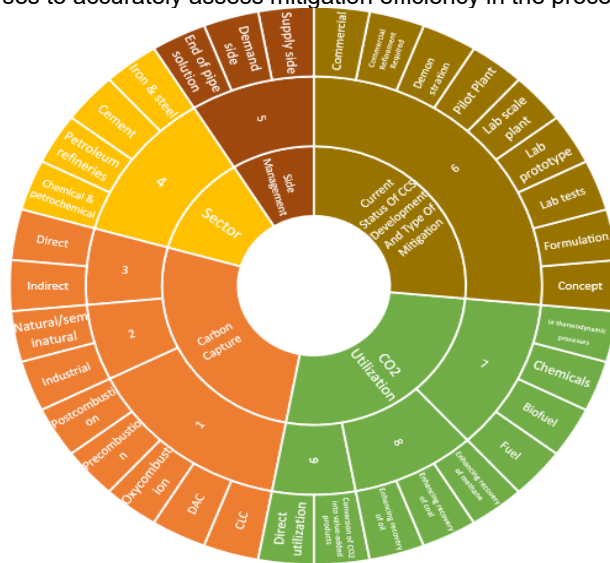


Figure 1 Criteria of CO₂ reduction's categorization in some reviews

The new classification system presented in this work serves as a practical tool for selecting the most appropriate CO₂ mitigation strategy based on specific applications. This system evaluates all methods by considering their long-term effects on atmospheric CO₂, incorporating key factors such as the time delay of CO₂ re-emission (when applicable) and the magnitude of CO₂ removal relative to the function performed. By accounting for variations in re-emission delays, which can range from short-term to long-term periods, and assessing the effectiveness of each strategy based on its CO₂ removal capacity, this classification offers a more precise method for evaluating the impact of different approaches. This allows the selection of strategies that are optimized for both immediate CO₂ reduction and long-term climate impact, tailored to the specific role CO₂ plays in the process, whether it is stored, utilized, or transformed into valuable products.

2. Overview and analysis of carbon dioxide removal technologies

Measures to mitigate the emissions of CO₂ can vary substantially in terms of strategies and techniques, each with its own limitations. Some approaches, such as CCS, do not eliminate CO₂ but instead prevent it from entering the atmosphere by capturing and storing it underground. CCS is a containment strategy, not a solution to the root cause of emissions.

Others focus on reducing emissions at the source, like improving energy efficiency, or using low-carbon materials in construction or changing raw material. For instance, research indicates that replacing traditional limestone-clay mixtures with civil construction waste in cement production can lower CO₂ emissions by 8.1% (Costa et al., 2020), and in Bahrain, implementing better insulation and glazing in air-conditioned commercial buildings led to a 25% reduction in energy consumption and a 7.18% decrease in net CO₂ emissions (Radhi et al., 2009). However, more advanced approaches go beyond just capturing or reducing CO₂—they repurpose it for practical applications. Such as in the food and beverage industry where CO₂ is used to carbonate beverages, while in other industries, it serves as a utility for chilling. Additionally, CO₂ can be used to enhance oil and gas recovery, helping to maximize resource extraction while simultaneously sequestering carbon. In this case, as soon as it is used, carbon dioxide will be reemitted in the atmosphere. But more important technologies convert CO₂ into valuable products such as synthetic fuels, building materials, or chemicals, reducing the need for virgin resources. By integrating CO₂ into useful applications rather than simply storing it, these solutions create a more sustainable and circular approach to carbon mitigation. Here, it is important to distinguish between two types of carbon conversion; conversion to short and long-life products. The reemission of CO₂ occurs quickly with short-lived products like the production of urea, used as fertiliser from CO₂, or the synthesis of synthesise compounds such as salicylic acid, a crucial component of aspirin. However, by converting CO₂ to long life products carbon dioxide is sequestered for extended periods. By converting CO₂ into plastics and polymers, durable products that can be used in various industries are obtained. These materials, traditionally derived from fossil fuels, can now be produced from CO₂, helping to sequester carbon and reduce dependency on fossil resources.

Similarly, construction materials can be obtained from CO₂ through carbon mineralization. By reacting CO₂ with minerals, stable carbonates are created that can be utilized to make carbon-absorbing concrete and other construction materials. These materials recycle CO₂ into useful products, effectively locking away carbon for extended periods of time and supporting a circular economy. In both cases, the conversion of CO₂ into long-lasting products not only helps sequester carbon but also supports sustainable material use and reduces the environmental impact of production. Different approaches have been developed to lower atmospheric carbon dioxide levels, as this section has described. To make a process greener, process engineers must consider all available options and decide on the optimal one. The particular process type, the circumstances, and the available resources should all be taken into consideration while making the choice. This guarantees that the selected course of action not only efficiently lowers carbon emissions but also remains viable and sustainable within the specified parameters.

3. New classification and possible applications

3.1 Presentation of the new classification

The effectiveness of various strategies in reducing CO₂ emissions is not equivalent; thus, the primary aim of the new classification is to underscore the efficacy of CO₂ removal associated with each method. Evaluation will take into account two main trait of the strategy: the timeframe and the functional role.

To begin, the assessment of this effectiveness should not be limited to the immediate and direct removal of CO₂ but should also consider the long-term implications to provide more accurate predictions regarding emissions. In this regard, it is essential to differentiate between scenarios where CO₂ emissions are merely reduced, those where CO₂ is removed and subsequently re-emitted within short (days, months) or large (years, centuries) intervals, and measures that can prevent emissions in specific applications.

In addition to the time delay, the functional role that CO₂ plays in each method can also be used to predict the impact of CO₂ mitigation methods. This role transitions from methods that primarily involve CO₂ sequestration

to those that utilize CO₂ as a raw material, utility, and ultimately, a final product. The quantitative impact of this evolution can be calculated by evaluating the CO₂ emissions per unit of product across different applications, or comparing scenarios with and without the proposed strategy. The efficacy of a method can be obtained by evaluating the extent to which it diminishes CO₂ emissions in comparison to the same process conducted without the application of that strategy. Thus, a more significant decrease in emissions attributable to the strategy indicates a higher level of success in alleviating environmental consequences.

Through the assessment of the magnitude of CO₂ removal and the timing of its release for each technology, CO₂ mitigation strategies have been restructured into new categories that better represent the influence of these technologies on atmospheric CO₂ levels. Looking ahead, these redefined categories could lay the groundwork for the development of decision-making tools that effectively analyze the long-term consequences of CO₂ removal strategies. Such tools would improve the precision of predictions concerning future emissions, enabling more strategic decision-making in climate change mitigation efforts.

3.2 Different aspects throughout the process

Usually process operations are divided into several essential steps, each playing a vital role in the environmental impact and carbon emissions of the overall process. The first step in all productions is the selection of raw materials, then their transportation to the site. The latter contribute significantly to carbon emissions, depending on the distance and transportation mode. After their arrival at the location, the raw materials must be prepared and treated. This can involve cleaning, refining, or other pre-production procedures to guarantee the resources fulfill the criteria needed for production.

The second stage or the core of the process is the production phase itself, where the actual transformation of raw materials into the final product occurs. This step typically requires various forms of energy and utilities. The efficiency and environmental impact of this stage depend heavily on the energy sources used and the technology employed. Finally, in the last level the process results in the production of the final product, ready for distribution. Throughout all these steps, it is essential to consider the environmental implications, such as raw material and final product selection, energy consumption, emissions, and waste generation, to ensure the process is as sustainable and eco-friendly as possible. The selection and treatment of raw material highly impacts the carbon emissions as explained in the previous section. Even though treating raw material can reduce emissions during the production process, this approach alone doesn't play a role in removing CO₂ from the atmosphere, it only minimizes the carbon footprint of the operation.

The long-term effectiveness of this approach depends on the type of products being created. Products with longer lifespans, such as polymers or building materials, can store the captured CO₂ for decade or even centuries, delaying its re-release into the atmosphere. In contrast, products with shorter lifespans, such as certain chemicals, fertilizers or fuels, will eventually release the stored carbon back into the atmosphere within days or months. Thus, the selection of CO₂ as a raw material, combined with the production of long-life products, represents a powerful tool in achieving meaningful carbon reduction and enhancing sustainability efforts.

Now, considering the overall utility aspect that can include the transportation, the use of CO₂ for other utility goals. For example, adapting CO₂ as a chilling agent, for cryogenic cooling systems or refrigeration, is a sensible and environmentally responsible strategy. Because this application uses CO₂ that has already been captured or made available, fewer alternative refrigerants that might have a higher global warming potential or produce and use more CO₂ emissions are needed. This usage of CO₂ does not, however, actively remove it from the atmosphere, but it may lessen the environmental impact of alternative refrigerants by reusing already-existing CO₂. By using CO₂-based systems, we can reduce additional climate change emissions while making use of a widely available material, improving the sustainability of cooling solutions.

Also, during transportation operations—whether it involves raw materials supply to the site or finished products distribution—it is essential to explore alternatives to conventional fossil fuels. One effective approach is to use fuels derived from CO₂ and biofuels. Although these fuels may re-emit carbon dioxide into the atmosphere relatively quickly, often within days, they offer distinct environmental advantages over traditional fossil fuels.

Fuels derived from CO₂ have already contributed in capturing carbon from the atmosphere when being produced, thus offsetting some of the emissions generated at their combustion. This means that, while they do re-release CO₂, the overall impact on atmospheric carbon levels is reduced. Moreover, these fuels tend to emit less carbon compared to conventional fuels, further lowering their environmental footprint.

Similarly, biofuels, produced from renewable organic materials, can also serve as a more sustainable alternative to fossil fuels. While biofuels do release carbon when burned, the plants used to produce them absorb CO₂ from the atmosphere during their growth, creating a more balanced carbon cycle. Incorporating these alternative fuels into the transportation process not only supports the reduction of greenhouse gas emissions but also aligns with broader goals of sustainability and carbon management. By transitioning away from conventional fossil fuels and embracing these greener alternatives, the overall environmental impact of transporting raw materials and distributing products can be significantly mitigated. By analogy, using green fuels for power generation during

the production process has a comparable impact to their use in transportation. the impact of utilizing green fuels for transportation is similar to that of using them for power generation during the production process. Lastly, renewable energy sources, such as solar, wind, hydroelectric, and geothermal power, offer an even more optimal solution for power generation. Unlike green fuels, which may still result in CO₂ emissions during use, renewable energies do not produce any direct emissions during operation. This makes renewable energy an ideal choice for creating greener and more sustainable production systems.

3.3 Applying the new classification to the process design

To refine the classification in a clearer way, it is structured around two axes: the time axis referring to the delay for CO₂ re-emission in the atmosphere after the implementation of a CO₂ mitigation strategy and it can be divided into days, months, years and centuries and on the other hand the functional axis that states the place of the strategy in the process if applied on raw material, products or utility).

Thus, the effectiveness of each CO₂ mitigation technique should be assessed in terms of how long it takes for captured CO₂ to be released back into the atmosphere. This entails choosing raw materials, energy sources, and industrial techniques that maximize the amount of time before any CO₂ is produced in addition to minimizing emissions. A thorough evaluation at every stage of the process is necessary. Emphasizing choices that support efficient CO₂ capture and long-term carbon storage when choosing raw materials. Production energy sources should be selected according to how effectively they may reduce CO₂ emissions, such as renewable energy sources like solar and wind or green fuels. Technologies that both shorten the time until any CO₂ is captured and lower it immediately should be implemented throughout the production phase.

In the transportation and distribution stages, alternative fuels and logistics strategies should be evaluated for their ability to reduce carbon emissions and incorporate re-emission delay. The choice of biofuels or fuels derived from CO₂ can be made on the basis of how well they sequester carbon dioxide and reduce emissions when compared to conventional fossil fuels.

Lastly, in order to extend the period of carbon storage, the end-of-life phase of products needs to be taken into account. Long-term sustainability and climate goals can be attained by designing products with longer carbon sequestration in mind and making plans for recycling or disposal techniques that further postpone CO₂ re-emission. By using this method, process designs are guaranteed to be efficient in lowering direct carbon emissions and promoting more general environmental goals.

For example, properly treating raw materials or replacing them with alternatives can reduce carbon emissions in the cement industry by approximately 4% and up to 8% respectively (Costa et al., 2020). Typically, the raw material processing stage is considered to contribute to a maximum CO₂ reduction of 10%. In this case, the process stage is assessed along the process axis, while the time axis remains at zero, as it only reduces emissions rather than removing CO₂ entirely. On the other hand, converting CO₂ into propylene for example can achieve a reduction of 80–87% per ton of product (Tähkämö et al., 2022) in CO₂ emissions per ton of product, with re-emission occurring over several decades. More examples can be found in Figure 2 below.

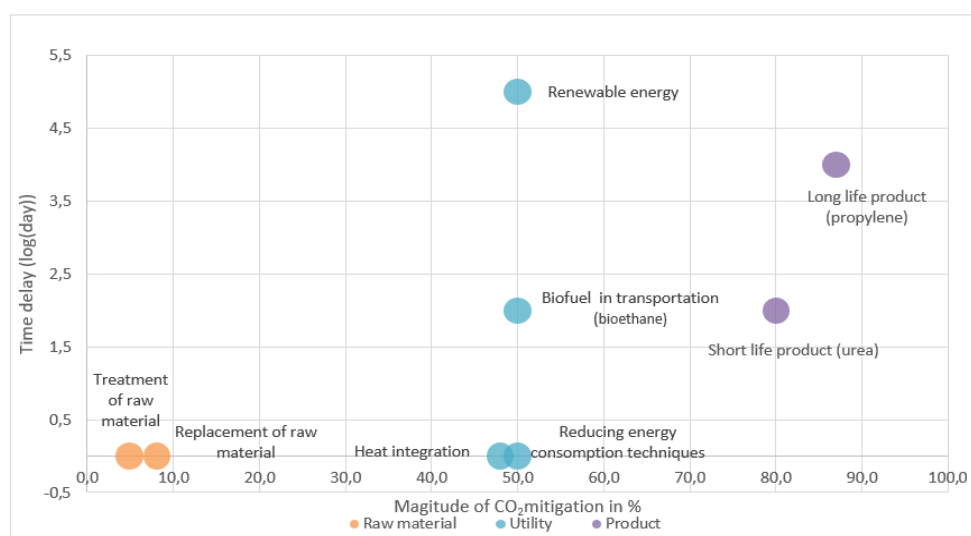


Figure 2 CO₂ mitigation strategies categorized by process stage and re-emission time delay.

As shown in Figure 2, methods applied on raw material generally has a low CO₂ mitigation potential, meaning its impact on reducing emissions is relatively limited. In contrast, utility can achieve a mitigation potential of up to 50%, making it a more effective option. Among all categories, focusing on strategies that target final products demonstrate the highest mitigation potential, significantly reducing emissions. However, the re-emission of CO₂ varies depending on the specific process and application, leading to different delays in its eventual release.

4. Conclusions

The study done in this paper has successfully addressed the research objectives, as shown by the results that were obtained. It highlighted the importance of the dynamic elements, especially when computing the CO₂ mitigated, by a thorough and precise examination. Furthermore, the findings underscored that different CO₂ mitigation strategies have varying levels of impact over short-term and long-term periods, highlighting the necessity of tailoring approaches to achieve optimal results. These outcomes will be crucial instruments for directing the choice of a suitable approach suited to the particular goals in the process industry. Decision-makers can guarantee that activities are both efficient and effective regarding carbon foot print by comparing the selected method with the intended goals.

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