# ΕΘΝΙΚΟ ΜΕΤΣΟΒΙΟ ΠΟΛΥΤΕΧΝΕΙΟ

ΣΧΟΛΗ ΜΗΧΑΝΟΛΟΓΩΝ ΜΗΧΑΝΙΚΩΝ

ΤΟΜΕΑΣ ΒΙΟΜΗΧΑΝΙΚΗΣ ΔΙΟΙΚΗΣΗΣ & ΕΠΙΧΕΙΡΗΣΙΑΚΗΣ ΕΡΕΥΝΑΣ


**Τεχνολογίες Δέσμευσης και Αξιοποίησης Διοξειδίου του Άνθρακα ($CO_2$) – οι ευκαιρίες, οι προκλήσεις και η μελλοντική χρηματοοικονομική βιωσιμότητά τους**

**Technologies of Capture and Utilization of Carbon Dioxide ($CO_2$) – their opportunities, challenges, and their future financial viability**


ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

του


**ΦΟΥΡΛΑΡΗ ΚΩΝΣΤΑΝΤΙΝΟΥ**

Επιβλέπων καθηγητής:

**ΚΩΝΣΤΑΝΤΙΝΟΣ ΑΡΑΒΩΣΗΣ**

Επιβλέπων βοηθός εκπόνησης διπλωματικής εργασίας:

**ΒΑΣΙΛΕΙΟΣ ΣΤΕΝΟΣ**



**Αθήνα, Ιούλιος 2022**

# Ευχαριστίες

Βρίσκομαι στην ευχάριστη θέση να προλογίζω την διπλωματική μου εργασία η οποία ήταν απαραίτητη για την ολοκλήρωση των σπουδών μου, σηματοδοτεί την αποφοίτηση μου από την σχολή των Μηχανολόγων Μηχανικών του Εθνικού Μετσόβιου Πολυτεχνείου και βασίζεται στην ερευνητική προσπάθεια που πραγματοποίησα το τελευταίο έτος. Το παρόν σύγγραμμα εκπονήθηκε στον τομέα Βιομηχανικής Διοίκησης & Επιχειρησιακής Έρευνας της σχολής Μηχανολόγων Μηχανικών του ΕΜΠ.

Θα ήθελα να εκφράσω την βαθιά ευγνωμοσύνη μου για όσους συνέβαλαν στην πραγμάτωση της εργασίας αυτής. Συγκεκριμένα, στον καθηγητή κ. Κωνσταντίνο Αραβώση ο οποίος μου έδωσε την ευκαιρία να ασχοληθώ με ένα επιστημονικό πεδίο για το οποίο ενδιαφέρομαι ιδιαιτέρως και μου προσέφερε την υποστήριξη του καθ’ όλη τη πορεία της ερευνητικής μου αυτής προσπάθειας.

Οφείλω πολλές ευχαριστίες επίσης στον βοηθό του κ. Αραβώση τον κ. Βασίλειο Στενό και ιδρυτή της εταιρίας Solmeyea, του οποίου οι συμβουλές, η υποστήριξη και η καθημερινή του αρωγή ήταν καταλυτικής σημασίας για την εξέλιξη της διπλωματικής μου εργασίας σε όλα τα στάδια της. Ταυτόχρονα, θα ήθελα να τον ευχαριστήσω για την έμπνευση που μου έδωσε να ασχοληθώ με ακόμα μεγαλύτερο ζήλο στο συγκεκριμένο επιστημονικό πεδίο δίνοντας μου ερεθίσματα που μαγνήτισαν το ενδιαφέρον μου και με έκαναν να συνειδητοποιήσω την σημασία τους για τις προκλήσεις που εγκυμονεί το μέλλον στον τομέα της ενέργειας και του περιβάλλοντος. Τέλος, θα ήθελα να τον ευχαριστήσω για την επιμονή του να γίνει η σύνταξη της συγκεκριμένης διπλωματικής εργασίας στα αγγλικά έτσι ώστε να μου δοθεί η δυνατότητα μιας προσεχώς δημοσίευσή της σε επιστημονικό περιοδικό.

Κλείνοντας την συγκεκριμένη ενότητα ευχαριστιών δεν θα μπορούσα να παραλείψω να ευχαριστήσω την οικογένεια μου, τους φίλους μου και την Ειρήνη για την διαρκή συμπαράσταση τους και την υποστήριξή τους.

## Abstract

The scope of this diploma thesis is to highlight the technologies of carbon dioxide ($CO_2$) - capture and utilization as a necessary mean of dealing with the effects of climate change. It is clear that climate change is already beginning to affect the lives of billions of people across the world with forecasts for the coming years being ominous in terms of its evolution. The main cause of climate change is the ever-increasing concentration of greenhouse gases in the atmosphere from anthropogenic activities. Carbon dioxide ($CO_2$) along with methane ($CH_4$) are the most environmentally burdening of the greenhouse gases. Moreover, the $CO_2$ is mainly released into the atmosphere from anthropogenic activities that are attributed to energy production and transportation needs. The science, academia and industry's response to this crisis so far is mostly limited to applications that mitigate the excessive release of greenhouse gases into the atmosphere. However, the aim of this paper is to show that such a policy doesn't exclusively solve the problem but in fact it mainly limits its rapid development, so that is as urgent as ever to develop and sponsor applications that will absorb the excess carbon dioxide from the atmosphere. Thus, this paper starts from listing the most common $CO_2$ capture and utilization technologies in terms of their benefits in combating climate change but also in terms of challenges and techno-economical barriers to their expansion into key greenhouse gases removal applications with their simultaneous comparison. Secondly, it breaks down the favorable legal and economic environment in which investors can rely on and finance such applications while gaining both profitability and contributing against climate change thanks to their involvement. Finally, the decision-making model is presented on which the above technologies could rely in order to better substantiate both the tangible and intangible benefits and attract suitable investors and thus further ensuring their future financial viability.

# Περίληψη

Σκοπός της παρούσας διπλωματικής εργασίας είναι η ανάδειξη των τεχνολογιών δέσμευσης και αξιοποίησης του διοξειδίου του άνθρακα ($CO_2$) ως απαραίτητο μέσο αντιμετώπισης των επιπτώσεων της κλιματικής αλλαγής. Είναι εμφανές ότι η κλιματική αλλαγή έχει ήδη αρχίσει να επηρεάζει την ζωή δισεκατομμυρίων ανθρώπων ανά την υφήλιο με τις προβλέψεις για τα επόμενα χρόνια να είναι δυσοίωνες ως προς την εξέλιξη της. Βασικό αίτιο της κλιματικής αλλαγής αποτελεί η διαρκώς αυξανομένη συγκέντρωση αερίων του θερμοκηπίου στην ατμόσφαιρα που προέρχονται από ανθρωπογενείς δραστηριότητες. Το διοξείδιο του άνθρακα ($CO_2$) μαζί με το μεθάνιο (CH4) αποτελούν τα πιο επιβλαβή περιβαλλοντικά αέρια του θερμοκηπίου. Επιπλέον, το $CO_2$ είναι αυτό του οποίου η έκλυση στην ατμόσφαιρα προέρχεται κατά κύριο λόγο από ανθρωπογενείς δραστηριότητες που κυρίως συνδέονται με την παραγωγή ενέργειας και τις μεταφορές. Η μέχρι τώρα απόκριση της επιστημονικής και βιομηχανικής κοινότητας σε αυτή την κρίση περιορίζεται ως επί το πλείστων σε εφαρμογές οι οποίες μετριάζουν την υπέρμετρη έκλυση αερίων του θερμοκηπίου στην ατμόσφαιρα. Ωστόσο, στόχος της παρούσας εργασίας είναι να αναδείξει πως μια τέτοια πολιτική αντιμετώπισης δεν επιλύει αποκλειστικά το πρόβλημα αλλά στην πραγματικότητα απλά κυρίως περιορίζει την ραγδαία εξέλιξη του με αποτέλεσμα να είναι όσο επείγων όσο ποτέ η ανάπτυξη και η χρηματοδότηση εφαρμογών οι οποίες θα απορροφούν το πλεόνασμα διοξειδίου του άνθρακα από την ατμόσφαιρα. Έτσι λοιπόν, σε πρώτο χρόνο, στην συγκεκριμένη εργασία καταγράφονται οι πιο διαδεδομένες τεχνολογίες δέσμευσης και αξιοποίησης του $CO_2$ ως προς τα οφέλη τους στην καταπολέμηση της κλιματικής αλλαγής αλλά και ως προς τις προκλήσεις και τα τεχνοοικονομικά εμπόδια τους για την επέκταση τους σε βασικές εφαρμογές απομάκρυνσης αερίων του θερμοκηπίου με ταυτόχρονη σύγκρισή τους. Σε δεύτερο χρόνο, εξετάζεται το ευνοϊκό νομικό και οικονομικό περιβάλλον στο οποίο μπορούν να βασιστούν επενδυτές και να χρηματοδοτήσουν τέτοιες εφαρμογές αποκομίζοντας ταυτόχρονη κερδοφορία αλλά και συνεισφορά στην καταπολέμηση της κλιματικής αλλαγής με την ανάμειξή τους σε αυτές. Τέλος, παρουσιάζεται το μοντέλο λήψης απόφασης στο οποίο πρέπει να βασιστούν οι παραπάνω τεχνολογίες ώστε να τεκμηριώσουν καλύτερα τόσα τα υλικά όσο και τα άυλα οφέλη από την εκτέλεση των εφαρμογών τους και να προσελκύσουν υποψήφιους επενδυτές εξασφαλίζοντας με αυτό τον τρόπο την μελλοντική τους χρηματοοικονομική βιωσιμότητα.

# Table of Contents

# Multimedia Table of Contents

## List of figures

## List of diagrams



## List of Tables

## Explanations of key abbreviations

**GHG**: Greenhouse Gases

**IPCC**: International Panel for Climate Change

**UNFCCC**: United Nations Framework Convention on Climate Change

**UN**: United Nations

**GA**: General Assembly

**SDG**: Sustainable Development Goals

**UNEP**: United Nations Environment Programme

**GDP**: Gross Domestic Product

**CCUS**: Carbon Capture Utilization and Storage

**CCS**: Carbon Capture Storage or Sequestration

**CCU**: Carbon Capture Utilization

**VRE**: Variable Renewable Energy

**PV**: Photovoltaic

**EU**: European Union

**DA(C)C**: Direct Air (Carbon) Capture

**ETS**: Emissions Trade System

**APS**: American Physical Society

**R&D**: Research and Development

**PEC**: Purchased Equipment Costs

**OPEX**: Operating Expenditures

**CAPEX**: Capital Expenditures

**NPV**: Net Present Value

**P**: Profit

**CF**: Cash Flow

**WACC**: Weighted Average Cost of Capital

**AF**: Annuity Factor

**LCOC**: Levelized Cost of Capture

**LCA**: Life Cycle Analysis

**UAE**: United Arab Emirates

**BPS**: Basic Points

**TVS**: Temperature-Vacuum-Swing

**EV**: Electric Vehicles

**EOR**: Enhanced Oil Recovery

**IP**: Intellectual Property

**ECBM**: Enhanced CoalBed Methane

**NGCC**: Natural Gas Combined Cycle

**NG**: Natural Gas

**LNG**: Liquid Natural Gas

**BEV**: Battery Electric Vehicles

**FCV**: Fuel Cell Vehicles

**SI**: Spark Ignition engine

**CI**: Compression Ignition engine

**RON**: Research Octane Number

**MON**: Motor Octane Number

**CN**: Cetane Number

**SAF**: Synthetic Aviation Fuels

**RWGS**: Reverse Water Gas Shift

**FT**: Fischer-Tropsch

**MeOH**: Methanol

**PtP**: Pollution to Products

**TBR**: Trickle Bed Reactor

**PBR**: Photo BioReactor

**VFA**: Volatile Fatty Acid

**IPTO**: International Power Transmission Operator (Greece's operator)

**CORSIA**: Carbon Offsetting and Reduction Scheme for International Aviation

**OTC**: Over The Counter

**AXC**: Air Carbon Exchange

**NGO**: Non-Governmental Organizations

**DMU**: Decision-Making Unit

**DMM**: Decision-Making Mechanism

**B2B**: Business to Business

**ESGs**: Environmental Social and corporate governance

# Introduction

## Emissions of $CO_2$ and legal framework of future goals towards inverting climate change

Emissions of greenhouse gases (GHG) from industrialization and urbanization lead to global warming and climate change, which is nowadays considered a planetary emergency (Sun, et al., 2021). On 11 May 2019, $CO_2$ levels in our atmosphere reached 415.26 ppm for the first time in human history. The last time $CO_2$ levels were this high was probably 2.5 to 5 million years ago, when temperatures were 2 to 3 K higher than today (Καρέλλας & Κακαράς , 2021). Rolling back time, in the third report of the International Panel for Climate Change (IPCC), it was mentioned that the decisive factor that leads to the increase of ambient air temperature was the rise in the concentration levels of greenhouse gases, where $CO_2$ is included. The world emissions of $CO_2$ were increase by 80% during the period 1970-2004 (Καρέλλας & Κακαράς , 2021). In the 15th conference of United Nations Framework Convention on Climate Change (UNFCCC), the capture process was proposed for the stabilization of greenhouse gases concentration, so as to keep the mean world ambient air temperature below 2 K in comparison with the mean temperature of the pre-industrial period. Essentially, that means the stabilization of the greenhouse gases concentration in 450 ppm $CO_{2eq}$ (including all greenhouse gases as $CO_2$ equivalent) and the reduction of those by 25% up to 40% for the developed countries and by 15% up to 30% for the developing countries for the time period of 1990-2020 (Καρέλλας & Κακαράς , 2021). After the 21st Conference of the United Nations concerning climate change in Paris 2015, the deal COP21 established a new reference point for the limitation of rising mean global ambient air temperature below 2 K. This was done to motivate the global community to invest in technologies that promote the reduction of greenhouse gases and to avert the most catastrophic effects of climate change. Then, in 2016 the United Nations General Assembly (UN-GA) officially set up the Sustainable Development Goals (SDG's) or Global Goals which are a collection of 17 interlinked goals designed to promote a more sustainable future for all. The SDG's achievement relies heavily on climate change mitigation and is intended to be achieved by 2030. In 2018, the United Nations Environment Programme (UNEP) proposed that global GHG emissions need to be cut by at least 25% of the 2017 levels by 2030 to meet Paris agreement targets (Sun, et al., 2021). In figure 1, the emissions pathway required to limit emissions within the IPCC budget 2 K is shown, as well as the evolution of the rise of $CO_2$ from the 1980 up until 2015 data ((EASAC), 2018). Leading scientific studies indicate that by mid-century 10 billion tons of carbon dioxide will need to be removed from the air every year to keep global warming in line with the limits of the Paris Agreement (Cooke, 2021).

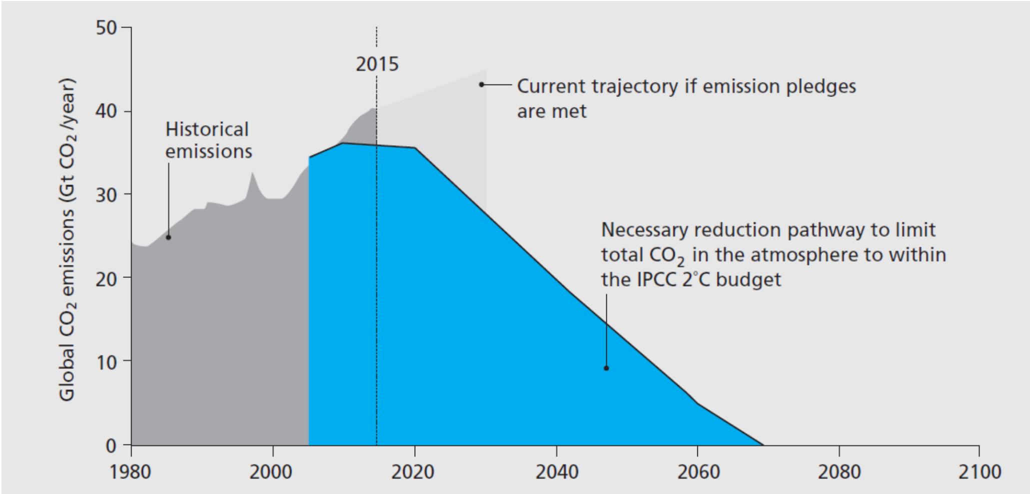


*Figure 1: Emissions pathway to limit emissions within the IPCC budget ((EASAC), 2018)*

GDP growth of every country has always been positively related with greenhouse gases emissions rise. Scope of this diploma thesis is to propose solutions to reduce the equivalent $CO_2$ footprint in the atmosphere as an urgent emergency nowadays in the battle against climate change but without the need to diminish the production process of industrial facilities and transportation.

## Current and projected climate change abatement policy

As far as the current abatement policy of greenhouses gases the world community sticks to four ways as shown in figure 2.

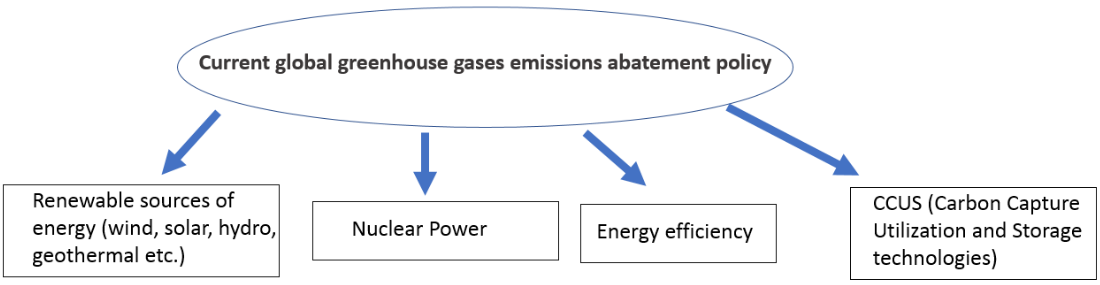


*Figure 2: Current greenhouses gases abatement policy*

Firstly, the systematization of the use of renewable sources of energy helps the energy sector to produce useful energy output with close to zero $CO_2$ emissions. For instance, an additional MWh of wind generation reduces Irish $CO_2$ emissions by 0,4 tons (Oliveira, et al., 2018). But all this up to a point. This point is defined by the laws of supply and demand of electric power in the system and the technical standards of hot reserves of conventional power units. Thus, the system operator of each region is responsible to clarify the share of Variable Renewable Energy (VRE) sources that will allow to operate at its full capacity in order to assure the adequacy of the system. This is because systems with a high share of VRE (wind and solar photovoltaic: PV mainly) represent a challenge for the system operator because of their intermittency, location-specific output, uncertainty, and limits in predictability. At a time, the operator may be forced to allow less wind and solar generation than is available; this energy that could potentially be used is known as curtailment. In this way, curtailment occurs by transmission or system balancing constraints on the local network (Guerra, et al., 2022). Therefore, we could argue that the penetration of renewables in the energy production sector is positively affecting climate change but since they are saturated, they are not enough to meet the goals of the Paris agenda. So, more sustainable technologies also need to be adopted by the energy sector.

Secondly, nuclear power represents a challenging pathway towards $CO_2$ emissions cut. Nuclear waste and a possibility of a nuclear accident give a hold status toward further expansion of these technologies in power generation in the fight against climate change.

Thirdly, energy efficiency is a talk point any new industrial facility wants to achieve. Firms and individuals invest significant amounts of money trying to build machines with the highest efficiency or in other words with the lowest cost of energy refueling. Indeed, big steps have been accomplished nowadays in the efficiency of modern power plants (e.g., utilization of excess thermal energy of a modern fossil fueled power plant for the purpose of a district heating of a city in order to avoid useful heat to escape to the environment increasing the efficiency of the plant). Although important, energy efficiency alone cannot meet the goals of IPCC. Energy efficiency can reduce the $CO_2$ emitted in the atmosphere compared to previous years but cannot invert the current increase in the concentration levels of $CO_2$ globally. Hence, there is an urgent need for new technologies of removing and utilizing $CO_2$ emitted from fossil fuels to be adopted in order to reverse the current situation.

Lastly, CCUS technologies are defined as Carbon Capture Utilization and Storage technologies and are about to play a very important role today since in IPCC's recent report ((IPCC), 2021) the means of achieving the 1.5 K threshold strongly depend on removing $CO_2$ from the atmosphere. $CO_2$ already in the atmosphere can affect climate change for hundreds to thousands of years. Even if we do cut most of carbon emissions down to zero by intensifying energy efficiency, emissions from sectors like energy generation and transportation are hard to abate. Also, several industry sectors depend on the consumption of carbon as raw material (e.g., steel, pulp, and paper industry). These can never be completely decarbonized. Thus, the importance of CCUS is even more evident now in the effort of a climate neutrality. EU policy makers plan the adoption of incentives and fundings of these technologies from the European Parliament. It is indicative that the European Commission President, Ursula von der Leyen, has highlighted that "Our most pressing challenge is keeping our planet healthy. This is the greatest responsibility and opportunity of our times. I want Europe to become the first climate-neutral continent in the world by 2050" (Platform, 2022). So, according to EU climate officials, for Europe to reach climate-neutrality by 2050, renewables, nuclear power, and energy efficiency, although important, will not be enough. CCS and CCU will be essential for the European transition to net neutrality, ensuring that power generation and industrial processes are secure, reliable, and sustainable.

## Cases of CCS (Carbon Capture Storage or Sequestration) and CCU (Carbon Capture Utilization) technologies

CCS technologies gather and store $CO_2$ that either is about to be released in the atmosphere after an industrial process that involves fossil fuel burning or that pre-exists in ambient air (post-combustion capture) or before the release of $CO_2$ in the combustion phase (pre-combustion capture) or during the combustion phase (oxyfuel) (Καρέλλας & Κακαράς , 2021). The most advanced and applied technology in scale of CCS that currently is in operation is Direct Air Carbon Capture (DACC) or just Direct Air Capture (DAC) which captures atmospheric $CO_2$ and splits it from the air. In this way, ambient air is free of $CO_2$. DACC is a post-combustion carbon capture technology as it captures gathered preexisted $CO_2$ in the atmosphere. DACC technology is the analog of tree's photosynthesis but in a bigger scale. ClimeWorks and Carbon Engineering are two firms that have scaled up DACC technology nowadays (Gutknecht, et al., 2018) and use these captured tons of $CO_2$ for permanent mineral storage sequestration in basalts in the case of Climeworks and for sequestration or further utilization in the case of Carbon Engineering.

On the other hand, CCU technologies focus on how to exploit gathered $CO_2$. We can divide them in two branches: in Conversion CCUs and non-Conversion CCUs. Conversion CCU involves processes in which $CO_2$ is used to produce a post-processed product useful for human consumption after either chemical treatment (e.g., liquid fuels, urea, polymers) or biological treatment (e.g., alga cultivation, micro-algae cultivation) or mineralization treatment (e.g., concrete, bauxite treatment, carbonates). Non-conversion CCU involves processes in which $CO_2$ is used to enhance another industrial activity (e.g., enhanced oil recovery, desalination) (Kenyon, 2015)

Of course, a combination of storage and utilization technologies of $CO_2$ counts for CCUS technologies. Figure 3 is indicative of major available CCUS pathways.

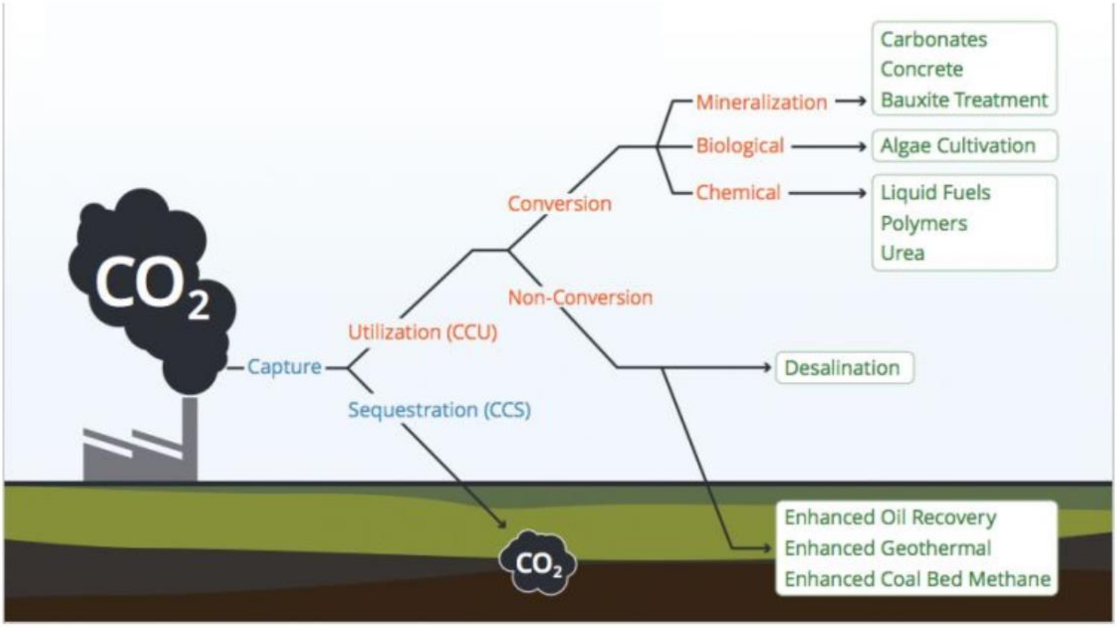


*Figure 3: Summary of major available CCUS pathways (Kenyon, 2015)*

## Structure of this diploma thesis paper and basic aspirations

In this diploma thesis paper, we try to present the major and most advanced application of CCUS technologies and compare them for their effectiveness and their challenges. In part 1, we analyze the challenges and benefits of CCS technologies, and we focus on the most implemented CCS technology which is Direct Air Capture (DAC). DAC also is the first in industrial scale application of capturing $CO_2$ from the atmosphere and has recently gained the attention of major investors and general public. In part 2, we also analyze the challenges and benefits of CCU cutting edge technologies by focusing on the author's most promising and reliable applications from a wide area of activities of utilization of $CO_2$. In Part 3, we present the legal framework where CCUs financial viability is based on and how the interaction between this legal framework and innovative carbon removal idea holders will allow the latter to set up profitable applications while contributing to climate change mitigation. In Part 4, we present extra opportunities that arise from the recent decarbonization law in Greece and the expansion of voluntary carbon offset markets. In Part 5, we present the decision-making model on how private energy intensive industries, the society and every individual are better off by promoting these types of applications and in particular the case of microalgae cultivation. Finally, in Part 6 we present the conclusions of the above research areas. Basic aspirations of this diploma thesis are to promote the urgency of adopting CCUS applications in everyday life since they are part of a circular economy that the world currently needs to tackle the effects of climate crisis. Another basic aspiration is to highlight which CCUS is to be preferred each time according to the geographical place of implementation, the readiness of the technology and the available resources.

# 1. Necessity and major active CCS technologies and their analysis

## 1.1. The urgency of the development of $CO_2$ capture from ambient air

Stabilizing atmospheric $CO_2$ will require drastic emission reductions. Nearly half of all $CO_2$ emitted will stay in the atmosphere for centuries. According to the IPCC, $CO_2$ emissions must be reduced by 30-85% by 2050 to be on track for stabilizing atmospheric $CO_2$ between 350 and 440 parts per million by volume (ppmv). Not only would emissions from coal have to essentially stop by 2050, but also emissions from other fossil fuels would have to be reduced. Beyond 2050, $CO_2$ emissions would have to continue to fall to levels approaching zero to achieve full stabilization of the atmospheric $CO_2$ concentration. It may even prove necessary to reduce excess $CO_2$ in the atmosphere below current levels or below future stabilization levels (Lackner, et al., 2012).

As mentioned in the introduction, carbon-free renewable and nuclear energy face a challenge from their intensification. It is unclear, however, whether these resources can be deployed rapidly and widely enough and overcome social-political obstacles related to cost, environmental impacts, and public acceptance. In a world that strives for continued economic growth, moving the energy infrastructure away from fossil fuels is a challenging risk. Whereas CCS technologies allow for the continued use of fossil fuels in power plants and in steel production while largely eliminating their $CO_2$ emission, air capture could also deal with fugitive emissions from the transport and storage stages of CCS and thereby manage the risk of $CO_2$ leakage from geological storage. Thus, the development of air capture CCS, even though itself uncertain, could be an insurance policy against low-probability high-impact events (Lackner, et al., 2012).

## 1.2. Additional incentives analysis for further expansion of DACC as a major CCS technology

The motivation for further implementation of DACC technologies apart from its immediate contribution to the mitigation of climate change can be found on the offsetting of transportation emissions, on the closed carbon cycle with $CO_2$ as a raw material for synthetic fuels, on the reduction of the need for $CO_2$ transport and on the insurance policy against $CO_2$ leakage from geological storage sites.

Firstly, through DACC the compensation or the offsetting of mobile $CO_2$ emissions can be implemented. Emissions associated with the transportation sector could be addressed by collecting $CO_2$ directly from the air while maintaining the current transportation infrastructure. Air capture could provide an alternative or a complement to the electrification of cars and to the exclusive reliance on biofuels in the remaining transportation sectors. We cannot know today which technology will prove the winner, but alternatives are certainly worth investigating. Without air capture, nonpoint sources of emissions will need to be phased out over the next few decades if we want to meet IPCC's targets. An 80% reduction of $CO_2$ emissions by 2050 in developed countries cannot be achieved even if all point source emissions were captured (Lackner, et al., 2012). The inclusion of maritime sector emissions after the inclusion of emissions from the aviation sector in EU ETS system shows that the political debate has already moved past point sources.

Secondly, DACC contributes to a closed carbon cycle. The intensification of renewables is yet questionable due to the ease of handling and exceptional volumetric energy densities of liquid hydrocarbon fuels (Lackner, et al., 2012). So, another incentive for DACC technology applications is if they become affordable to be also economical for closing the carbon cycle by using synthetic fuels and preserve the advantages of liquid hydrocarbon for the next generations.

Third motive for DACC expansion is that through this technology a reduction for the need of $CO_2$ transportation can be achieved. $CO_2$ pipelines network is a massive project, because $CO_2$ would need to be carried from the place where it is captured to the storage site, a route that may involve thousands of miles. Building pipelines would be expensive, necessitate difficult to obtain legal permissions, and face risks and environmental issues as well as public scrutiny where pipelines cross populated or protected areas. International geopolitics may intervene when pipelines cross borders and physical obstacles may limit transport over mountains or bodies of water (Lackner, et al., 2012). By contrast, air capture can operate at the storage site and would eliminate the need for transporting $CO_2$ over long distances.

Another motive for DACC technology expansion constitutes the undergoing legal framework for any possible $CO_2$ leakage. Air capture cannot prevent the damages associated with a catastrophic gas loss but provides a means of recapturing leaked $CO_2$, thereby insuring against gradual leaks. Air capture can be used to compensate and offset any leakage done either by accident or deliberately. The owner of a storage reservoir that leaks $CO_2$ into the atmosphere should be considered an emitter who has to make compensation for the $CO_2$ lost (Lackner, et al., 2012). Without a means of recapturing the leaked $CO_2$, CCS deployment could be hindered as leaks are not entirely preventable and, in the future, may not fit within the remaining $CO_2$ budget. The price of air capture could thus affect the price of geological storage, perhaps as part of mandatory leakage insurance policy. So, reducing the potential cost of leakage also opens the door to more accurate accounting of $CO_2$ storage and as a result increased accountability of the operator in turn would encourage better reservoir choices (Lackner, et al., 2012).

### 1.3. Current state of major CCS technology: Direct Air Carbon Capture (DACC) technology and it's future financial forecast

The most significant DACC technologies up until now are Carbon Engineering and Climeworks as referred in the introduction section. These two companies operate based on the same concept of capturing $CO_2$ from ambient air. They bring large quantities of air into contact with sorbent chemicals which are involved in regenerative cycles to capture, concentrate, liberate, and then safely store the atmospheric $CO_2$ permanently underground (Daniel, et al., 2021). The differences are only spotted in the procedures of these applications. The reason behind the prevalence of DACC as the major CCS technology and the promotion of these two major firms is found in the concentration of $CO_2$ in ambient air. Even if, point sources have high purity of $CO_2$ compared to ambient air and relative lower capture costs (de Kleijne, et al., 2022), because of the ratio of air to $CO_2$ molecules (2,500:1), air capture systems cannot afford the effort to prepare or modify air, which eliminates capture technologies that put energy into the air, such as heating, cooling, or pressurizing air in as similar storage perspective (Lackner , et al., 1999). The only feasible techniques involve either absorption or adsorption on a sorbent as it is the application of both Carbon Engineering and Climeworks. With such techniques, energy is required only to regenerate the sorbent. It is useless for any further energy to be used for a possible better adduction of ambient air since $CO_2$ emissions associated with the use of energy could partially or completely cancel out air capture.

As far as the financial perspective of these DACC firms to play a substantial role in managing $CO_2$ in the atmosphere, they need to become economically feasible on large scale. Estimates of future costs for a fully established technology, keeping in mind the uncertainty of this innovation technique are placed from as low 28.5€ (30$) per metric ton of $CO_2$ (t $CO_2$) to 950€ /t $CO_2$ (1000$ /t $CO_2$). The American Physical Society (APS) argues that DAC is unlikely to play an important role if capturing costs are estimated from 570€ /t $CO_2$ (600$ /t $CO_2$) and above (Lackner, et al., 2012). In estimating the costs of a new device or plant, there are three cases-classes to consider: an existing system built already, a one-of-a-kind fully developed but never built system and a new untested technology. The third class of estimates attempts to establish the cost of a system that is still subject to research and development (R&D) and has not yet been fully designed. This third class applies to air capture technology. An accurate estimate today of future costs is simply impossible; a system that can be built now should be seen as a straw man to be replaced with improved designs. Not surprising but cost estimates of novel technologies have often been wrong from the initial ones (Lackner, et al., 2012). The costs of new technologies can drop by orders of magnitude as they develop, and mass production ensues. For example, the cost of solar panels has dropped almost 100-fold since the 1950s (Nemet, 2006). Efficiency improvements in gas turbines have moved them from a scientific curiosity in the 1930s to a mainstay in the power generation and aviation today (Ferioli, et al., 2009). Also, policies towards wind and hydro energy are based on the assumption that R&D and learning by doing will continue to drive prices down. As such DACC technology must be considered. So, since it is impossible to accurately predict the cost of an undeveloped technology, it is instructive to ask instead what cost targets must be met to make air capture a useful technology for climate change mitigation and to make it also financially sustainable.

An obvious target is for these technologies to meet the targets of the European Emissions Trade System (ETS). EU ETS works on the principle of 'cap-and-trade'. It sets an absolute limit or ‘cap' on the total amount of certain greenhouse gases that can be emitted each year by the entities covered by the system. This cap is reduced over time so that total emissions fall. Under the EU ETS, regulated entities buy or receive emissions allowances, which they can trade with one another as needed. At the end of each year, regulated entities must surrender enough allowances to cover all of their emissions. If a regulated entity reduces its emissions, it can keep the “saved” allowances to cover its future needs or sell them to another installation that is short of allowances. A regulated entity is considered every power and heat generation unit, energy-intensive industrial sectors, and the aviation sector. These sectors combined account for 41% of the EU’s total emissions. Also, maritime sector will be included to the ETS by 2023 (Commission, n.d.). So, considering the above, the target for these DACC technologies to be financially sustainable by their own is to bring the cost of every ton of $CO_2$ captured down and lower than each time’s trade price of the EU ETS’s allowances. In May 2022 the price of carbon allowances was around 80 € / t $CO_2$ (84.26 $ /t $CO_2$) with forecast to rise even more in the coming months (Org, n.d.). Another target could be the capturing cost to meet the social-political limit that is adopted each year. For instance, if climate change was universally perceived as a serious calamity, air capture as an emergency measure might be valuable at costs much higher than 95€ /t $CO_2$ (100$ /t $CO_2$). But the financial forecast even in this lenient target is not ideal for the financial sustainability of these DACC technologies. It is more likely that if air capture were above 95€ /t $CO_2$ (100$ /t $CO_2$) and there was no credible path for cost reductions, alternatives to fossil fuels would be more developed (e.g., biofuels) and eventually displace them. If realizable below 47.5€ /t $CO_2$ (50$ /t $CO_2$), air capture would be a strong contender among the various options and would not necessarily be tied to fossil fuels. For example, the availability of $CO_2$ from the air would open the door to algae-based and microalgae-based fuel production schemes than require $CO_2$ as an input (Lackner, et al., 2012).

### 1.4. Sorbent choice analysis

The cost estimates of air capture rests on two observations. Firstly, the concentration of $CO_2$ in air is relatively high enough to allow for small collector devices. Secondly, the binding energy required from an air capture sorbent that removes $CO_2$ in its regeneration phase is only slightly larger than that required for scrubbing $CO_2$ from the flue stack of a coal-fired power plant. Because there is nearly 0.4 L of $CO_2$ in every cubic meter of air, it requires little air movement for a collector to contact a large amount of $CO_2$ (Lackner, et al., 2012).

The sorbent choice is crucial since it is the main component of DAC procedure. Figure 4 illustrates a schematic diagram for a generic DAC system and how it works.

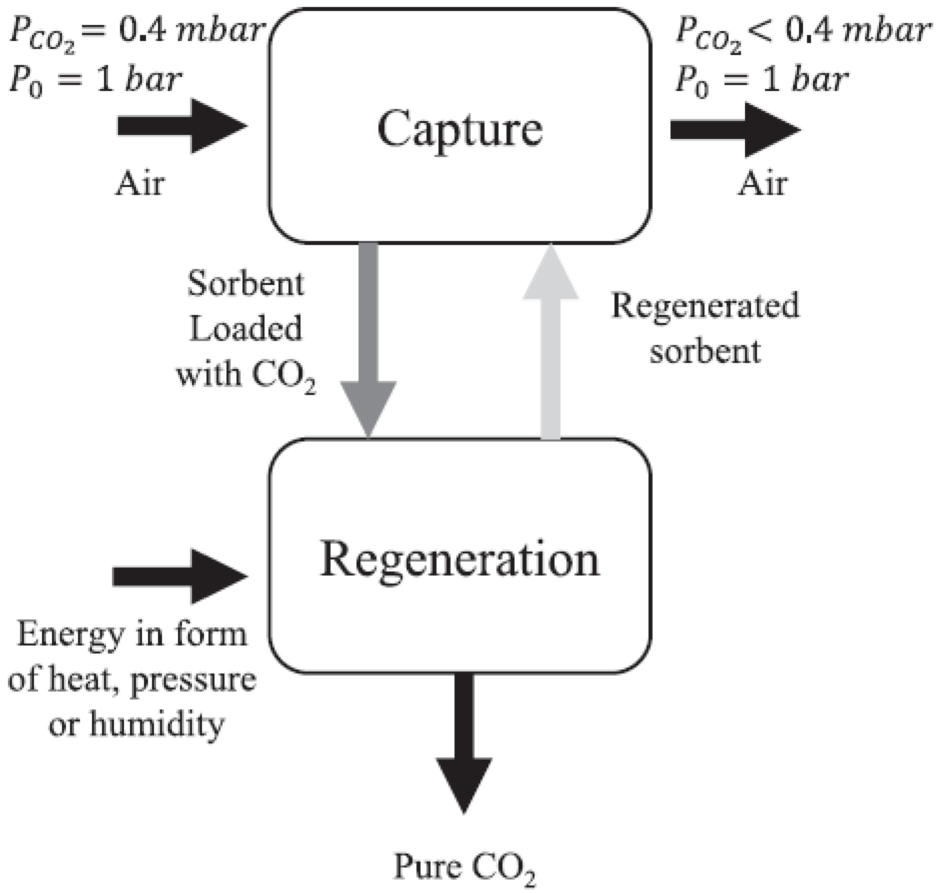


*Figure 4: A schematic view of an air capture device (Azarabadi & Lackner, 2019)*

Ambient air with a more or less constant composition is the source of $CO_2$ and a liquid or solid sorbent binds the $CO_2$ molecules in the capture stage. Capture is based on the physical or chemical interaction between $CO_2$ and the active ingredient of the sorbent. In the capture stage, $CO_2$ binds to the sorbent, in the regeneration stage the captured $CO_2$ is separated from the sorbent. The required energy for detaching $CO_2$ from the sorbent can be provided by heat, exposure to near vacuum pressure, or moisture. Different combinations of temperature, pressure and moisture swings can be used, and an optimal choice will depend on the type of sorbent. After the $CO_2$ has been removed from the sorbent in a regeneration chamber, the regenerated sorbent is ready for reuse while the captured $CO_2$ is further processed, e.g., compressed and stored. Different research groups have proposed various approaches to DAC with sorbents ranging from hydroxide solutions to solid amine sorbents (Azarabadi & Lackner, 2019). All have in common a capture cost that exceeds that of post-combustion scrubbing. The main challenge for DAC is that $CO_2$ in the air is about 300 times more dilute than in a typical flue gas stream and this is the reason why sorbent techno-economics in DAC devices are so important compared to a typical power plant $CO_2$ scrubber (Azarabadi & Lackner, 2019).

So, for $CO_2$ collectors standing passively in the air, the cost of a sorbent regeneration dominates the cost of contracting $CO_2$. The cost of regenerating a fully loaded sorbent depends on its mass and volume and on the binding energy that must be overcome, making it as previously stated the most crucial choice for DACC firms. For a chemical sorbent, the volume or mass per unit of $CO_2$ bound does not depend on the initial concentration in the gas stream. The minimum required binding strength of the sorbent, however, depends on the concentration of the $CO_2$ in the gas stream. The relationship between the Gibbs free energy of adsorption and minimum concentration is logarithmic (Society, 2011)

In detail, plausible DAC processes such as are the cases of Climeworks and Carbon Engineering use solid sorbents or aqueous basic solutions as the fly ash derived adsorbent capture media as it is shown in figure 5 process.

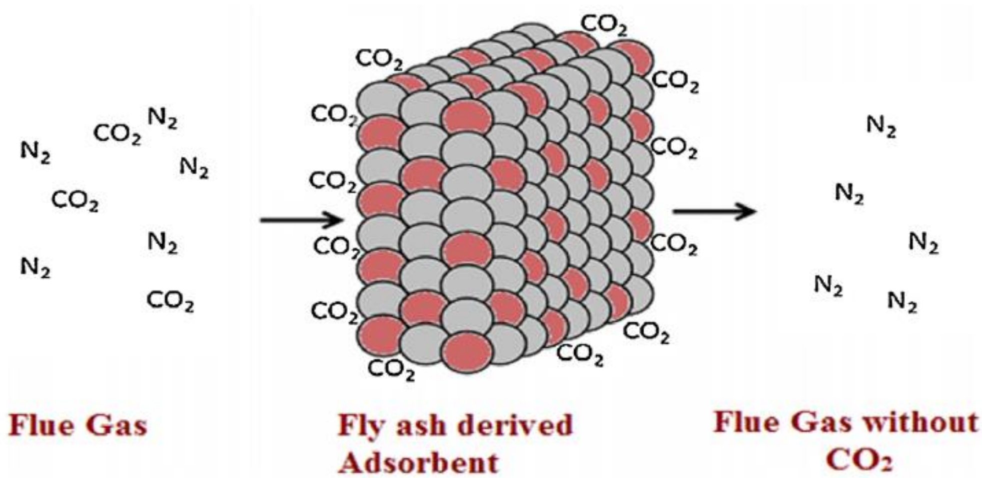


*Figure 5: $CO_2$ sorbent capture mechanism (Kaithwas, et al., 2012)*

Solid sorbents offer the possibility of low energy input, low operating costs, and applicability across a wide range of scales. The challenges of solid sorbent designs are firstly, the need to build a very large structure at low cost while allowing the entire structure to be periodically scaled from the ambient air during the regeneration step when temperature, pressure, or humidity must be cycled. And secondly, the inherently conflicting demands of high sorbent performance, low cost, and long economic life in impure ambient air (Keith, et al., 2018).

On the other hand, aqueous sorbents offer the advantage that the contactor (e.g., the analog of $CO_2$ collector in the case of Climeworks) needed for the process can operate continuously, can be built using cheap cooling-tower hardware, and the liquid surface is continuously renewed allowing very long contactor lifetimes despite dust and atmospheric contaminants that are always present in ambient air. Once captured, $CO_2$ can be easily pumped to a central regeneration facility allowing economies of scale and avoiding the need to cycle conditions in the inherently large air contactor. Disadvantages of aqueous systems include the cost and complexity of the regeneration system and water loss in dry environments (Keith, et al., 2018).

## 1.5. Cost breakdown of these major Direct Air Carbon Capture (DACC) technologies

Sticking now to the computing side of the cost breakdown of DACC technologies we can derive the following:

1. Capital Costs

DACC's plants capital costs are estimated using a combination of methods, such as direct estimation where data is available or through calculating the purchased equipment cost (PEC) (Daniel, et al., 2021). In general, capital costs are computed by summing up all the components needed for the investment of the DACC plant to be functional.

2. Operating Costs

The costs for the plant raw material and utilities constitute the variable operating expenditure ($OPEX_{var}$) with operation, maintenance, and other charges independent of operation rate constituting the fixed operating expenditure ($OPEX_{fix}$). $OPEX_{var}$ costs include raw materials (i.e., KOH for the air contactor of Carbon Engineering as we will see in the following chapter) and utilities (i.e, fuel, process, electricity). $OPEX_{fix}$ includes labor, maintenance, taxes, and rent. The sum of $OPEX_{var}$ and $OPEX_{fix}$ constitutes the total operating costs of the plant (Daniel, et al., 2021).

3. Cash Flow

Cash flow represents the movement of cash to or from a company during the plant lifetime and is, thus, used to assess the profitability of a project. Cash flows are based on the estimate of the gross profit (P) of the plant which is given in equation 1 (Daniel, et al., 2021).

$$P = Revenue - OPEX \qquad (1)$$

Due to the significant external funding investment sometimes also governmental or even institutional or corporate ones are required for DACC plant to stay in business (such as, Microsoft recent placement on the Climeworks company, recently closed equity-based $650M fund-raising round), it is assumed that any installation would run as not for profit for the medium run and so would be unaffected by tax. Hence the cash flow is simply equal to the gross profit as shown in equation 2 (Daniel, et al., 2021).

$$CF = P \qquad (2)$$

The sum of the individual annual cash flow of a project gives the net present value (NPV) of the project as shown in equation 3 (Αραβώσης, et al., 2011)

$$NPV = \sum_{y=0}^{n} \frac{CF_y}{(1+i)^y} \qquad (3)$$

Where n is the assumed plant lifetime of roughly 25 years, and i is the interest rate.

4. <u>Levelized Costs</u>

Carbon Capture technologies are mainly compared using levelized costs whereby the cost of capturing a unit of $CO_2$ (LCOC) is derived according to the equation 4.

$$LCOC = \frac{(Capital\ Costs * AF) - CF}{annual\ carbon\ capture} \quad (4)$$

Where AF is the annuity factor, shown in equation 5.

$$AF = \frac{WACC(1 + WACC)^n}{(1 + WACC)^n - 1} \quad (5)$$

Where WACC is the weighted average cost of capital, and n is the plant lifetime (Daniel, et al., 2021).

DACC technologies rely heavily on external funding to stay in business. The cost for such an innovative technology is difficult to be distributed exclusively to equity. The innovation and the urgency of DACC in the climate change mitigation is the key factor that raises awareness in the public and offers fertile ground for investors to fund the following projects. Breyer et al. (2019) predict the costs falling particularly drastically post 2040, with expectation based on the maturing of the technology, widespread implementation, and falling energy costs. There is a potential for even greater cost reductions; however, it is unlikely that standard DACC will ever be able to negotiate, thus consequently lower its costs (Breyer, et al., 2019).

## 1.6. The technology of Climeworks and Cardfix project

As part of the EU-funded CarbFix2 project, Climeworks and Reykjavik Energy have partnered to combine direct air capture (DAC) technology with the injection of $CO_2$ into basalts, for permanent storage by mineralization of the injected carbon. Climeworks, a Swiss based company, is the one that has been chosen by Microsoft to help it achieve negative emissions by 2030 and remove company's historic emissions by 2050. The technology will be a key component of Microsoft's carbon removal efforts. Climeworks meets the assessed negative emissions' technology attributes set by Microsoft on four criteria to decide which technologies to use to meet its climate goals, which are: scalability, affordability commercial availability and verifiability (Cooke, 2021).

Climeworks has combined its DAC technology with the CarbFix method. Most of the ongoing carbon storage projects are injecting $CO_2$ into sedimentary basins where the $CO_2$ is injected as a separate buoyant phase anticipated to be trapped below an impermeable cap rock. In Iceland where the company's plant "Orca" (as shown in figure 6) is based, an alternative method is being developed as a part of the CarbFix project, where the $CO_2$ is dissolved in water before or during its injection into porous and fractured basaltic rocks. Because the $CO_2$ is dissolved, it is not buoyant; in fact, the injected fluid is denser than the surrounding reservoir fluid due to the $CO_2$ and thus has tendency to rise. Therefore, solubility trapping happens immediately, and no cap rock is required.


*Figure 6: An exhibition replica of the newly manufactured Orca plant in Iceland (Gutknecht, et al., 2018)*

Fundamentally, the Climeworks DAC design is based on an adsorption/desorption process on alkaline functionalized adsorbents. Ambient air is adducted to the $CO_2$ collector with a fan and after a chemical reaction process is cleared of all $CO_2$ molecules. Carbon dioxide is captured on the surface of a highly selective filter material that sits inside the collectors ("adsorption"). After the filter material is full of carbon dioxide, the collector is closed. The temperature is increased to between 80 and 120 °C and this releases the carbon dioxide ("desorption") which can be collected in high purity and concentration. $CO_2$ adsorption is performed without treating the incoming air stream, and $CO_2$ desorption is performed through a temperature-vacuum-swing (TVS) process. During this process the pressure in the system is reduced and the temperature is increased as referred from 80 to 120 $^oC$, thereby releasing the captured $CO_2$. After a cooling phase, the whole process is repeated (Gutknecht, et al., 2018), as illustrated in figure 7.

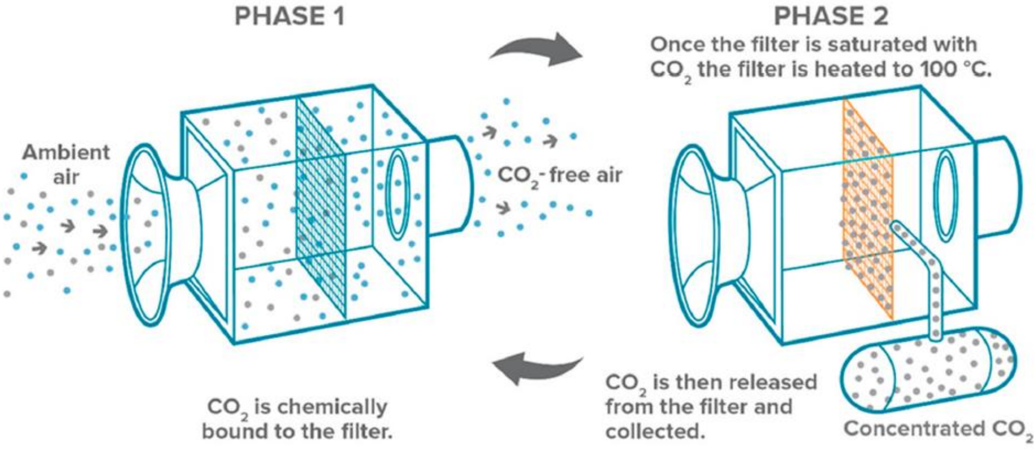


*Figure 7: Schematic illustration of Climework's direct air capture process (Gutknecht, et al., 2018)*

Climeworks adopted a modular design to reduce operating costs, support scalability and enable automated manufacturing. $CO_2$ adsorption and desorption are performed within the same device, referred to as the "$CO_2$ collector" or just "Collector". Collectors are engineered to fit efficiently into a steel frame, with six collectors fitting into a standard 40-foot shipping container. The only significant moving part in the collector is the fan to draw in air for adsorption. Another important characteristic of the Climeworks DAC process is that a large share of the energy demand can be met by heat in the range of 80-120 $^oC$, which is available from a variety of sources including industrial low-grade waste heat, or as in the case of the CarbFix process, geothermal heat which is abundant in Iceland where the Orca plant currently operates.

The CarbFix project which permanently stores underground the $CO_2$ captured by Climeworks technology aims to develop safe, simple, and economical methods and technologies for permanent $CO_2$ mineral storage in basalts. The results, that were published in 2016 by CarbFix as a complete study of the process, confirm the rapid mineralization of the injected gases (Gutknecht, et al., 2018).

Following the success of the initial pilot injections, the CarbFix project was scaled up to an industrial scale and managed to inject about one-third of the $CO_2$ emissions from Hellisheidi power plant, or about 10,000 tons annually at current injection rate (Sigfusson, et al., 2018). The gas mixture consists of 65% $CO_2$ and 35% $H_2S$, which are the most abundant geothermal gases in the Hellisheidi field and are of magmatic origin. The gases are dissolved and injected at depths below 700 m and temperatures about 250 $^oC$, where the gas charged fluid reacts with the basaltic bedrock and forms stable carbonate minerals. It is anticipated that more than 950 Gt of $CO_2$ could theoretically be stored within the active rift zone in Iceland where Climeworks's Orca plant currently operates. The largest storage potential lies offshore where it is anticipated that $CO_2$ from the burning of all fossil fuels on Earth could theoretically be stored as carbonate minerals within the oceanic ridges (Gutknecht, et al., 2018).

The successor of this successful Cardfix project is called Cardfix2 and one of its new goals is to combine the storage approach with DAC technology, the case of

Climeworks, and thus create an integrated $CO_2$ removal solution with a potential for global application. The implementation and testing process of this Cardfix2 project has as following. A Climeworks DAC module has been installed at the Hellisheidi power plant that utilizes heat from the separator water to capture $CO_2$ from ambient air for permanent storage underground, thus creating a carbon removal solution as shown in figure 8.

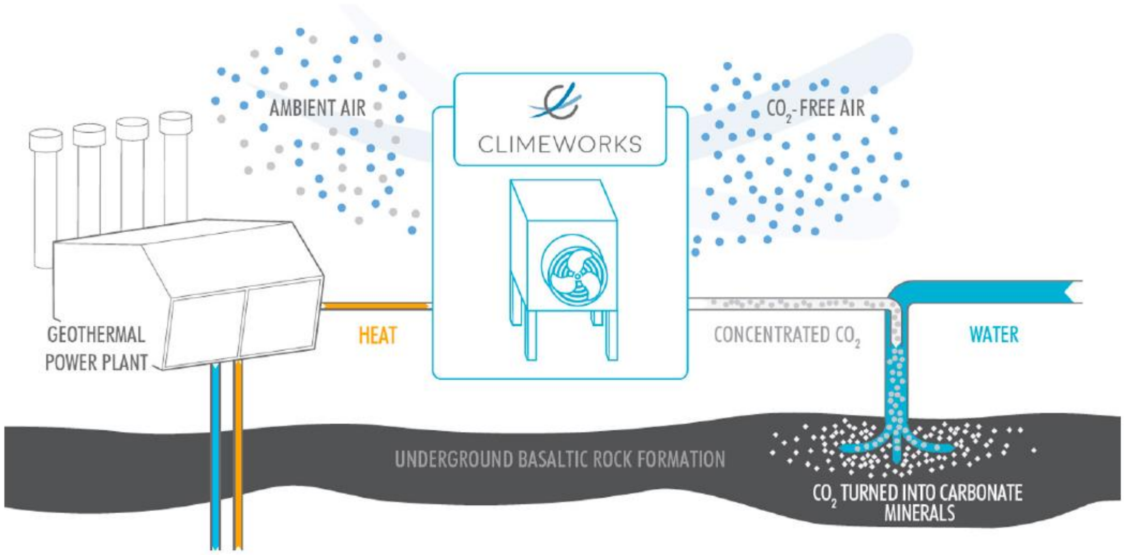


*Figure 8: Schematic illustration of the Climeworks-Carbfix injection at Hellisheidi, Iceland (Gutknecht, et al., 2018)*

The module-collector draws in ambient air and captures the $CO_2$ with a filter as it is the implementation of Climeworks technology. The filter is then heated with 120 $^oC$ separator water from the plant to release the $CO_2$. The pure $CO_2$ is then compressed and mixed with condensate from the plant and the resulting mixture is then piped to the injection well. The mixture is maintained under pressure down the injection well and into the reservoir to prevent degassing. There the $CO_2$-charged water is released into the basaltic reservoir (Gutknecht, et al., 2018). A major goal of this process trial in Hellisheidi power plant is to test how Climeworks technology works with the specific weather conditions at the location in Iceland before the DAC operations are substantially scaled up.

Concerning the capacity of the Climeworks project, the present nominal annual $CO_2$ collector capacity is 50 tons of $CO_2$, an amount which is anticipated to increase as the technology is optimized. For instant comparison, a Climeworks' collector is equal to the afforestation of 2000 trees. As a whole, the Orca plant which combines Climework's direct air capture technology with the underground storage of carbon dioxide provided by Cardfix on a much larger scale, has the potential of capturing 4,000 tons of $CO_2$ per year (Cooke, 2021). By capturing 4,000 tons of carbon dioxide per year, it will be the world's biggest climate-positive facility to date for carbon capture storage.

On the financial aspect the investment cost for the Orca plant in Iceland was estimated around 9.5 million € (10 million $) by the company while the levelized cost of capture is 1140 €/ton of $CO_2$ (1200 $/ton of $CO_2$) with decrease trends as the Climeworks technology matures from these initial calculations (Judge, 2021). Also, a percentage of 10% of re-emitted carbon dioxide can be attributed to the whole process of Climeworks from a typical Life Cycle Analysis of its energy needs, the lowest by far for every DAC technology in operation nowadays. The re-emitted percentage of carbon dioxide is that low thanks to the abundant geothermal energy in Iceland that Climeworks exploits (Judge, 2021).

Climeworks with partner Carbfix having such scaled up and optimized operations in place is crucial as deployment of $CO_2$ removal at gigaton scale will have to start as early as 2030 in order to reach international climate targets by the end of the century. Nevertheless, Climework's air captured carbon dioxide technique apart from Carbfix that removes carbon dioxide from the air by permanently storing it underground can also be coupled with a recycling process that uses captured carbon dioxide as a raw material (e.g., to produce e-fuels or biofuels). The only rationale behind this possible new option is of course the direct air capture machines to be powered solely by renewable energy or energy from waste since as the RWTH Aachen University study also confirms (Cooke, 2021) that direct air capture has a low carbon footprint when powered by low-carbon energy, such as the previously referred waste heat or renewable energy.

## 1.7. The technology of Carbon Engineering

Carbon Engineering, a Canadian company who is also focusing on DAC commercialization, has built its first pilot plant in Squamish (a replica of it is shown in figure 9), British Columbia (Azarabadi & Lackner, 2019).

*Figure 9: An exhibition replica of Carbon Enginnering's first pilot plant (Carbon Engineering Ltd.)*

Even if, its technology has been implemented later in industrial scale than Climeworks has no big difference from it. They both remove permanently $CO_2$ from ambient air making them two firms that implement DAC technology with some small different patents. Their differences can be spotted in the sorbent that they use to capture $CO_2$ from the air resulting in a slightly different process each time. Carbon Engineering exploits captured $CO_2$ either for sequestration, as was the case of Climeworks where $CO_2$ was permanently stored underground, or for further utilization in a productive activity as a raw material. So, Carbon Engineering can be well qualified as a CCUS technology firm.

The innovative aspect of Carbon Engineering's patent was to invest in research about finding the right sorbent in their $CO_2$ removal process that will offer them the best possibility of low energy input and of low operating costs. Similar to Climeworks in Carbon Engineering it is true that the only rationale for a DAC technology to operate is to be fueled by renewable energy sources or zero emissions fuels to ensure an energy carbon footprint that is significant minor to the carbon quantities it can absorb. This requirement of minor energy input carbon footprint is met by the right selection of the sorbent during its regeneration phase

Carbon Engineering after extensive research on solid or aqueous types of sorbent solutions has been developing an aqueous DAC system since 2009. Their process comprises two connected chemical loops as shown in figure 10. The first loop captures $CO_2$ from the atmosphere using an aqueous solution with ionic concentrations of roughly 1.0 M $OH^-$ , 0.5 M $CO_3^{2-}$ , and 2.0 M $K^+$. In the second loop, $CO_3^{2-}$ is precipitated by reaction with $Ca^{2+}$ to form $CaCO_3$ while the $Ca^{2+}$ is replenished by dissolution of $Ca(OH)_2$. The $CaCO_3$ is calcined to liberate $CO_2$ producing CaO, which is hydrated or "slaked" to produce $Ca(OH)_2$ (Keith, et al., 2018).

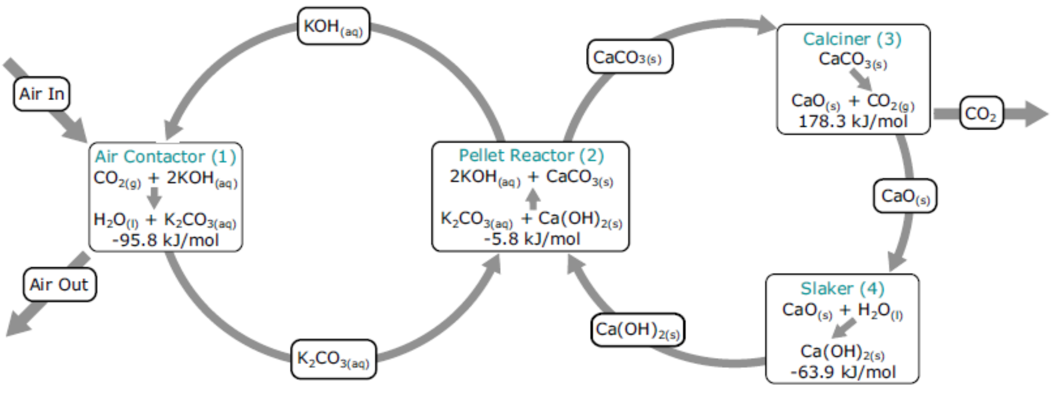


*Figure 10: Schematic illustration of Carbon Engineering's DAC technology (Keith, et al., 2018)*

Carbon Engineering has developed a process to implement this cycle at industrial scale by building their own plant which will be fully constructed at the end of 2023. At full capacity, this plant captures 0.98 Mt of $CO_2$/year from the atmosphere and delivers a 1.46 Mt of $CO_2$/year stream of dry $CO_2$ at 15 MPa. The additional 0.48 Mt of $CO_2$/year is produced by on-site combustion of natural gas to meet all plant thermal and electrical requirements (Keith, et al., 2018) and thus a percentage of 45% or re-emitted carbon dioxide can be attributed to the whole process of Carbon Engineering from a typical Life Cycle Analysis of its energy needs.

Concerning the capital and levelized cost of Carbon Engineering we should point out that since we are dealing with an almost brand-new technology, the cost of this technology is inherently uncertain. As the founder of Carbon Engineering David W. Keith points out (Keith, et al., 2018) while technology developers may have the most relevant knowledge, they may also have incentives to underestimate costs. In considering the cost of DAC, or in other words the cost of running their firm, it is useful to distinguish between two types of technologies. The adsorption-based technologies that typically require manufacture of hardware not yet available in a competitive market at a relevant price, and technologies such as the process described in the case of Carbon Engineering that require construction of an industrial facility that will perform a novel process, but that is conducted using commodity equipment and methods.

Uncertainties in the first case arise from scaling up a manufacturing process for a new product (the absorber) system, while the uncertainties in the second arise from estimating project construction costs for a new facility. In both cases, additional uncertainty comes in estimating the performance (e.g., capture rate) and from the cost of energy inputs.

For the capital cost or investment cost, Carbon Engineering's cost estimating process starts with vendors of the major nonstandard unit operations: air contactor, pellet reactor, and calciner/stream-slaker. Specialized vendors have each worked closely with Carbon Engineering throughout years of development, and each have provided to the firm's budgetary estimates for commercial equipment. The character of these estimates varies with the business model of the vendor. All other components are common industrial process equipment available from multiple vendors. Cost estimates for these components start with rough estimates using consultants. Carbon Engineering's engineering group then uses simple multiplicative cost estimating factors to go from equipment costs to estimates of total plant cost. They also hired Solaris, an independent firm which has worked with major vendors of these types of equipment to provide a substantially independent project cost estimate and verify their initial capital cost calculations. As calculated the capital cost of Carbon Engineering was 1,069,547 € (1,126,800 $) for a plant design that has a capacity of 0.98 Mt of $CO_2$/year from the air (Keith, et al., 2018).

For the levelized cost per ton $CO_2$ captured from the atmosphere Carbon Engineering has taken the sum of the levelized capital cost, non-fuel and energy costs and has estimated it around the range of 90-220 € /ton of $CO_2$ (94-232 $ /ton of $CO_2$) (Keith, et al., 2018). Figure 11 is indicative of the financial and technical characteristics of the current in operation plant of Carbon Engineering.

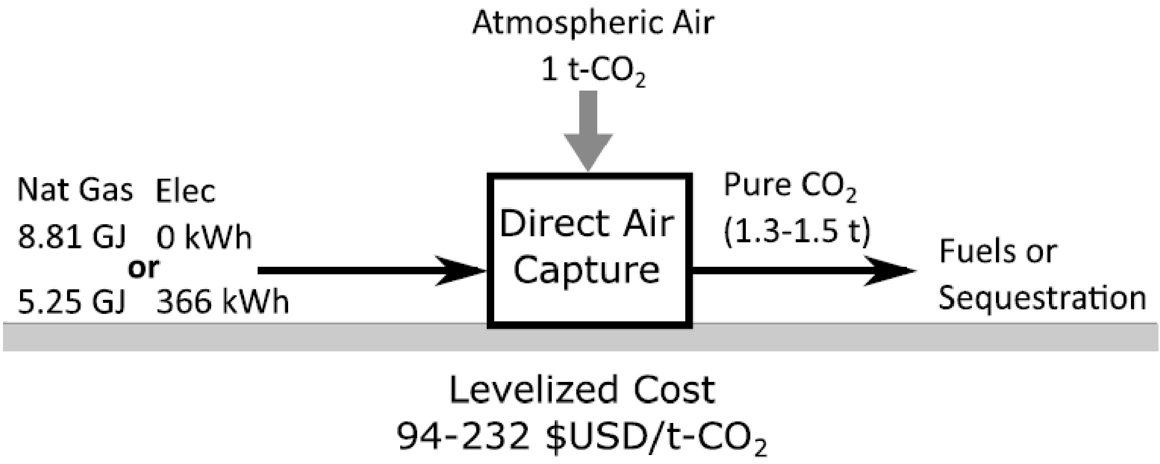


*Figure 11: Major financial and technical results of Carbon Engineering plant in operation (Keith, et al., 2018)*

## 1.8. Comparison between Climeworks and Carbon Engineering

Table 1 is indicative of the major technical and financial characteristics of these two firms that have scaled up or are about to fully scale up in industrial level $CO_2$ removal from direct air capture technology and are the current leaders in CCS technology.

| **Table 1** | Climeworks | Carbon Engineering |
|---|---|---|
| $CO_2$ capture potential (thousands t $CO_2$/year) | 4 | 980 |
| $CO_2$ re-emission percentage (%) | 10 | 40 |
| Investment Cost (millions €) | 9.5 | 1.07 |
| Levelized cost (€ / t $CO_2$) | 1140 | 200 |
| Plant full capacity completion (year) | End 2021 | End 2023 |

*Table 1:Major technical and financial characteristics between Climeworks and Carbon Enginnering*

As we can see from Table 1 Carbon Engineering has significant greater capture potential than Climeworks and in a more efficient way since Carbon Engineering's levelized cost is lower than the one of Climeworks. However, the results from table 1 might be misleading and underestimating the potential of Climeworks. Climeworks an initial start-up firm was pioneer in carbon capture technology from ambient air. For that reason, that is for being the first ever start up firm to become industrial positive for climate change, it impressed and thus earned the funding from Microsoft to implement this an innovative technology.

The results sometimes may seem minor compared to the potential of Carbon Engineering, but two factors must be taken into consideration: the maturity of the technology and the meeting of energy needs. Climeworks as the first climate change positive firm managed to develop a research technology never implemented before and thus must be seen as a straw man to be replaced with improved designs, whereas Carbon Engineering plant completion is forecasted for the end of 2023. Already, Climeworks' Orca plant is the largest $CO_2$ removal plant in the world. In the second factor, which is meeting the energy needs is where lies the lower capture potential of Climeworks. As analyzed before, the Orca plant exploits the geothermal energy of Iceland to meet its energy needs and manages to keep the re-emission percentage of $CO_2$ to as low as 10%. On the other hand, Carbon Engineering to achieve higher capture potential also required greater energy needs than Climeworks did. Therefore, its combination of a DACC unit with a power unit of natural gas or electricity that can also be accounted as an extra $CO_2$ point source as it increases the $CO_2$ re-emission percentage to a level of 40%.

Even if, we do compare the anticipated results of these two firms a deeper comparison between Climeworks and Carbon Engineering might be useless since these two firms are based on different business models and must be seen as complements and not as perfect substitutes of one another. Climeworks in order to impress and earn a valuable funding to implement its idea decided to operate at lower scale which was necessary in the learning curve of this innovative technology. On the other hand, Carbon Engineering in order to be competitive to Climeworks decided to operate in a way bigger carbon capture potential and combine carbon capture not only with sequestration but with further utilization of $CO_2$. So, in conclusion there is no point judging either Climeworks or Carbon Engineering as better. Both two firms although based on the same technology operate in different scales and target groups and the one thing that matters for each one, as will be explained further in this diploma thesis paper, is to attract clients and find ways to operate by their own means without the need for external funding or governmental aid toward the accomplishment of their contribution vision of climate change mitigation.

## 1.9. Discussion and long-term considerations of DACC as major CCS technology

CCS technologies and more specific carbon air capture, as analyzed on the previous chapter, on large scale could create net negative emission and reduce excess $CO_2$ stored in the atmosphere, oceans, and terrestrial biomass. However, there is still skepticism among the public about the benefits of DACC compared to afforestation. It is well known that afforestation, especially in urban areas, offers a significant source of environmental amenities and ecosystem services by reducing air pollution, while also serving as natural habitats for species and promoting outdoor recreation and exercise (Jones, 2021).

If done well, afforestation comes with several important benefits also such as reduced soil erosion and increased biodiversity. However, afforestation is a solution that cannot be scaled indefinitely because it requires lots of water and surface area. Also, the permanence of the removed $CO_2$ cannot always be guaranteed with trees: wildfires or deforestation can destroy the trees and release the $CO_2$ back into the atmosphere. On the other hand, the DACC process is also much faster: if trees are planted, it will typically take at least 10 years (Royal Society & Royal Academy of Engineering, 2018) until the same quantity of $CO_2$ is removed from the air whereas Climeworks' carbon dioxide removal for instance takes between 2 and 5 years to be completed. So, of course, afforestation is much needed in today's world for the various environmental and life quality benefits it can offer but it cannot serve as well as the DACC firms do. That stated, it can be used as an insurance policy for permanent $CO_2$ removal from the atmosphere.

Also, growing skepticism rests on the possibility that $CO_2$ levels could actively be lowered through improved and more efficient CCUS technology as the latest matures rather than the current net negative emission technologies of direct air capture. This skepticism raises the concern that it might be used by energy and environment policy makers to justify inaction. A wait-and-see attitude is ill-conceived for several reasons. Firstly, one should not rely on a future promising CCS technology that has not been demonstrated at a large scale rather than the one that currently operates. Secondly, the impact of excessive (GHG) greenhouse gas concentrations is not immediate. Thus, it could be too late for action by the time the scope of the damage becomes clear. It is necessary to act, even in the presence of uncertainty. Thirdly, some damage may be irreversible, and inaction will increase the risk of such damage. Fourth, the available time is short, and actions are necessary on all fronts. Carbon mitigation costs will not come down until action is taken (Lackner, et al., 2012). Lastly, the ability of a technology that has proven its ability to reduce $CO_2$ concentration in ambient air could provide support in an overshoot scenario because the world is probably already in an overshoot scenario. The optimal $CO_2$ stabilization point could well be lower than the current $CO_2$ concentration in the air. The $CO_2$ level that the world may reach with any best possible effort will be higher than what we can or should accept. And even if most of the world agrees upon a comprehensive system of (GHG) greenhouse gas regulation, rogue nations (i.e., North Korea of the future) will always create a risk of unpredictable emissions. Hence, it is important to develop technologies that can reduce the $CO_2$ concentration in the air (Hansen, et al., 2008).

In real terms, the expansion of DACC as major CCS technology or a possible new technology apart from the climate urgency will depend on the affordability of each technology. As we saw, the competitiveness and the sustainability of both Climeworks and Carbon Engineering rests on environment policy makers to promote and provide the sufficient funding for these firms to continue operating. EU ETS will provide to these firms a way to negotiate their costs by earning allowances for each ton of $CO_2$ captured. But even in the case of a worldwide application of a universal system like EU ETS, the sustainability of DACC technology rests on the price that every allowance of $CO_2$ will be traded. So, for now, CCS and DACC technologies that focus only on sequestration of carbon dioxide should pay attention on the maturity of this technology in order to lower their levelized costs (€/ t $CO_2$ captured) and anticipate the urgency of climate change to bring carbon prices to a level that through EU ETS can negate the majority of their costs.

Summing up, the end results of the implementation and expansion of CCS and DACC technologies for the future rest on the perception and the political will to solve the problem of climate change as the technology still matures. A reduction rate of $CO_2$ in the air comparable to today's emission rate is feasible, but further action must be done now before the scale of climate change becomes enormous, and in that case, it would be even more difficult for air capture to solve this problem and provide immediate results. A reduction by 100 ppmv appears plausible, whereas a reduction by many hundreds of ppmv is likely to be prohibitively expensive, even if one assumes cost-effective implementation of air capture technology (Lackner, et al., 2012). This example demonstrates that the possibility of affordable air capture technology does not provide any justification for a delay-and-overshoot global strategy. So, the message for the future of CCS is clear; the inability to produce accurate cost estimates for a nascent technology should not be a reason for withholding support toward research and development of this and of any relevant technology.

# 2. Necessity and major CCU technologies and their analysis

## 2.1. Current status of the development of CCU technologies and major applications

CCU technologies single or bundled with the carbon storage ones that account for CCUS technologies have a significant advantage for greenhouse gases mitigation; they can re-use $CO_2$ as a raw material for further production processes or just to enhance an industrial activity. Via this way they offer the chance to close the carbon cycle and build up for a sustainable future. The main difference from CCS technologies and specifically direct air capture as analyzed on the previous chapter of this diploma thesis is that $CO_2$ life cycle doesn't end with sequestration and permanent underground storage, but it can be recycled for further production processes. Companies that operate in the implementation of CCUS technologies have the possibility of an extra revenue stream than companies focusing only on the $CO_2$ sequestration, that is the export of a product that has earlier absorbed the gathered $CO_2$. So, CCUS technologies business plan includes income cash flow through carbon allowances from EU ETS and through the sales of $CO_2$ post-processed products. However, as it anticipated the levelized cost (€ / ton of $CO_2$) is expected to be much higher from direct air capture for example since a whole facility must be manufactured close to the $CO_2$ storage point for its further utilization.

CCU technologies are as urgent as CCS technologies with sequestration in the effort of tackling climate change. The reason why CCU could contribute to climate change mitigation is that it replaces fossil feedstocks, avoids upstream emissions, and temporarily keeps $CO_2$ out of the atmosphere until re-emitted in the use phase of the product. CCU appeals to policymakers and the general public because it is seen as part of the circular economy and a form of sustainable waste processing. It also appeals to industry because CCU creates value from waste through $CO_2$-based products while avoiding the storage costs and concerns of geological storage $CO_2$, well known as CCS technologies (de Kleijne, et al., 2022).

A vast social debate has already started globally over whether funding activities with close to zero carbon footprints, is the most detrimental action to be taken. Legal frameworks try to give motives to substitute liquid hydrocarbon fuels with alternative ones, the latter of which will have been produced from the absorption of excess $CO_2$ such as are e-fuels, biofuels, and batteries for EV (electric vehicles). For instance, Liberty Media an American company who owns Formula 1 championship has stated in its current technical regulations that fuel in formula 1 cars must include 5.75% of bio-components. Pat Symonds the current chief technical officer of formula 1 has stated that Formula 1 is looking to raise this threshold to 10% with a vision to transition to fully 100% advanced sustainable biofuels to power their cars beyond 2025 (Formula1, n.d.). Another example is the prohibition zone for cars to enter the center of big metropolises such as Athens and Paris if their cars are not powered by lithium batteries or any other sustainable fuel alternative (CNN, n.d.). These examples show that the market size for companies who produce sustainable fuels grows day by day. CCU companies are the ones that are projected to increase their market share in the fuel production sector. That is because sustainable fuels are defined as those ones who have net zero carbon footprint and in order to be net zero, they need to have absorbed more quantity of $CO_2$ than the quantity of $CO_2$ that gets back into the atmosphere emitted. Of course, this can be achieved through exploitation of gathered and stored $CO_2$.

However, the relevance of CCU in climate change mitigation is still questioned in the literature (de Kleijne, et al., 2022), based on several concern. Firstly, CCU products may not always substantially reduce emissions compared with their conventional counterparts that do not require the energy-intensive $CO_2$ capture and conversion steps. Secondly, the utilization of captured $CO_2$, rather than permanent geological storage, may result in a higher global warming effects because utilized $CO_2$ is typically re-emitted when the CCU product is used or disposed of. Thirdly, CCU may not be economically feasible because of the high financial costs associated with the energy-intensive $CO_2$ storage and conversion steps. Fourthly, CCU may form a political distraction from reducing $CO_2$ emissions, in particular when replacing CCS, because the scale at which $CO_2$ could be utilized is limited compared with the scale at which $CO_2$ could be stored geologically (de Kleijne, et al., 2022). On the contrary of the above concerns, it is in the hands of policymakers to ensure that energy intensive $CO_2$ capture and conversion steps are powered exclusively by renewable energy for CCU energy intensive applications and in the hand of CCU companies to find out the business advantage over CCS to persuade the general public to support more their innovative idea.

Concerning the major CCU applications nowadays there are several pathways that firms may follow towards the utilization process of gathered $CO_2$ from biological to chemical conversion up to application with no conversion as it is shown in figure 3. In this diploma thesis we will focus on the most widely applied and promising technologies in conversion and non-conversion CCU by examining their financial sustainability and their contribution to climate change mitigation. In non-conversion CCU technologies, we will focus on enhanced oil recovery (EOR) and its potential for better and more sustainable oil extraction, a technology that is very popular in oil producer countries, such as United Arab Emirates (UAE), and direct uses of $CO_2$. In conversion CCU technologies, we will focus on chemical applications for the production of liquid fuels and polymers where the market share is in rising pathway and on biological application, we will mainly focus on a promising biotech venture still as its start-up level while implementing its IP (Intellectual Property) protected system of a hybrid vertical microalgae cultivation, with simultaneous $CO_2$ conversion.

### 2.2. Enhanced Oil Recovery (EOR)

Enhanced Oil Recovery (EOR) is a tertiary approach applied to mature oil reservoirs to improve oil recovery. EOR is a method where $CO_2$ is injected into the subsurface to recover oil from almost depleted reservoirs. EOR is the most mature CCU technology that has been practiced commercially for decades, starting in the early 1970s in North America. Similarly, $CO_2$ can be used to recover natural gas from coalbeds (enhanced coalbed methane [ECBM]), although there are currently no active ECBM projects. Although traditionally the source of $CO_2$ for EOR is natural $CO_2$ reservoirs, EOR can be well performed also with $CO_2$ captured from point sources or DAC (de Kleijne, et al., 2022). When supplied by combustion $CO_2$, it can help mitigate certain (GHG) greenhouse gas emissions in major oil producer countries such as United Arab Emirates (UAE) as a form of circular economy as figure 12 points out.

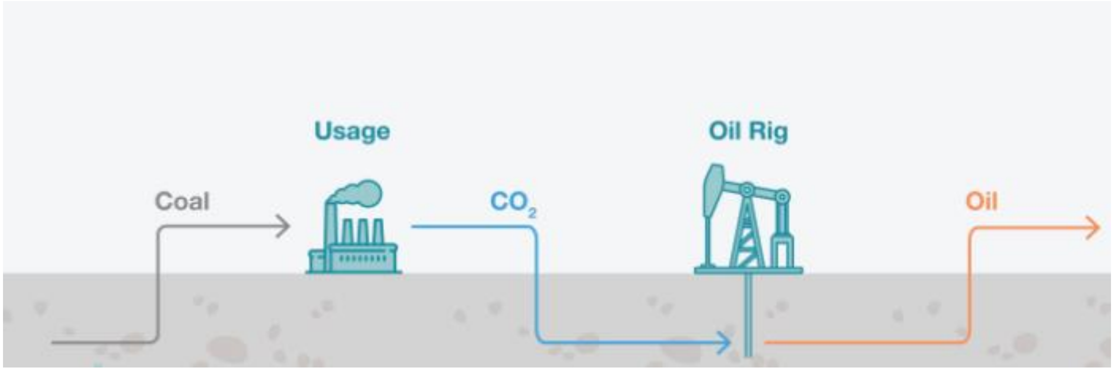


*Figure 12: A schematic illustration of EOR as a form of a circular economy process*

There are three main temporal phases in oil extraction: primary recovery, at the early stage of oil production, geological pressure and pumps can push oil from the wellbore to the surface; secondary recovery maintains the pressure of the reservoir and improves oil productivity through injection of water or gas; tertiary recovery, which can recapture 30 up to 60% of the original oil in place. Tertiary recovery can utilize three techniques: first gas injection (e.g., $CO_2$, nitrogen, methane), second thermal recovery and third chemical injection such as polymer and foam used to fight water mobility and segregation respectively. Gas injection and $CO_2$ injection particularly is dominant in oil companies in UAE. $CO_2$ injection helps to decrease the viscosity of the remaining oil, swell it, and detach it from the formation (Santos, et al., 2021). This allows it to move freely in the reservoir reaching the production well. Although, there are many approaches to implement EOR at tertiary stage, $CO_2$-EOR coupled with Carbon Capture and Storage (CCS) should present the lowest carbon footprint. This is due to the fact that more than 95% of anthropogenic $CO_2$ used in EOR can be permanently stored in oil reservoirs (Melzer, 2012)

$CO_2$-EOR with CCS can use of $CO_2$ from combustion activities, trapped $CO_2$ (Usman, et al., 2014) and $CO_2$ contained and running in a closed loop in EOR activities. This $CO_2$ can be permanently stored in the reservoir after its decommission by repurposing the site of storage. The post-closure activity should be accompanied with subsurface monitoring and surveillance to verify $CO_2$'s long-term sequestration. This process offers the potential to reduce $CO_2$ from the locked-in sources that will be developed for the coming decades. However, the exact potential of $CO_2$-EOR in mitigating emissions depends on factors that mainly are affected by the performance of oil production economy and the technical characteristics of $CO_2$-EOR. Some of those are (Santos, et al., 2021):

- Global oil demand
- Demand of tertiary oil production at country level thinking to the fact of aging of oil reservoirs (share of EOR wells going to $CO_2$-EOR operation)
- Characteristics and types of $CO_2$ sources ($CO_2$ net utilization factor)
- Availability and matching of low-cost $CO_2$ sources that include transportation costs
- Policies such as carbon market credits (similar to EU ETS for UAE) that cover in part the cost of CCS technology used
- Actual operation of $CO_2$-EOR
- Injectivity (e.g., reservoir and fluid properties)

In this non-conversion CCU technology, the benefits and the challenges of utilizing $CO_2$ storage and $CO_2$-EOR, as alternatives to higher carbon footprint EOR mechanisms, in lowering $CO_2$ emissions at the country level are examined. In EOR, life cycle analysis (LCA) studies are used to calculate the lifecycle of (GHG) greenhouse gases emissions from each barrel of oil while considering $CO_2$ storage element.

Figure 13 shows a stock and flow diagram representing the dynamics of $CO_2$-EOR with CCS system. The boxed variables (stocks) represent the level of accumulation of state variables at a given time, and the valves (flows) represent their rate of change (Santos, et al., 2021). Figure 13 is indicative of the block chains of the $CO_2$-EOR procedure.

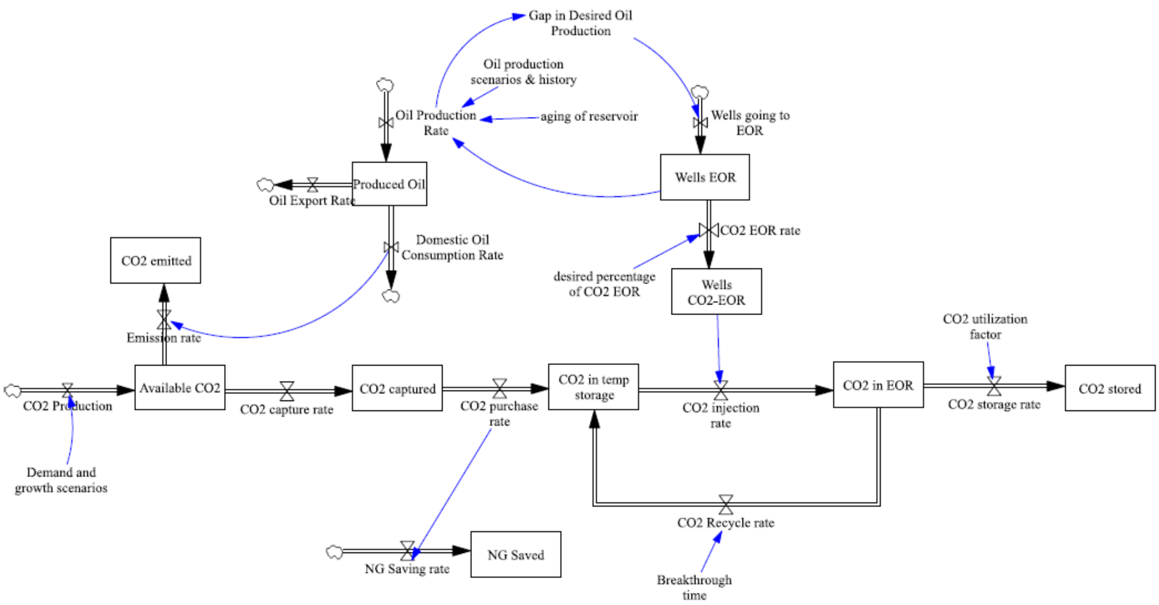


*Figure 13: Stock and flow diagram of $CO_2$-EOR network system including all influence parameters (Santos, et al., 2021)*

As we can see also from figure 13, $CO_2$-EOR procedure faces a lot of external challenges that are indifferent from the maturity and financial profit of this CCU technology. The most important of those that affect immediately this CCU technology are the wells going to $CO_2$-EOR activity and the $CO_2$ utilization factor. First, the demand of $CO_2$ for EOR depends on oil productivity history and aging of reservoirs, which in turn influences the stocks of wells going to EOR operation. The percentage of these wells going to $CO_2$-EOR operation is related to the amenability of these resources to $CO_2$ flooding in addition to availability of $CO_2$ at reasonable cost. This will affect the purchase rate of $CO_2$ for EOR, which will impact the number of projects going to CCS and the $CO_2$ capture rate. The initiation of $CO_2$-EOR projects will increase the rate of $CO_2$ injected into the reservoir, which in-turn enhances oil production and make available the displaced natural gas (Santos, et al., 2021) that would otherwise be used for EOR and thus avoiding excess greenhouse gases from being emitted into the atmosphere. A second challenge for EOR comes from the $CO_2$ utilization factor. $CO_2$ utilization factor which represents the amount of oil produced per ton of $CO_2$ injected, plays an important role in achieving environmental targets and defining carbon prices needed to cover the cost of CCS. Of course, higher $CO_2$ utilization factor makes EOR activity more profitable and beneficial in mitigating climate change.

On the cost side, oil production from $CO_2$-EOR wells per year creates a demand for $CO_2$ which mainly depends on the technical performance of $CO_2$ injection in the $CO_2$-EOR wells and on the economic parameters related to this injected $CO_2$. Santos et al. (Santos, et al., 2021) found that the adoption rate of CCS to different $CO_2$ sources intended for $CO_2$-EOR depends on the cost of capture and economic parameters shown in Table 2 and the demand created by EOR. The transition rate of wells to $CO_2$-EOR activity creates a demand for $CO_2$, which is compared to the total amount of $CO_2$ captured stock. This creates a gap, which impacts the desired capacity of CCS attached to the cheapest $CO_2$ source. This desired capacity would increase until the target CCS ratio from the cheapest $CO_2$ source reaches saturation. If there is still a demand gap in $CO_2$, the second cheapest source is retrofitted with CCS facility. This sequence will continue until closing the gap in the demand of $CO_2$.

| Table 2 | |
|---|---|
| **Type** | **Value (€ / ton $CO_2$)** |
| Natural Gas Combined Cycle (NGCC) power plant | 81.28 |
| Aluminum | 75.9 |
| Steel | 29.6 |
| Cement | 120 |
| $CO_2$ Transportation | 15.57 |
| $CO_2$ Compression | 7.34 |
| $CO_2$ Injection | 3.05 |

*Table 2: Capture costs for main sources of $CO_2$ intended for $CO_2$-EOR and main economic parameters* (Santos, et al., 2021)

The main cost uncertainty that is derived from Table 2 is about the transportation cost of $CO_2$. A network of $CO_2$ pipelines is a difficult and expensive solution and as Lackner et al (Lackner, et al.,2011) have found geopolitical and financial reasons may create unsurpassed obstacles towards that network creation. However, as EOR is widely popular in UAE a $CO_2$ pipeline network is financially sustainable to match industrial activities of NGCC, aluminum, steel, and cement processing with wells of $CO_2$-EOR activity making $CO_2$ transportation cost of 15.57 € per ton of $CO_2$, a reasonable price to negotiate general EOR costs.

In the final results, Santos et al. (Santos, et al., 2021) analyzed 12 scenarios of $CO_2$-EOR in UAE starting from the business as usual scenario of stable or rising oil production in the coming years to the scenario of diminishing oil production due to environmental factors to measure the potential of $CO_2$-EOR in mitigating GHG emissions in the country where this CCU technology is most implemented. They found that with constant oil production of 3.5 million barrels per day or higher in UAE, this potential ranges from 1.5-25 % across all scenarios. The lower range of contribution is related to low demand for EOR due to lower oil production and lower $CO_2$ utilization factor. The higher range in $CO_2$ mitigation is associated with increased oil production, constant oil demand and higher $CO_2$ utilization factor.

All in all, Enhanced Oil Recovery represents a market for $CO_2$ large enough to impact climate change. It is anticipated that the rise in carbon price from today's price level will close the gap between the cost of CCS intended for $CO_2$-EOR and highlight the benefits of EOR in addition to saved natural gas (NG). Santos et al. (Santos, et al., 2021) have presented that a higher carbon price is required initially, becoming lower over time due to the increasing oil and gas production along with the availability of recycled $CO_2$. A carbon price range between 10 and 20 € / ton of $CO_2$ is sufficient for the financial sustainability of EOR in UAE with the exception of the high $CO_2$ utilization factor that require a carbon price of 68 € / ton of $CO_2$. This high utilization factor scenario requires a high amount of $CO_2$ needed per barrel of oil, which results in higher financial support from external or governmental funds to cover the extra costs of CCS. Sticking to this scenario, approximately for every metric ton of $CO_2$ permanently pushed into the ground, 1 ton of oil (about seven barrels) can be recovered. Hence, a 68 € / ton of $CO_2$ for EOR would raise the price of oil in oil demand market by only 9.3 €/barrel ($10/barrel) (Lackner, et al.,2011). So, EOR as a CCU technology requires a detailed business plan to take into consideration all aspects besides this technology itself that will influence the income channels, making it difficult for start-up or other firms to operate this technology without an existing aging oil production well and a cheap mean of accessing resources of $CO_2$. However, $CO_2$-EOR can make significant profits with the current carbon price levels and contribute in a big way towards climate change mitigation in countries with scaled up oil production. This was the case in UAE where $CO_2$ availability and low $CO_2$ transportation costs allowed $CO_2$-EOR oil production firms to negotiate their costs through selling more quantities of oil and a minimum external-governmental aid.

## 2.3. Direct uses of $CO_2$

In the non-conversion CCU technologies are included also applications that require $CO_2$ without any aftertreatment. This non-converted $CO_2$ can be used directly in several sectors. In horticultural production, elevating $CO_2$ concentrations in greenhouses increases crop yields by approximately 50%. This process is called $CO_2$ enrichment and is traditionally achieved by combustion of fossil fuels such as diesel or natural gas, which has the dual purpose of greenhouse heating. Because more $CO_2$ is required to reach the desired $CO_2$ concentrations than is produced for heat, captured $CO_2$ can be used (Oreggioni, et al., 2019). $CO_2$ can also be used directly as a refrigerant (as shown in figure 14 right) for supermarket applications (refrigerant R744 as is officially named), replacing hydrofluorocarbons with higher global warming potentials, reducing risks of leakage, and associated global warming effects. $CO_2$ can also be used as a carbonating agent in sugar productions and soft drinks (as shown in figure 14 left), as a solvent for extraction of flavors, in the decaffeination process, as dry ice, in fire extinguishers, and in the pharmaceutical industry as a respiratory stimulant (de Kleijne, et al., 2022). As we can see the area of options for importing $CO_2$ as a feedstock without any conversion is immense and significant financial beneficial for CCS technologies either from DAC or point-source that aren't limited in sequestration of the gathered $CO_2$ to gain profits in addition to their carbon allowances.

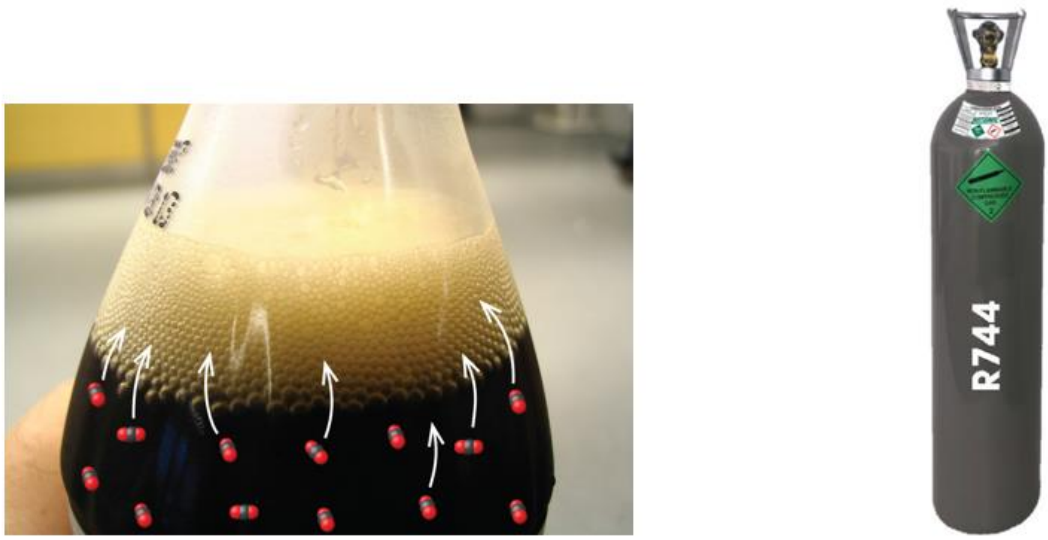


*Figure 14: Applications of direct uses of $CO_2$; on the left $CO_2$ in a Coca Cola soft drink and on the right a flask of $CO_2$ refrigerant*

On the cost side, for direct uses of $CO_2$ only the transportation cost of $CO_2$ burdens the operator of these activities which varies depending on the origin.

## 2.4. $CO_2$ derived e-fuels

### 2.4.1. E-Fuels making process

$CO_2$-neutral fuels (e-fuels) are a case of chemical conversion CCU technologies. They are considered to be a pragmatic and practical way of decreasing overall $CO_2$ emissions derived from the transportation sector. However, for e-fuels to succeed and have a short-to-medium impact on climate mitigation, they should be fully compatible with existing fuel distribution infrastructure and vehicle technologies, such that they become literally drop-in replacements (Ramirez, et al., 2020). E-fuels are made by using $CO_2$ and $H_2$ as raw material as it is shown in figure 15. E-fuels can be the substitutes of typical hydrocarbon liquid fuels that derive from crude oil refining. For their making a synthesis process needs to be done between molecules of $CO_2$ and $H_2$ to produce the desired each time hydrocarbon chemical type ($C_xH_YO_Z$) that represent a substitute fuel of the original chemical compositions of diesel, methanol, liquid natural gas (LNG) and kerosene. Again, the only rationale for the whole process as it is shown in figure 15 is the electrolysis process where the $H_2$ is generated to be powered exclusively by clean energy so as the produced e-fuels to be $CO_2$-neutral fuels.

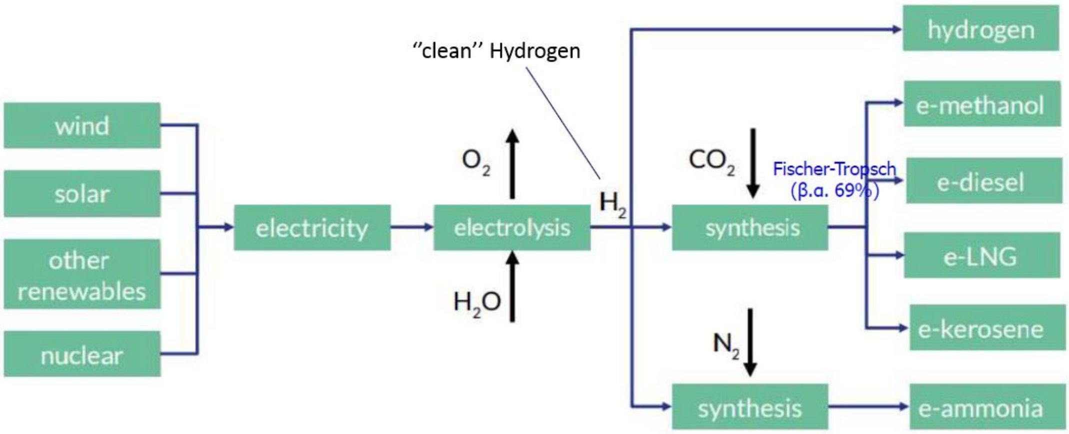


*Figure 15: E-fuels production process ((TNO), n.d.)*

### 2.4.2. E-Fuels, why more discussed now?

Liquid hydrocarbon fuels are widely used in road, air, and marine transportation, but the fossil feedstocks used to generate these fuels have significant environmental consequences. The entire transport sector is responsible for nearly a quarter of total $CO_2$ emissions and consumes more than 50% of the total liquid hydrocarbons produced, with more than 95% of the sector today continuing to rely on liquid hydrocarbons (Administration, 2019). One way of decarbonizing mobility is to adopt battery electric vehicles (BEVs) and hydrogen fuel cell vehicles (FCVs) that do not rely on the combustion of petroleum derived fuels. These technologies are rapidly increasing in commercialization and should be supported together with decarbonizing power generation and hydrogen production to lower life cycle emissions.

However, even in the most ambitious scenarios for 2040, BEVs and FCVs account for only 30-50% of new car sales; nearly 75% of light-duty vehicles on the road globally will still have internal combustion engines operating on liquid hydrocarbon fuels. Therefore, to meet global climate targets, there is an imminent need to commercialize low-carbon or carbon-neutral liquid hydrocarbon fuels using renewable $H_2$ and $CO_2$ as the building blocks, the so-called e-fuels, opening via that way a vast industry of this CCU technology. E-fuels offer the only reliable approach to decarbonize the large number of combustion engines that will remain in operation in the transport sector to at least 2050. In this matter, the conversion of $CO_2$ to these carbon-neutral fuels is a highly promising field that could tackle both our growing $CO_2$ emissions and the energy demand (Ramirez, et al., 2020).

However, to completely replace the use of petroleum hydrocarbons, it is important for e-fuels to be fully (or to require very minor adaptions to be) compatible with existing fuel distribution infrastructure and vehicle technologies, so as they are literally drop-in replacements. E-fuels that are not drop-in replacements face significant hurdles to widespread adoption due to increased costs of vehicle modifications and infrastructure development. Therefore, the current ideal drop-in e-fuels that match the above challenge are nonoxygenated hydrocarbons with molecular structures not much different to those found in petroleum-derived fuels (Ramirez, et al., 2020).

### 2.4.3. Fuel Requirements for a Hydrocarbon Mixture

Conventional petroleum-derived fuels are complex mixtures of hundreds to thousands of individual components resulting from various crude oil refining steps aimed at meeting specific target fuel properties. Therefore, the principal feature of a candidate e-fuel should be its ability to match fuel properties. In detail, for spark ignition (SI) engines a candidate e-fuel should have a research octane number (RON) above 90-95 and a motor octane number (MON) above 85-90 to meet fuel's ability to avoid knock as in traditional SI engines (Ρακόπουλος & Χουντάλας , 1998). For the case of compression ignition (CI) engines, a candidate e-fuel should have a cetane number (CN) values between 45-55 in order to have the appropriate fuel reactivity for combustion (Ρακόπουλος & Χουντάλας , 1998). For the aviation sector, aircraft require high-energy-density fuels, so there is an imminent need to develop synthetic aviation fuels (SAFs) (e.g., e-fuels) with molecular compositions similar to current hydrocarbon fuels (Ramirez, et al., 2020). So apart from the conversion process of $CO_2$ to e-fuel any possible CCU firm in this fuel sector should also optimize the characteristics of the produced output in order to meet the above strict technical requirements. This requirement becomes almost mandatory for e-fuels CCU firms so as to become competitive since for them competitiveness and financial sustainability comes from achieving the drop-in replacement of classic hydrocarbon liquid fuels.

### 2.4.4. Limitations of $CO_2$ conversion to fuels

The main challenge in the conversion of $CO_2$ to fuels lies in the inertness of the $CO_2$ molecule and the associated substantial energy required for the carbon reduction as $CO_2$ is a very stable molecule. Additionally, controlling the selectivity of the desired product is not trivial due to the multiple competing reactions involved, like reverse water-gas shift (RWGS) or FT (Fischer-Tropsch) synthesis process. Figure 16 is indicative of these catalyst reactions in the formation of e-fuels from $CO_2$. Therefore, the development also of active and highly selective catalysts is crucial to improve process sustainability.

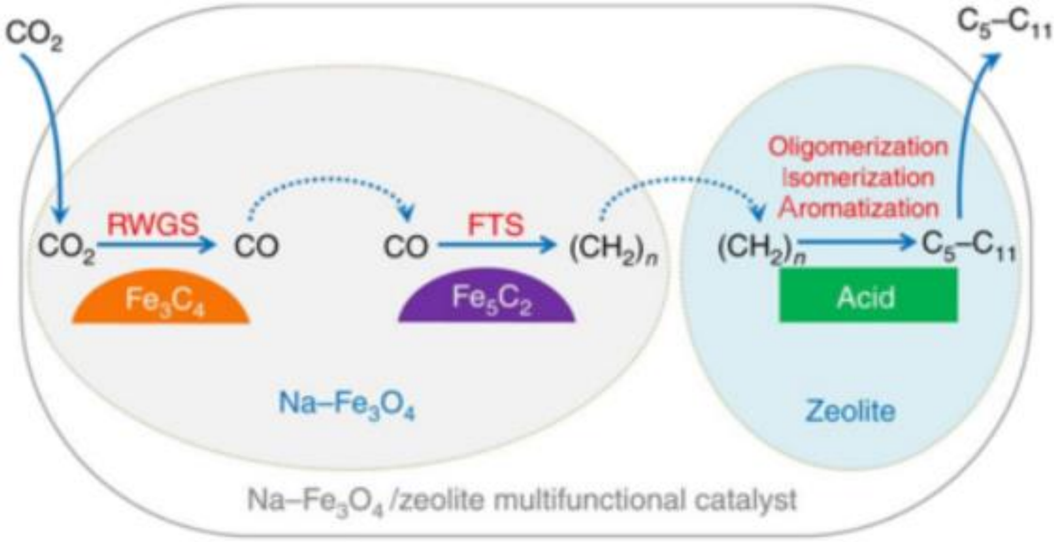


*Figure 16: Chemical reaction process for the formation of e-fuels (Ramirez, et al., 2020)*

Another useful output of figure 16 process that is worth mentioning is MeOH (Methanol). MeOH is the simplest and safest to store and transport liquid oxygenated hydrocarbon and, although it cannot be used directly as drop-in e-fuel in vehicles engines, it can be efficiently used to generate electricity in fuel cells or as liquid energy storage. Furthermore, MeOH is likely to be one of the easiest products to obtain from $CO_2$ with high selectivity and low undesired byproducts (Bowker, 2019) which makes it an indispensable partner to achieve the net zero $CO_2$ emissions target (Ramirez, et al., 2020).

### 2.4.5. Technoeconomic considerations and future sustainability

It is evident already that there are some promising bifunctional catalytic systems (e.g., figures 15 & 16) that could eventually yield drop-in e-fuels. However, little effort has been dedicated to assessing how these results will fit into a real industrial process. From the process point of view, process simulations in the $CO_2$ conversion field have primarily focused on the $CO_2$ to methanol reaction. It is found by Ramirez et al. (Ramirez, et al., 2020) that with the current green hydrogen prices the $CO_2$ conversion to MeOH is not financially viable, and $H_2$ prices below 1.9 € per kilogram are needed to reach the breakeven point. Therefore, either severe taxation of $CO_2$ emissions or a drastic increase of MeOH or other e-fuels are currently needed. Moreover, most of the process simulations are conducted assuming that the $H_2$ will be delivered at 30 bars from the electrolyzer, which is not realistic, therefore the $H_2$ compression costs should also be included. This will undoubtedly further hinder the viability of the process, as $H_2$ compression is one of the most expensive processes in industry and, even with the 30-bar feed assumption, these compression steps are already the most expensive units in figures 15 & 16 processes, followed by heat exchange network. Hence, economic considerations must be taken into consideration and the process must be kept as simple as possible, in order to overcome the drawback of the high hydrogen price while always looking towards highly selective catalysts to minimize hydrogen consumption

All in all, $CO_2$ derived e-fuels appears to be a very promising CCU technology since the political debate has already started in substituting liquid hydrocarbon fossil fuels for transportation with alternatives sustainable ones leading to an increasing market share year by year for the implementation of this CCU technique. Considering also that the existing infrastructure, in terms of distribution and transportation, will remain nearly unchanged for years to come, along with more than urgent need to move our society towards carbon neutrality, the great opportunity for e-fuels is evident. However, as it is mentioned before, it is of the highest importance for those operating and creating business plans in the field to realize that the chances for these $CO_2$ derived fuels to succeed will strongly depend on their compatibility with existing technology and infrastructure. Any deviation from the drop-in conditions will lead them to significant costs and minimum market share to operate leading them to stay out of business inevitably. Last but not least, improvements in the harvesting of renewable energy and its utilization for the manufacture of green hydrogen and $CO_2$ capture, along with the development of appropriate policies for $CO_2$-neutral fuels, will define the economic viability of these CCU technologies.

## 2.5. Polymers, biofuels, and chemicals

On the chemical side of the conversion CCU technologies, they offer another big field of operations that is the creations of polymers and other liquid fuels that are useful for the chemical industry.

One of the most impressive partnerships in this field was between Twelve, a carbon transformation company and LanzaTech, a start-up firm of off gas fermentation from $CO_2$ to biofuels that partnered together in order to transform $CO_2$ into polypropylene an important product for the chemical industry. Twelve's carbon transformation technology converts $CO_2$ into materials that are traditionally made from fossil fuels. The company helps brands eliminate emissions by replacing the petroleum derived chemicals in their products and supply chains with $CO_2$-derived carbon negative chemicals and materials, as well as carbon neutral fuels. LanzaTech's carbon recycling Pollution to Products (PtP) technology uses nature-based solutions to produce ethanol and other materials from waste carbon sources that are considered as biofuels. The partnership will bring together the two platform technologies to enable additional product development from $CO_2$ streams, representing just one of many pathways to scale carbon transformation solutions. On the financial aspect, to pursue the partnership, Twelve and LanzaTech have been awarded a 187,200 € grant from Impact Squared, a 1 million € fund that was designed and launched by British universal bank Barclays and Unreasonable, a catalytic platform for entrepreneurs tackling some of the world's most pressing challenges. So, with the Impact Squared grant, Twelve and LanzaTech are taking a collaborative approach to reduce the fossil fuel impact of essential products (Catalysts, 2021).

However, since fuels and chemicals are based on energy-dense fossil fuel products, producing these chemicals or fuels from $CO_2$ (e.g., biofuels, e-fuels) often requires an energy-intense conversion process at high pressure and increased temperature, supported by catalysts, because $CO_2$ is an inert and thermodynamically stable molecule as referred before in the e-fuels applications and applies also here. So, conversion processes for the above partnership include either electrochemical or photocatalytic or both conversions (de Kleijne, et al., 2022). The costs of these conversions must be taken into consideration since they skyrocket the investment costs for start-up firms operating in this field making external funding necessary for their initial operation as it is here the case of the partnership between Twelve and LanzaTech.

## 2.6. Biological Conversion – Microalgae Cultivation – Solmeyea

### 2.6.1. Microalgae cultivation as a carbon removal solution

Microalgae cultivation is a case of a biological conversion CCU technology. Microalgae are considered to be as a third-generation biomass and one of the most interesting solutions. Microalgae use sunlight and $CO_2$ to grow and produce $O_2$ based on the photosynthesis process. Therefore, it is a great potential for $CO_2$ capturing and utilization either directly from the air or by feeding into the system a gathered $CO_2$ exhaust flue gas. On the other hand, microalgae have also the potential to produce different value-added products that can be used in various markets such as food, drug, health, cosmetics, and energy which can be used for commercializing and reducing the costs of $CO_2$ capture. Microalgae's advantage over typical trees is that they have a higher rate of photosynthesis efficiency, require lower water consumption and have the ability to capture $CO_2$ at low concentrations (Maghzian, et al., 2022)

Using microalgae for direct carbon-capturing is not only a potential for $CO_2$ emissions and global warming reduction but also the produced microalgae is a great source of bioenergy such as biofuels and biogas. In addition to bioenergy, other value-added products can be also extracted from microalgae as it is mentioned before that are not limited only in the energy sector. These latter products can be economic leverages for the commercialization of culturing and harvesting microalgae for capturing carbon dioxide (Maghzian, et al., 2022).

Microalgae cultivation may prove a game changing option for climate crisis since the interest for the latter is steadily growing. As Maghzian and his team point out (Maghzian, et al., 2022) the pace of publishing articles in this field has increased rapidly over the last 16 years before 2015. This can be a convincing reason to show the increasing attention of researchers and investors to this CCU application. Also, Melo and his team (Melo , et al., 2022) have concluded that given the upcoming improvement of the efficiency of microalgae biomass harvesting and the integration of microalgae production in industries using wastewater, this CCU technology can emerge as a major tool to achieve the global goal of clean alternatives renewable energy generation.

Figure 17 shows the above rise in the pace of publishing articles where microalgae is linked with hundreds of key words of research.

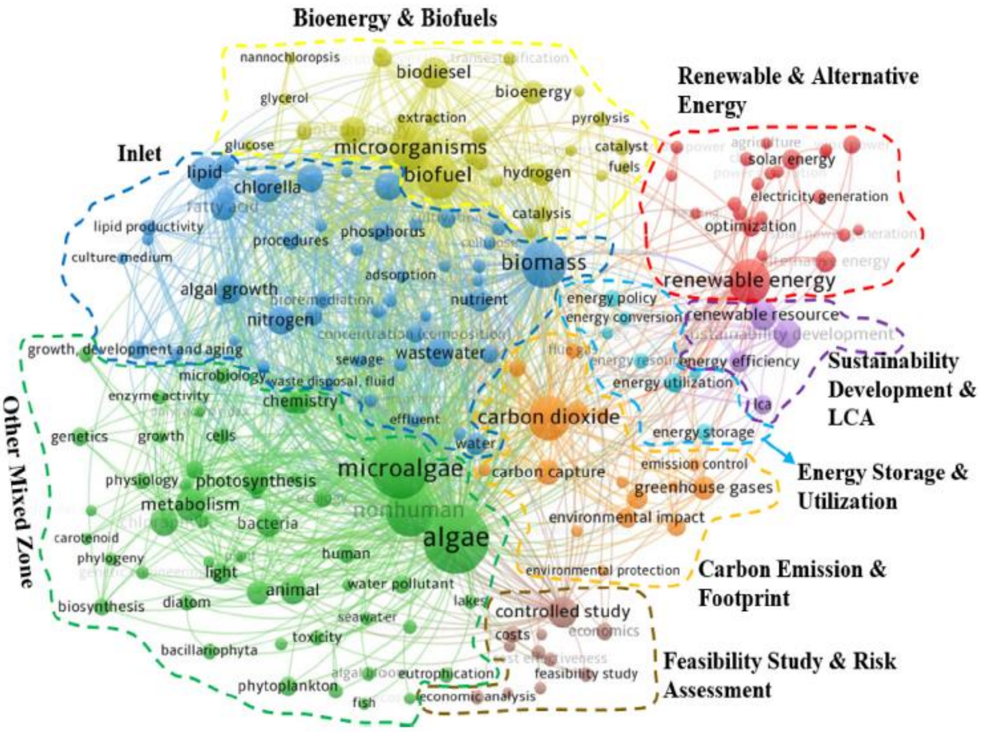


*Figure 17: Network visualization of research connections to microalgae in the literature (Maghzian, et al., 2022)*

In the above figure 17 the bigger key word circle shows the higher intensity of research done that are linked with or just referred to the word of microalgae.

Obviously, bioenergy industries like biofuel produced from microalgae are sustainable energy resources with great potential for $CO_2$ neutral production, capturing and utilization. In addition, LCA of capturing carbon by microalgae can provide scientists a bright insight into how much carbon will be captured through this process and provide investors with the approximate time of financial retrieval (Maghzian, et al., 2022). These investigations are necessary in order to motivate scientists and companies to upscale carbon removal solutions using microalgae.

For microalgae cultivation the higher the carbon capture feasibility, the higher the microalgae potential as alternative energy. So, microalgae carbon removal potential is positively related with the quantity of $CO_2$ injected into the system.

However, there are some techno-economic challenges for the wide commercialization of microalgae mainly due to the high cost of the whole process. Although various technological signs of progress have been accomplished to reduce the cost of microalgae cultivation, Maghzian and his team (Maghzian, et al., 2022) are of the opinion that different techniques of cultivation should also be considered for different regions due to the fact that not only the weather condition effects on microalgae open pond cultivation but also significant factors have an influence on microalgae upscaling such as $CO_2$ emission, fuel price, and technology costs.

### 2.6.2. Carbon – $CO_2$ fixation, the solution of Solmeyea

There are several macroalgae & microalgae growing companies closely related to $CO_2$ absorption through their photosynthetic growing methods. Among all, few of these companies prioritize more intensified methods of $CO_2$ assimilation, the latter of which being produced in large volumes as part of burning or gasification processes.

One of the most developed examples of this cohort of companies is the hybrid Climate-BioTech startup, named "Solmeyea", which core-concept has to do with a two-steps process (1) off-gas fermentation (gasification) and (2) the intensified vertical microalgae growing process.

Gasification is the complete thermal breakdown of solid carbonaceous feedstock into a combustible mixture of gasses (usually known as synthesis gas or syngas and consisting mainly of CO, $H_2$ and $CO_2$. Gasification takes place in an enclosed reactor (gasifier) in the presence of an oxidizing agent (e.g., air, $O_2$, $H_2O$ etc.), which is supplied externally at a ratio lower than it is required for the complete oxidation of the feedstock.

Syngas can directly be used for the generation of heat and power. However, it can also serve as feedstock for production of liquid fuels, chemicals and materials. Because of this flexibility of application, gasification has been proposed as the basis for refineries that would provide a variety of energy and chemical products, including electricity and transportation fuels. Raw materials for gasification may be of fossil origin (e.g., coal), however, the focus should be on sustainable options such as biomass and wastes. Biomass such as lignocellulosic energy crops are potential candidates for gasification. Nonetheless, the increase in arable land required for farming of these feedstocks has indirect implications on land use and food prices (see "food vs fuel" debate), bringing about a ripple effect with negative environmental and socio-economic impacts in many regions of the world. As a result, alternative sources of second-generation biomasses are preferable. Such sources are lignocellulosic biomass waste like residues from the forestry, agricultural and food sector, which come with very similar characteristics with the above-mentioned woody biomasses but also some additional challenging carbonaceous material such as sewage sludge, municipal solid wastes or waste plastics that also come with disposal problems. Syngas poses similar challenges to $CO_2$ capture due to its constituent gasses and other pollutants (e.g., tar, ash, dust), and as a result reduced efficiency, which leads to higher costs is encountered.

In order to remove gas from off-gas and syngas, a process more correctly referred to $CO_2$ fixation, which fixates $CO_2$ into other products, useful as intermediate or final products for other processes or for sale and commercial exploitation.

The prime $CO_2$ fixation technologies employ catalysts, electrochemical processes, or biological processes using micro-organisms. The use of microorganisms for $CO_2$ fixation (e.g., into acids) is becoming widely adopted in industry and the research community. Typically, $CO_2$, Carbon Monoxide (CO), nutrients, and Hydrogen ($H_2$) are inputted into a Trickle Bed Reactor (TBR) where selected and/or modified microbes convert the gas inputs into methane, fatty acids, and/or other products. Figure 18 shows on the left the inputs of the TBR in a diagrammatic illustration as a part of the whole process of Solmeyea.

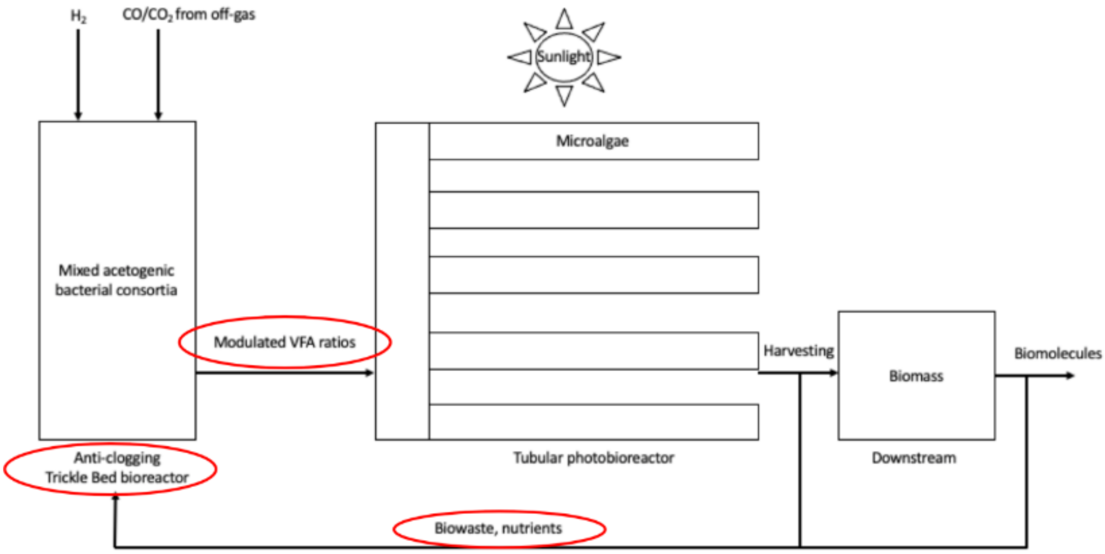


*Figure 18: A diagrammatic illustration of the inputs/outputs of the TBR highlighted in red cycle as a part of the whole Solmeyea process and (Solmeyea Ltd.)*

A TBR is a solid-liquid-gas contacting device, usually in the form of a tube, or tubes connected in parallel and oriented vertically or inclined, wherein a liquid stream flows downward over a bed of catalyst (e.g., in the form of beads, granules, pellets, etc.) with pressure difference serving as the driving force for the liquid to trickle onto the catalyst and form fine films, rivulets or droplets. The gas stream can either flow concurrent with the liquid or countercurrent to it through the bed. TBRs are primarily operated in continuous mode but are sometimes used in semi-batch processes.

TBRs may be run in stable-continuous, pulsing, spray, or bubble flow regimes depending on the application.

TBR are very well known and widely used. Their efficiency depends on several parameters, including the choice of microbes, the liquid and nutrients fed on the microbes, the operating temperature, pH, and flow. Other influencing factors are pollutants, gas mixtures, purity of the microbes, etc. As skilled persons know, the control of all these parameters for increasing the efficiency of TBRs is not an easy task, especially considering that off-gas differs significantly from syngas, while both gases may vary considerably in their gas mixtures, leading to significant variations in the efficiency of the TBR. Furthermore, due to the inherent limitations of TBRs their end products are not always in a form suitable for processes and products commonly used in the chemical industry.

Other technologies for $CO_2$ fixation include the use of Photo BioReactors (PBR), which contain micro-algae, fed with $CO_2$, CO, glucose, acetate or other fatty acids, organic carbon, etc. for cultivating microalgae. The cultivated microalgae are then harvested and used to produce fuels, food supplements, plastics, etc.

On the other hand, PBR known in the prior art rely on the provision of acetate and other products which are sourced from the market and are usually produced from petrochemicals or other source materials that significantly raise costs, and at the same time require the production of more greenhouse gases than those they consume for the cultivation of the microalgae.

PBR technologies are preferred over race-pond technologies, which are open systems, because their closed-system nature allows better control of their operation and higher productivity. PBRs based on mixotrophy of microalgae (i.e., microalgae that uses a mix of different sources of energy and carbon) using acetate is a well-known concept.

Mixotrophy in PBRs presents the advantages of a higher productivity than autotrophy (i.e., microalgae that use energy from light to photosynthesize or inorganic chemical reactions – takes $CO_2$ as input and outputs biomass, but has low productivity) and heterotrophy (i.e., microalgae that cannot produce its own food, and relies on taking nutrition from other sources of organic carbon, mainly plant or animal matter) while enabling production of light-dependent biomolecules (e.g., pigments).

However, mixotrophy (takes organic carbon source as input and outputs $CO_2$ and biomass and has higher productivity than autotrophy) requires an organic carbon source as an input (generally glucose, acetate or glycerol) which represents a big part of the operational costs, and which implies a positive $CO_2$ balance of the process.

Furthermore, known TBR and PBR systems need to be maintained, e.g., disinfected and cleaned for avoiding productivity drop, resulting in long downtime and interruption of their operation. For example, TBRs are proposed as typically filled with packing material that provides a higher surface-to-volume ratio. This packing material needs to be regularly cleaned from impurities resulting in the interruption of the operation of the TBR for long periods of time and the disturbance of the microbe culture with negative effects on the TBR operation and its financial implications.

For the reasons, preciously presented, it is obvious to a person skilled in $CO_2$ fixation technologies that a solution to the problem of sustainably boosting $CO_2$ fixation is needed.

This way the Solmeyea Biotechnologists and Chemical Engineers contribute to the problem of how to sustainably boost $CO_2$ fixation for growing microalgae. In a first exemplary embodiment, a system, comprising a Trickle Bed Reactor (TBR), a Two-phase flow system in tubular Photo Bioreactor (PBR), and a feedback module is used to sustainably boost $CO_2$ fixation for growing microalgae. The TBR comprises a packing material in the form of non-porous particles with a high surface-to-volume ratio, forming a substrate for attachment of Volatile Fatty Acid (VFA) producing microbes.

The TBR and the microbes it contains are fed with $CO_2$, $H_2$, nutrients, and a moistening liquid for moistening the packing material without soaking or flooding it, for boosting productivity of VFAs. The output of the TBR, containing VFAs, is fed to the PBR which uses micro-algae modified for increased productivity in the presence of VFAs. No $CO_2$ needs to be fed to the PBA. The overall $CO_2$ balance of the system operation is negative, while increased productivity is achieved without requiring feeding the system with externally produced VFAs.

In a second exemplary embodiment, the system of the first exemplary embodiment is modified to include a microalgae harvester module connected to the output of the PBR. The microalgae harvester module extract microalgae from the liquid output from the PBR and the feedback module takes the effluent liquid full of macronutrients produced by the microalgae harvester module and fed back to the TBR as a source of nutrients. The overall $CO_2$ balance of the system operation is negative, while increased productivity is achieved without requiring feeding the system with externally produced VFAs.

A simplified depiction of the combination of the above two exemplary embodiments is figure 19.

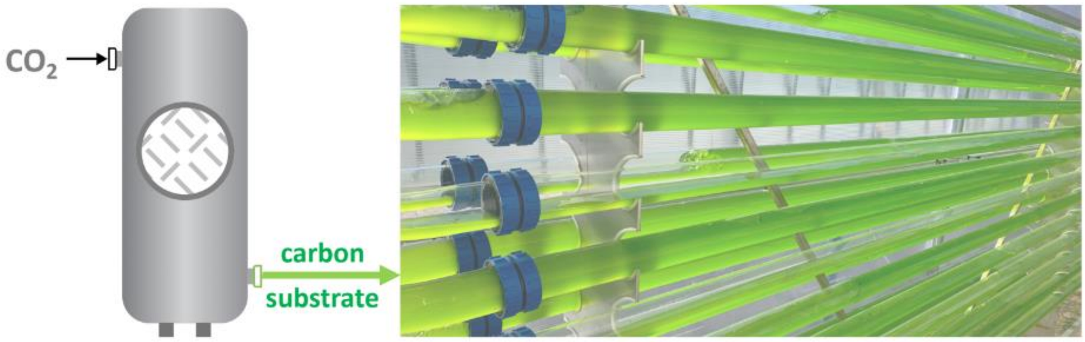


*Figure 19: A simplified depiction of the combination of the above exemplary embodiments (Solmeyea Ltd.)*

A first embodiment of a methodology is executed at the first exemplary embodiment system or at its modifications. The methodology starts by introducing VFA-producing microbes, $CO_2$, $H_2$, moisturizing liquid and nutrients to a TBR, followed by introducing in a PBR modified algae, suitable for maximum productivity in a liquid containing VFAs. The TBR (and the VFA-producing microbes) are allowed to produce a liquid containing VFAs, while continuously (or at intervals) sensing $CO_2$ concentration, and one of more of temperature and pH, in the liquid content of the TBR, which contains VFAs produced by the VFA-producing microbes. Using the reading(s) of the sensing step the flow of a part of the liquid content of the TBR (which contains VFAs) into the PBR is adapted, the TBR is allowed to cultivate the modified microalgae using the VFAs contained in the liquid content of the TBR that is supplied to the microalgae inside the PBR. A part or all of the aqueous solution content of the PBR (which includes microalgae) is output and selectively fed to either a liquid distribution device of the TBR as a nutrient, or to a backflush input device of the TBR for unclogging or cleaning/disinfecting packing material in the TBR. In the first step of the methodology, syngas or off gas or a combination of the two, containing $CO_2$ is input to the TBR (left part of figure 19).

A second embodiment of Solmeyea's methodology is executed at the second exemplary embodiment system or at its modifications. In the second embodiment of the methodology, the first embodiment of the methodology is modified to include the step of outputting the aqueous solution content of the PBR to a microalga farming module, which extracts part or all the algae contained in the aqueous solution fed to the algae. The feedback module, then, feeds a part of the effluent liquid, which may still contain microalgae, from the algae farming module to the TBR, as nutrient. Modifications of the second embodiment of the methodology are executed at the second exemplary embodiment system.

All these are going to be hosted at Solmeyea's 1,100 $m^2$ Demo-scale facility, hosted at "Demokritos - NSCR" – Greece's National Science & Research Center.

The Solmeyea's IP-protected two-step proven technology of "hybrid vertical microalgae farming" including $CO_2$ conversion and assimilation to highly functional and valuable food ingredients, derived from microalgae is nine times more efficient compared to an equal square footage conventional forest, concerning the $CO_2$ volumes it converts into $O_2$. Moreover, this "hybrid vertical microalgae" CCU method does not compete against any fertile, arable land or against any conventional crop-land or forest. Instead, it can be applied on any underutilized, infertile, non-arable land guaranteeing valuable end-products for different food, feed, pharma & cosmetics with the lowest ever environmental footprint, concerning Land, Water and Carbon impact. Figure 20 is a summary of the whole Solmeyea process with its requirements and its final outputs.

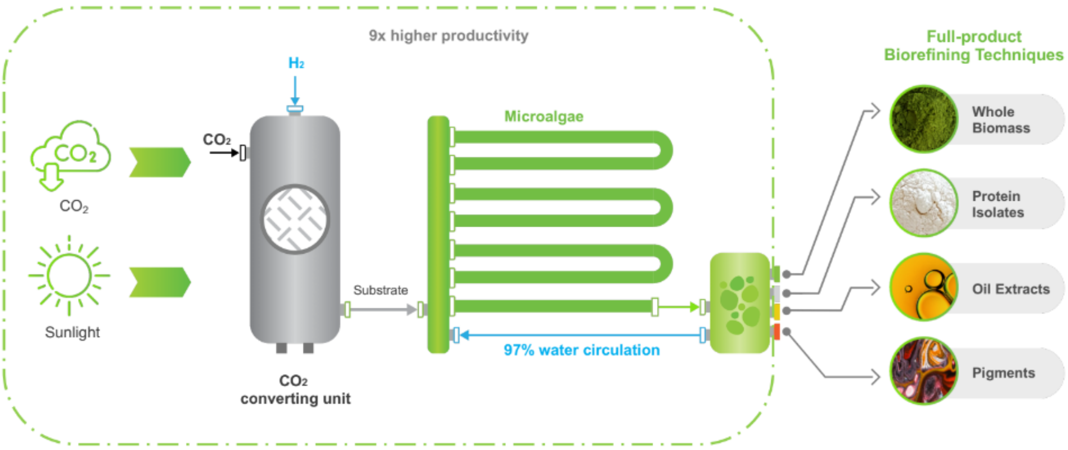


*Figure 20: Summary of the whole Solmeyea process including its requirements and its final products (Solmeyea Ltd.)*

All in all, the described CCU technology, comprising a Trickle Bed Reactor (TBR), a Two-phase flow system in tubular Photo BioReactor (PBR) (the right side of figures 18, 19 and 20), and a feedback module is used to sustainably boost $CO_2$ fixation for growing microalgae. The TBR output is fed to the PBR which uses microalgae modified for increased productivity in the presence of VFAs. No $CO_2$ needs to be fed to the PBR. At least part of the output of the PBR is fed by the feedback module back to the TBR either as a source of nutrients or for as a means back flushing for unclogging or expulsing the packing material from the TBR for cleaning/disinfection. Most importantly, the overall $CO_2$ balance of the system operation is negative.

## 2.7. CCU technologies comparison and long-term considerations

As we can see from the above applications of CCU technologies there is a wide area of post-processed products than can be produced using $CO_2$ as feedstock. Although the benefits of CCU technologies are evident about climate mitigation, in contrast with CCS technologies earlier discussed in Part 1, CCU's expansion doesn't rely only on its technology maturity or its cost of conversion. There are further external reasons that influence which CCU technology will prevail in the coming decade. As we saw in EOR oil demand and aging oil reservoirs heavily influence the need for oil producers to go in EOR. In the case of $CO_2$ derived e-fuels the condition of drop-in replacements of conventional liquid fuels without the need of creating new infrastructure is vital for the expansion of this application. Lastly, in the case of chemical and biological conversion (e.g., LanzaTech, Solmeyea) the compatibility of their products with the needs of their industrial clients will define their future viability. The only applications of CCU up to date that are most implemented are the direct uses of $CO_2$ since they don't need any further processing.

Summing up, whether a CCU technology will prevail over other possible applications the below criteria apply:

- Technology readiness level
- Greenhouse gases emissions from $CO_2$ capture and conversion
- Achievement of SDG's 2030 agenda
- Operational costs

Technology readiness is related on how mature a CCU technology is to be implemented without the need for creating new infrastructure to support it. E-fuels is a typical example that high value in this criterion compared to the other 3 criteria is vital for its financial viability since the requirement of drop-in replacement of typical hydrocarbon fuels is fundamental for any possible investment opportunity. According to Kiane de Kleijne and her team (de Kleijne, et al., 2022), direct uses of $CO_2$ followed by $CO_2$-EOR have the highest value in technology readiness from all CCU applications. Then Fischer-Tropsch fuels (or in other word e-fuels) are followed and then the case of Solmeyea.

Greenhouse gases emissions from $CO_2$ capture and conversion are related with the efficiency of the energy intensive conversion processes and the life cycle analysis of the $CO_2$ transportation emissions. Unlike with CCS technologies and DAC, CCU applications use $CO_2$ as feedstock in their activities. So, for their activities either $CO_2$ must be supplied to them through distribution network of pipelines or through transport of gathered quantity of $CO_2$ from point sources. This transportation process includes an emission cost to the whole CCU application process that must be taken into consideration. Also, the carbon footprint of conversion processes in the case of e-fuels making, LanzaTech's and Solmeyea's includes an extra emission cost. Therefore, a CCU application is also evaluated on its re-emission percentage of $CO_2$. At the moment, $CO_2$-EOR in UAE faces the lowest re-emission percentage of $CO_2$ due to the fact of an already existing distribution network of pipelines of $CO_2$. Other CCU technologies can significant lower this criterion either by operating close to $CO_2$ point sources or by creating another efficient way of $CO_2$ transportation.

Achievement of the SDG's 2030 agenda is related with the potential that the final products from a CCU implementation could meet the sustainable goals set up by UN GA. In fact, even if direct uses of $CO_2$ have a high technology readiness level and relative low greenhouse gases re-emissions they can't achieve much of SDG's since they don't further exploit $CO_2$. Whereas, Solmeyea followed by LanzaTech through their applications produce final products that are useful for food, cosmetics and many other areas that can eventually achieve many SDG's. For instance, Solmeyea's initiative already serves 9 out of 17 SDG's (Solmeyea, 2022). So, in funding and attracting investors for CCU technologies the quality of their final products which is reflected through SDG's achievements must be taken into consideration in order to justify the rationale behind any possible external funding or economic assistance.

Finally, operational costs similarly to the ones discussed about CCS technologies play a major role in the early stages of every CCU application. Diminishing them adds profitability and financial viability in the same way for every CCU. Now, assuming that the transportation cost of $CO_2$ feedstock for the above applications is about 30 €/t $CO_2$, this cost must be added in every levelized cost of each of the above application. This mean value is estimated to be reasonable for the different types of $CO_2$ transport (by truck, vessel, existing pipeline network) (Peters , et al., 2022). Table 3 sums up the levelized costs and the investments cost of the above applications as found in the literature in order to reflect the expenses of the operations of the above applications (Peters , et al., 2022), (Roberts, 2019) (Solmeyea, 2019).

| Table 3 | Levelized cost (€ / t $CO_2$) | Investement cost (in millions €) |
|---|---|---|
| EOR | 40+30 | 40, if we don't assume an existing oil reservoir |
| Direct uses of $CO_2$ | 30 | We assume existing infrastructure |
| E-fuels | 278+30 | 0.95 |
| LanzaTech | 80+30 | 300 |
| Solmeyea | 18000 up to 250 +30 (Depending on the scalability) | 2.2 |

*Table 3: Levelized and investment costs of the above examined applications (Roberts, 2019) (Peters , et al., 2022) (Solmeyea, 2019)*

# 3. EU Emission Trade System (ETS) and the opportunities and challenges from its implementation as a legal framework for CCUS technologies

## 3.1. EU ETS implementation history and its current utility

The EU ETS may prove a powerful incentive to advance operations of $CO_2$ capture, storage, and utilization in the European Union, provided that the $CO_2$ market price is sufficiently high and predictable, and all CCUS operations will be included in the system (Wartmann, et al., 2009).

Having been set in 2005, the EU ETS is the world's first international emissions trading system. It is now in its fourth phase of operation (2021-2030). The earlier phases of operations were phase 1 (2005-2007), phase 2 (2008-2012) and phase 3 (2013-2020). Phase 1 was a 3-years pilot phase of learning by doing which followed the 1997 Kyoto Protocol where (GHG) greenhouse gas reduction was first globally discussed under a legal framework and the European green paper. The latter has acted as a brainstorming of indicative first ideas for the design of EU ETS in March 2000. During the (2005-2007) pilot phase 1, EU ETS covered only $CO_2$ emissions from power generations and energy-intensive industries and almost all allowances were given to businesses for free (Commission, 2022). In January 2008, while entering the second phase of the EU ETS operations, the European Commission released its proposal for an enabling policy framework for $CO_2$ capture and storage in the European Union. The most outstanding element of this proposal was a Directive for the Geological Storage of $CO_2$, opening the way for CCS with sequestration operations, which would effectively regulate the risks of $CO_2$ storage. The Directive up to date regulates proper site selection, complemented with appropriate monitoring. According to the EU ETS proposal for a review (January 2018), the European Commission considered that from 2013 onwards, installations capturing, transporting, or storing or further utilizing $CO_2$ should be covered by the trading scheme in a harmonized manner, in order to encourage and incentive large scale deployment of the option. Following 2013, the EU ETS began its phase 3 of operations. The core difference of this framework was the absence of free allocation of emissions' allowances for installations in the power sector. Since 2013, all carbon allowances should get auctioned, and $CO_2$ captured and transmitted for storage or further utilization will not count as emitted under the new EU ETS framework. This is another example, substantiating the policy makers' focus on motivating CCUS technologies to operate near pollutant power installations (Wartmann, et al., 2009).

Currently, we run the EU ETS fourth phase of operations, being active/valid in all EU countries plus Iceland, Norway and Lichtenstein. This way there is an intention of limiting carbon emissions from around 10,000 installations in the power sector and manufacturing industry, as well as airlines operating between those countries. As a result, the current EU ETS fourth phase of operations may end up covering approximately 40% of the EU's (GHG) greenhouse gas emissions. More specifically, it covers $CO_2$ emissions that can be measured and verified with a high level of accuracy from: (Commission, 2022)

- Electricity and heat generation
- Energy-intensive industry sectors including oil refineries, steel works, and production of iron, aluminum, metals, cement, glass, ceramics, acids and bulk organic chemicals
- Commercial aviation within the European Economic Area

EU ETS is also anticipated to cover the emissions from the maritime sector (Commission, n.d.) in order to intensify EU abatement policy against climate change, until the end of 2023. Figure 21 shows the prospect of all sectors that are intended to get covered by EU ETS in the following years along with the inclusion of maritime sector.

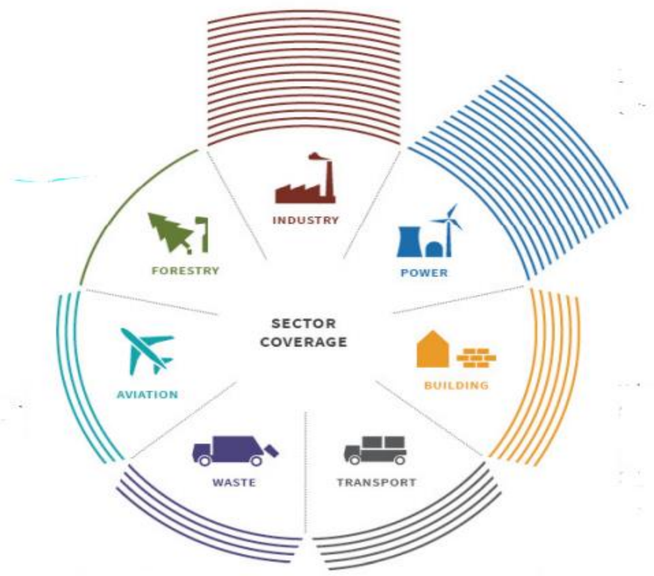


*Figure 21: Sectors that are projected to be covered by EU ETS in the coming years in addition to the maritime sector (more peripheral lines show more intensity of activities in each sector) (Serre, 2015)*

EU ETS utility is important since it gives the incentives for start-up ventures & ClimateTech spinoffs to further innovate and operate towards carbon neutral activities and ensure the corresponding funding through carbon allowances for their operations. EU ETS is a legal framework on credibly measuring, monitoring, crediting and consequently reducing emissions and imposing laws aiming to meet the 2015 Paris Agreement going as well as the UN 2030 Sustainable Development Goals agenda (Nations, 2022). Moreover, the international community & global policy mechanism organizations have also gotten inspired and motivated from the EU ETS operations by initiating the global debate for imposing similar greenhouse gases emission reduction and trading frameworks in a global spectrum of operations and business activities. All in all, we anticipate EU ETS or any other similar global application to play significant role in the coming decades in energy and environmental sectors and promote the technology around Carbon Capture and Utilization.

## 3.2. How EU ETS does it work?

The EU ETS works on the "cap and trade"' principle. A cap is set on the total amount of certain greenhouse gases that can be emitted by the installations covered by the system. The cap is reduced over time so that total emissions fall. Within the cap, installations buy or receive emissions allowances, which they can trade with one another as needed. The limit on the total number of allowances available ensures that they have a value. After each year, an installation must surrender enough allowances to fully cover its emissions, otherwise heavy fines are imposed. If an installation reduces its emissions, it can keep the spare allowances to cover its future needs or else sell them to another installation that is short of allowances. Trading brings flexibility that ensures emissions are cut where it costs least to do so. A robust carbon price also promotes investment in innovative, low-carbon technologies (Commission, 2022). In the CCUS technologies carbon allowances are given to firms when it is ensured that $CO_2$ is fully absorbed from being emitted to the atmosphere or is further utilized as a raw material. For that reason, every entity that is about to gain carbon allowances must be certified and monitored firstly by EU ETS officials in order to ensure the integrity of the system and that every ton of $CO_2$ carbon allowance corresponds to the exact ton of $CO_2$ permanently removed. This certification is laid down by EU ETS in the Monitoring and Reporting Guidelines (Wartmann, et al., 2009).

## 3.3. CCUS income channel flows and how do they gain carbon allowances from EU ETS

Entering the phase 3 of EU ETS in 2013, there is no free allocation of carbon allowances; hence all allowances are gained either through trading or through funding for permanent carbon removal. CCUS technologies interact with both way with the EU ETS. In other words, a CCUS entity gains carbon allowances that is considered as funding by the EU Commission for either permanently removing $CO_2$ from the atmosphere (case of DAC) or absorbing it in some post-processed products (case of EOR). So, for CCS ventures the major revenue streams are derived from trading their gained allowances with other entities that are inelastic on reducing emissions such as the airline companies, or certain vessel types of the maritime sector. However, CCU is not included yet in the above legal framework under EU ETS due to lack of evidence and measuring methodologies. Still, the CCU entities, responsible and accredited for blocking certain $CO_2$ volumes are also going to be included soon in the EU ETS (Commission, 2022). So, CCU technologies main income for now relies heavily on private and public funding schemes. On the other hand, a CCS entity in order to be able to gain allowances first it must be certified by EU ETS that every ton of $CO_2$ is really sequestered or absorbed so that every ton of carbon allowance to be equal to the ton of $CO_2$ permanently removed. This certification process is always present as a yearly basis check by EU ETS to verify every time that every ton of $CO_2$ corresponds to the right amount of carbon allowances gained by a CCS entity (Commission, 2022). Nevertheless, apart from EU ETS for CCS, external funding for both CCU and CCS is vital taking into consideration the maturity of the technology discussed in parts 1 and 2.

All in all, the main difference between CCS and CCU in their revenue streams is illustrated in figures 22 and 23. Figure 22 illustrates CCS revenue streams.

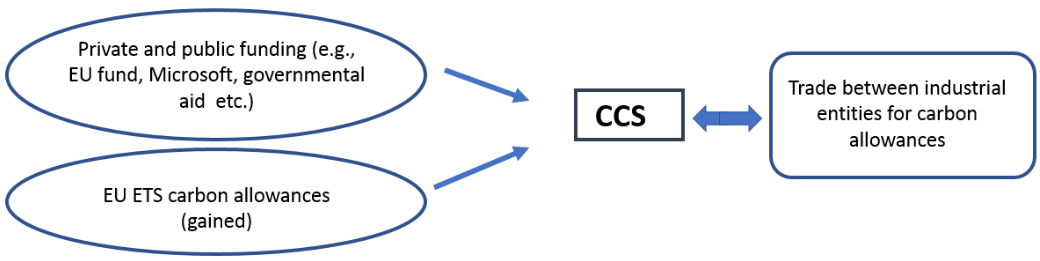


*Figure 22: CCS firms revenue streams for 2022*

Figure 23 illustrates CCU revenue streams.

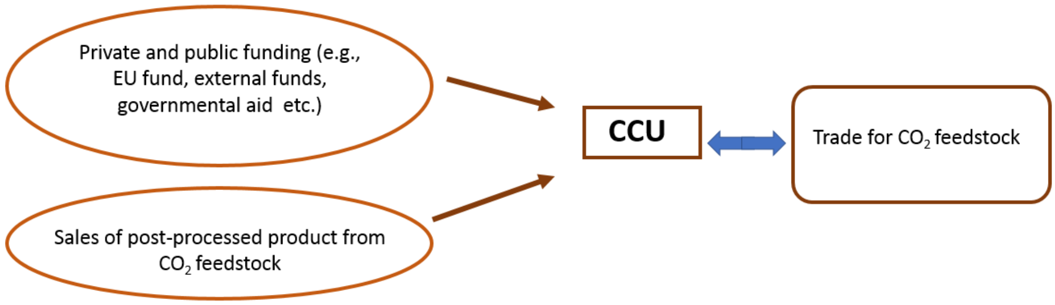


*Figure 23: CCU firms revenue streams for 2022*

Aside from the external needed funding for both CCS and CCU firms, moreover on their early stage of operations, CCS relies on EU ETS carbon allowances trading for income inflows, whereas CCU trade either gathered $CO_2$ feedstock or $CO_2$ based output with different areas of industrial activities. Thanks to the CCU inclusion by EU ETS, the investment opportunities shift clearly in favor of CCU firms since the latter ones will gain an additional revenue stream. As a next move, considering the CCU companies and advanced combining technologies can drive their levelized costs down to the level of CCS, is expected to be more attractive business solutions than CCS in the coming years.

### 3.4. EU ETS carbon pricing; present situation, trends, and interaction with CCUS

Carbon pricing or setting a price for every ton of $CO_2$ carbon allowance is the fundamental value of the whole EU ETS operation. The concept is that coal power plants, aviation or any other energy intensive activity should emit the exact quantity of the carbon allowances that possess or else they have to pay a high price penalty or further buy carbon allowances via EU ETS. The price of every ton of $CO_2$ is a commodity meaning that prices fluctuate constantly following the geopolitical stock markets' turbulence. So, the price of carbon allowance cannot be considered at all stable and trading them feels the same as trading stocks and bonds since apart from the EU ETS trade platform, secondary and OTC (Over the Counter) markets are also legitimate in this trading process. However, the price range of $CO_2$ carbon allowances is mainly affected by the EU ETS trade platform since it sets the price benchmark and trends for all secondary/parallel carbon trading markets. Focusing on the price of carbon allowances presented by the EU ETS platform (as €/ton of $CO_2$) we can observe the price fluctuation's significance as illustrated on diagram 1.

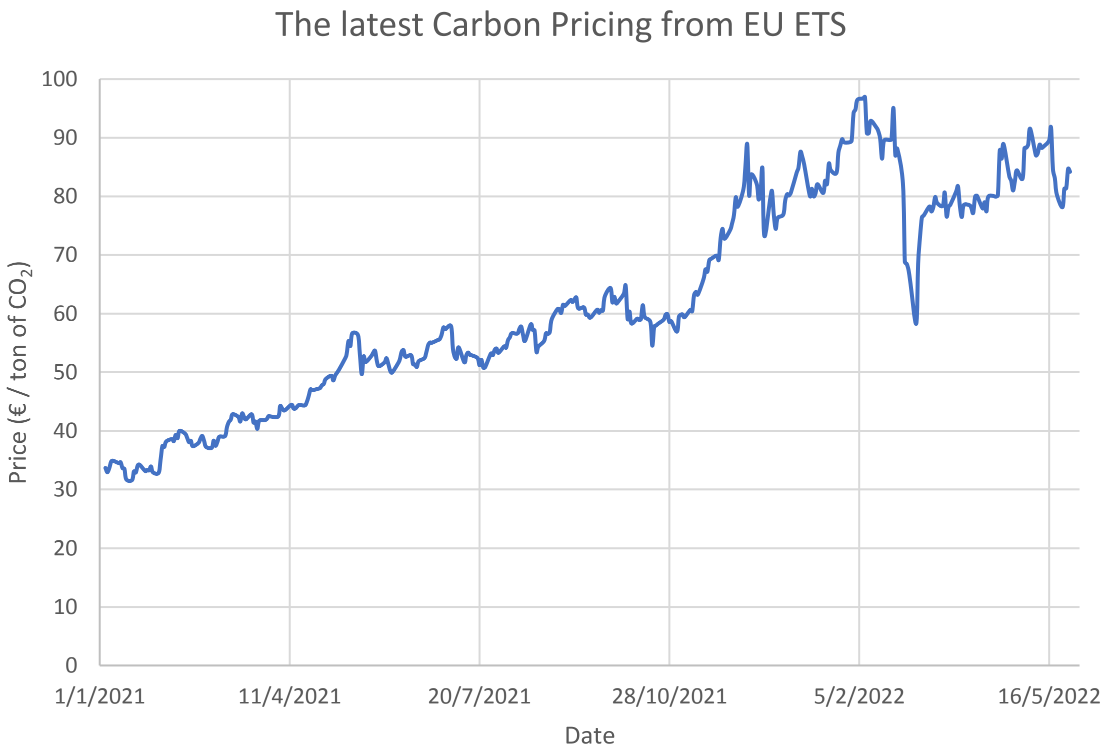


*Diagram 1: EU ETS carbon prices from 1/1/2021 up to 27/5/2022 (Org, n.d.)*

Undoubtedly, there is an upward climbing trend of the carbon prices, leading to the highest ever carbon price that recorded in the whole EU ETS history. This was spotted at 8/2/2022 at a price of 96.7 €/ ton of $CO_2$ of carbon allowance very close to the 100 €/ ton of $CO_2$ milestone. The sudden fall after this historic high price may be explained due to the war in Ukraine that started in $24^{th}$ of February 2022 and resulted in a significant fall of carbon prices as depicted on diagram 1. Still, as shown on the same diagram the upwards trend recovered after some weeks leading to the conclusion that the trend of carbon prices since 1/1/2021 up until now is still rising.

Moreover, having further retrieved the data from the same diagram 1 we came up with the weighted average monthly carbon prices that are illustrated on diagram 2.

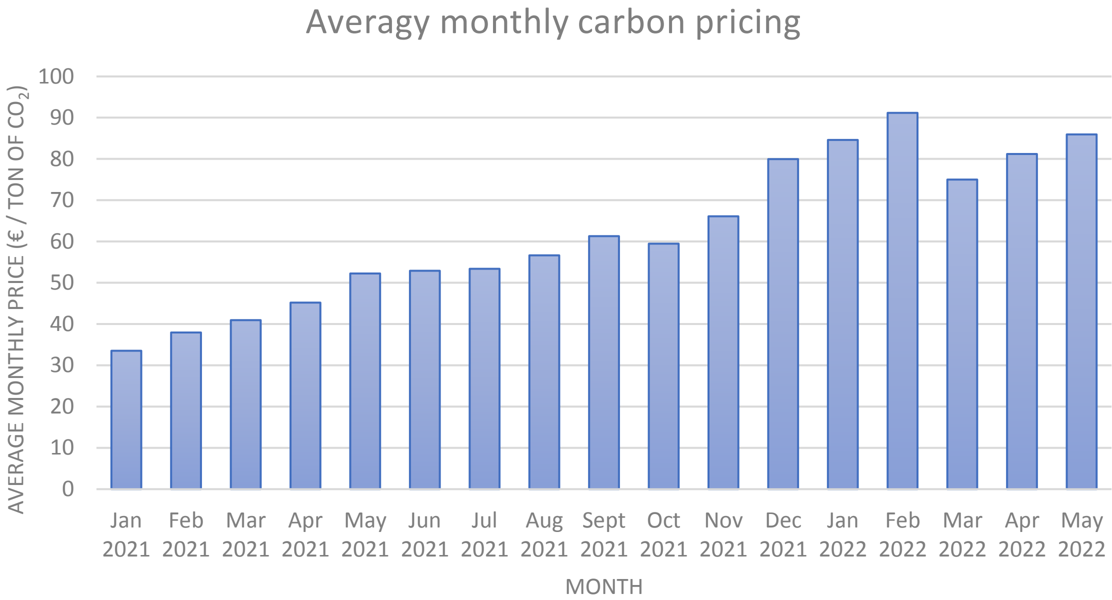


*Diagram 2: Average monthly carbon prices from the latest EU ETS data*

The same upwards trend from diagram 2 is evident even on a monthly based price format with the excemption of March 2022 (Ukrainian war).

As further analyzed on the first part of this diploma thesis, about the financial viability of DACC technology firms and in general CCS applications, higher carbon prices favor these firms since they can sell carbon allowances in the EU ETS market at a higher price and thus mitigate better for their raised costs. This observation applies also with CCU firms and in general CCUS firms. In the case of CCU technologies higher carbon prices are even more important for the early stages of the firms since the levelized cost per unit of $CO_2$ for further utilization (case of CCU) is significantly higher than it is for sequestration (case of CCS).

Considering the above, this increase in carbon price seems very realistic in the coming years leading the way to some promising business operations activating in CCUS technologies. The European Commission is keen on tightening EU ETS targets so as to be in line with the European Green Deal and handle more smoothly the impacts on the decarbonization of the EU power sector (Pietzcker, et al., 2021). As the EU ETS is the key climate policy to drive the decarbonization of the EU electricity system and the EU heavy industry sector, such a tightening will have substantial implication for utilities across Europe, fundamentally influencing and motivating the investment into new technologies.

The breakeven point for CCS firms according to Lackner et al. (Lackner, et al., 2012) as it was presented in part 1 is little higher than 95 € / ton of $CO_2$ if climate change was universally perceived as a serious calamity. Similarly, to this direction, the forecast seems promising since according to Pietzcker and his team (Pietzcker, et al., 2021) carbon prices within the EU ETS are expected to climb to as high as 129 €/ ton of $CO_2$ by 2030. That high carbon prices further straighten the argument that by 2030 the climate change will be considered as a serious threat. As a consequence, tightening the EU ETS prices will prove a one-way direction given the effectiveness of this system right now.

On the other hand, for CCU technologies where the cost of further utilization of $CO_2$ is normally significantly higher than it is for sequestration no breakeven point is solely expected to happen in the current decade, unless there is further innovative combination of technologies and secondary usages of the sequestered $CO_2$. However, this should not discourage ambitious entrepreneurs to allocate their attention and resources in CCU methodologies since as mentioned previously, their income channels aside from $CO_2$ storage, transportation and feedstock comes from the sales of post-processed goods from $CO_2$ that can offset their high costs, also correlated with relatively low prices of carbon allowances.

A great opportunity that is presented for both CCS and CCU technologies from the EU ETS carbon allowances trading perspective, is that those "carbon allowances trading" market shares willing to procure carbon allowances from CCUS entities is about to emphatically flourish, setting up a completely new barely unchartered niche market opportunity. The rationale behind this estimation relies on that carbon allowances are needed for every energy intensive activity and power generation that uses fossil fuels. If one of the previous stated industries decides that due to the increase in carbon price its operations cost is significant higher, it may pick one of the two business directions. Assuming, we are dealing with a coal power plant that by 2025 needs to modify its operations in order to diminish the impact of high carbon prices on its energy revenues, it may. Firstly, it can allocate financial resources to improve the efficiency of the turbine or of the whole plant so as to produce the same energy output but with less fuel consumption resulting in lower carbon allowances' demand. Alternatively, it can invest money to modify completely the infrastructure of the plant and host a zero-emission fuel, as the energy ignition phase, instead of the previously used fossil fuels (e.g., substitute lignite with biomass). Building up on this scenario, serious funds are needed in order to be invested at a conventional power plant's transformation to a zero-emission tone. Even though, this may seem an unorthodox business solution for a conventional power plant while aiming at tackling the rising carbon prices, it still is an option that leads to a potential client's loss from the CCUS perspective where carbon allowances could have been sold. Driven by this formatted assumption, we may all agree about the infeasibility of this scenario while referring to the aviation and maritime sectors, given the currently available technologies. Airlines companies are the major clients for CCUS. Those companies do constantly try to grow, by conducting more business, translated into more flights resulting into more $CO_2$ emissions. As a consequence, the airline companies seem to be an ideal CCUS customer interested in ongoing purchasing of carbon allowances, the costs of which may also willingly get transferred to each private flying retail customer, who is being given the option of paying more at his/her will towards offsetting their individual $CO_2$ atmospheric burden. Following the maritime sector’s inclusion in the EU ETS by the end of 2023 the only feasible way for both airlines and shipping companies to offset their $CO_2$ emissions is by buying carbon allowances. $CO_2$ emissions in aviation and maritime sector are unavoidable and offsetting them cannot be done with any other alternative infrastructure for the running decade. As a consequence, CCUS’ today’s major market share of buying carbon allowances which is the aviation sector will remain unchanged and it will only expand by 2023 with the inclusion of the maritime one. So, we can conclude that investors operating in CCUS technologies will face a steadily growing market share in trading their gained carbon allowances.

# 4. Technoeconomic analysis of CCS and CCU concerning their future viability and financial opportunities

## 4.1. Greece's first climate law – a roadmap to carbon neutrality

Following the roadmap to carbon neutrality that has been discussed in European level many times since the Paris Agreement in 2015, Greece's first Climate Law 4936/2022 was enacted a few days ago (27/5/2022) by the Hellenic Parliament, aiming at establishing a coherent framework for improving the climate resilience of Greece paving the way for business operations of CCUS activities. Further to the adoption of measures at international (Paris Agreement) and EU level (Regulation no 2021/1119), this is the first attempt of the Greek legislator to set forth binding measures concerning a wide array of industries and sectors, both public and private, in an effort to reduce carbon emissions and reach carbon neutrality by 2050. The new legal framework is very ambitious and is expected to bring a major shift in Greece's power production and overall economy in the years to come, designating environmental considerations as one of the key drivers for sustainable growth and development (Zepos & Yannopoulos, 2022).

In 2021, the distribution of electricity generation in Greece was powered mainly by fossil fuels (e.g., lignite coal and natural gas). 59.6 % of the electricity produced in 2021 in Greece came from fossil fuels. Figure 24 is indicative of Greece's power distribution in 2021 (Statista, 2021).

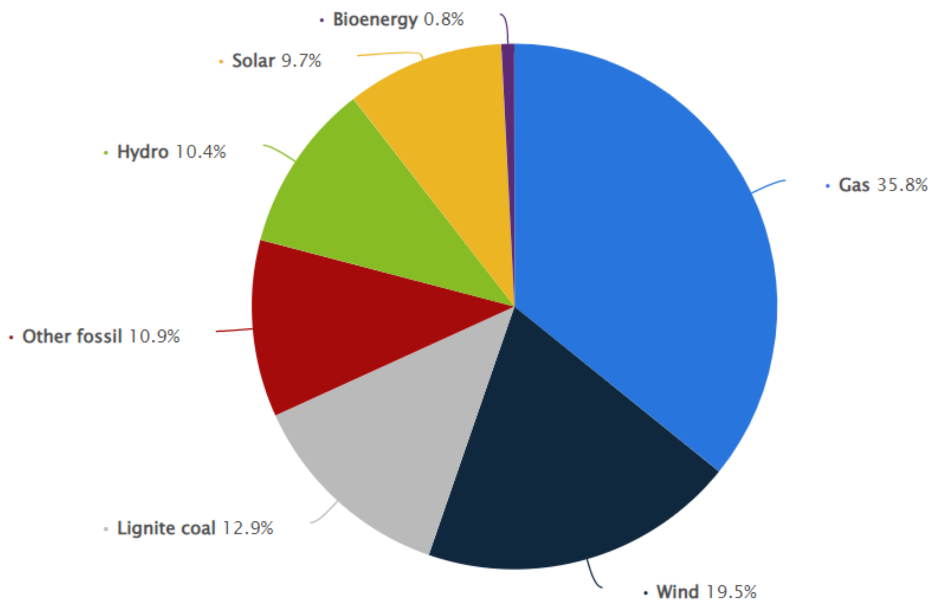


*Figure 24: Distribution of electricity generation In Greece in 2021 (Statista, 2021)*

Following Greece's first climate law lignite should be phased out by 2028. As of 31/12/2028, power generation from lignite-fired power plants shall be prohibited. Existing lignite-fired power units shall be decommissioned or converted to a different use in accordance with the pertinent guidelines to be included in the national strategy for climate change adjustment (Zepos & Yannopoulos, 2022). In other words, 12.9% of the electricity produced in 2021 must be substituted with a zero-emission energy solution. In order to reach this goal this deficit in energy production should be either covered by a higher share of renewable sources of energy (In Greece, solar, hydro, wind and bioenergy) or $CO_2$ emissions that derive from these lignite coal power plants must be offset. As discussed in the introduction sector the share of renewables is saturated by the system operator (IPTO in case of Greece). So, carbon offsetting from lignite coal power plants, seems like a one-way path, offering a great opportunity for CCUS activities to operate in Greece, as well.

Also, in the heating and cooling of the housing sector the legislation provides that as of 1/1/2025, the sale and installation of oil boilers for heating purposes will be entirely prohibited, while from 1/1/2030 onwards the heating oil to be sold must be mixed with renewable liquid fuels by at least 30% by volume. Sanctions are foreseen in case of non-compliance with the aforementioned obligations (Zepos & Yannopoulos, 2022). The mix of oil with renewable liquid fuels highlights a potential CCU application that was mentioned in Part 2 about e-fuels and biofuels that derive from $CO_2$ as a feedstock. So, again the legislation in the housing sector offers some interesting motives for a CCU activity in Greece.

All in all, Greece's first climate law and the tightening of EU ETS offer great opportunities for CCUS activities in Greece. Especially given the intense seismiogenic activity in Greece that makes CCS technologies including subsurface $CO_2$ sequestration a risky pathway, CCU activities are projected to monopolize the interest in Greece, same way in the State of California (US). From the major power generation sector all the way to the household's heating one carbon offsetting or zero-emissions fuels that derive from $CO_2$ utilization seem to be urgent more than ever under the most recent legislation of Greece concerning climate change. So, funding from governmental funds or from the EU's exclusively carbon-technologies' related Innovation Fund are about to thrive in reference to the implementation of CCU technologies in Greece under this legal framework raising up to the question as of which technology is more mature to prevail in Greece for the coming decade. The answer remains to be seen on the basis of the benefits that it can offer and of its levelized cost (€ / ton of $CO_2$)

## 4.2. Voluntary carbon offsets markets

### 4.2.1. Opportunities for CCUS from carbon offsets markets and how it works

Voluntary carbon markets offer another opportunity for CCUS technologies to expand their activities. 2021 could well be remembered as the year when carbon finance emerged as a talking point among a wide range of industries. As analyzed on Part 3 of this diploma thesis many policy makers, like the EU with its own emission trading system, have mandatory carbon markets covering specific industry sectors and gases. All these preliminary mechanisms and initiatives shape up an important infrastructure

& tangible proof of the efforts towards meeting the Paris Agreement targets, still not enough for a substantial change, themselves. For that reason, other sectors have taken a cue from compliance schemes and pledged to offset their (GHG) greenhouse gas emissions by voluntary participating in carbon markets.

Voluntary carbon markets allow carbon emitters to offset their unavoidable emissions by purchasing carbon credits emitted by projects scoped at removing or reducing GHG from the atmosphere. Each credit which corresponds to one metric ton of reduced, avoided or removed $CO_2$ or $CO_2$ equivalent GHG can be used by a company or an individual entity to compensate for the emission of one ton of $CO_2$ or equivalent gases. When a credit is used for this purpose, it becomes an offset. It is moved to a register for retired credits, or retirements, and is no longer tradable.

Companies can participate in the voluntary carbon market either individually or as part of an industry-wide scheme, such as the case of Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which was set up by the aviation sector to offset its (GHG) greenhouse gas emissions. International airline operators taking part in CORSIA have pledged to offset all the $CO_2$ emissions they produce above a baseline 2019 level (Favasuli & Sebastian, 2021).

While compliance markets are currently limited to specific regions, as we presented in the European Union with EU ETS, voluntary carbon credits are significantly more fluid, unrestrained by boundaries set by nation states or political unions. They also have the potential to be accessed by every sector of the economy instead of a limited number of industries offering another great market share for trading carbon credits between CCUS projects and different entities.

In detail, with a schematic illustration voluntary carbon offsets markets work as shown in Figure 25.

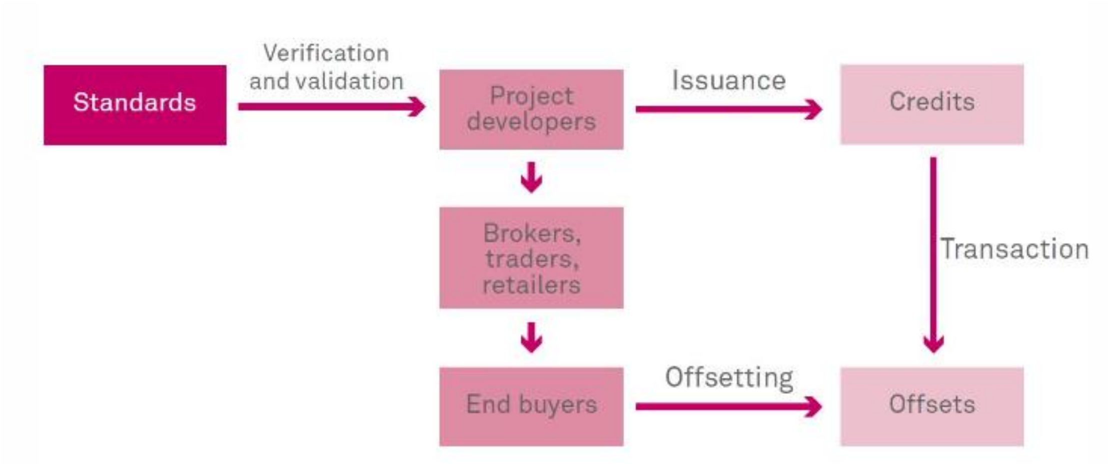


*Figure 25: Schematic illustration of the structure of the voluntary carbon offset markets (Favasuli & Sebastian, 2021)*

### 4.2.2. Project developers

Project developers are the ones creating the carbon offset project (Sanchez, 2021). They set up the projects issuing carbon credits, which may range from large-scale, industrial-style projects like a high-volume hydro plant, to smaller community-based ones like clean cookstoves. Moreover, entity that absorbs or further utilizes excess $CO_2$ or in other words every CCUS entity, falls under the project developers category. Each credit that is issued has a specific vintage, which is the year in which it was issued, and a specific delivery date, which entails the timing when the credit will be market available.

### 4.2.3. End buyers

End buyers represent the downstream market and include both companies as well as - individual consumers – that are committed to offset parts or all of their GHG emissions. Among the end buyers of carbon credits are tech companies such as Apple and Google, Microsoft, airlines, and oil and gas majors. As of recently, more industry specific sectors, including finance, are joining the market as they set their own net-zero targets or looking for ways to hedge against the financial risks posed by the energy transition (Favasuli & Sebastian, 2021).

Two worthy real-life examples concerning how actively does the voluntary system function by end buyers already, have to do with a major tech giant and the globally leading business consulting company. Firstly, as referred to Part 1 of this thesis, Climework's carbon dioxide removal solution and the Carbfix project in the creation of Orca plant in Iceland (Cooke, 2021) has been selected as part of Microsoft's carbon removal portfolio to help reach negative emissions by 2030 and remove the company's historic emissions by 2050. This could well be classified as a voluntary end buyer that wanted to offset the carbon footprint of its operations and thus funded a DAC company to permanently store underground excess $CO_2$ from the atmosphere.

Secondly, Boston Consulting Group (BCG), one of the world's leading strategic management consultancies, has signed a ten-year partnership with Climeworks. This is the first of several agreements in direct air capture and advanced decarbonization technology BCG experts to sign, and has two key elements. First, as part of BCG's commitment to reach net-zero climate impact by 2030, the firm will purchase Climework's carbon dioxide removal service to capture carbon dioxide directly from the atmosphere and permanently store it underground. Second, BCG will provide consulting services to Climeworks focused on the broader adoption and scaling of their services. This comes as part of BCG's commitment through its net-zero climate strategy to offset and reduce its $CO_2$ emissions from business travels by 48.5% by 2025 using 2018 as a baseline ((BCG), 2021)

In practice, the implementation of Article 6 of the Paris Agreement on November 13 of 2021 at the UN Climate Conference, or COP26, in Glasgow set the rules for a crediting mechanism to be used by the 193 parties to the Paris deal to reach their emission reduction targets or nationally determined contributions. The article implementation has made it possible for countries to buy voluntary carbon credits, as long as Article 6 rules are respected (Favasuli & Sebastian, 2021).

#### 4.2.4. Retail Traders

While trying to interlink supply and demand, there are brokers and retail traders, similarly to any other commodity markets. Retail traders purchase large amounts of credits directly from the supplier, bundle those credits into portfolios, ranging from hundreds to thousands of equivalent tons of $CO_2$, and sell those bundled credits to the end buyers, typically with a mark-up commission. While most of the transactions are currently happening in private conversations and over the counter (OTC) deals, some exchanges are also getting revealed. Among the largest exchanges for carbon credits at the moment are the New York-based Xpansiv CBL and Singapore based AirCarbon Exchange (ACX). Exchanges have been trying to simplify and speed up the trade of carbon credits – which have a high level of complexity due to the high number of factors affecting their price – by creating standard products, which ensure some basic specifications are respected (Favasuli & Sebastian, 2021). Retail traders facilitate the whole status and bring closer promising start-up CCUS firms to significant early funding for its operations. So, their role in this voluntary carbon offsetting market is crucial since they operate also as a kind of evaluation entity to attract investors for an innovative idea by making profits through these activities.

#### 4.2.5. Standards

Standards bodies review the projects against a criterion and operate a registry to allow the issue and retirement of the carbon offsets (Sanchez, 2021). Traditionally, standards are organizations, usually NGOs, which certify that a particular project meets its stated objectives and its volume of emissions. Standards have a series of methodologies, or requirements, for each type of carbon project. For example, a reforestation project will follow specific rules when calculating the level of $CO_2$ absorption of the planned forest and therefore the number of carbon credits it produces over time. A renewable energy project will have a different set of specific rules to follow when calculating the benefit in terms of avoided $CO_2$ emissions and carbon credits generated over time (Favasuli & Sebastian, 2021).

#### 4.2.6. Pricing a diverse supply

Pricing a voluntary good is not a straightforward activity but it is very important for the whole operation of this market. When a company turns to a voluntary carbon market as a potential way to compensate for its carbon emissions, one of the key pieces of information it looks for is the price of carbon credits. With this information, a company can decide how ambitious it can be when setting its emission reduction target and whether voluntary markets can really help in reaching it. At the same time, a clear price signal for carbon allows players already involved in the market to make sure they are trading their credit at a price that reflects the real market value. But putting a price on carbon credits is far from a straightforward operation, mostly because of the wide variety of credits in the market and the number of factors influencing the price. Projects issuing carbon credits can be of many different types and sub-types. The nature of the underlying project is one of the main factors affecting the price of the credit. Carbon credits can be grouped into two large categories or baskets: avoidance projects (which avoid emitting GHGs completely therefore reducing the volume of GHGs emitted into the atmosphere) and removal (which remove GHGs directly from the atmosphere) (Favasuli & Sebastian, 2021).

The avoidance basket includes renewable energy projects but also forestry and farming emissions avoidance projects.

The removal category includes projects capturing carbon from the atmosphere and storing it. They can be nature-based, using trees or soil for example to remove and capture carbon. Examples include reforestation and afforestation projects. They can also be tech-based and include technologies like direct air capture or carbon capture and storage and utilization highlighting the aforementioned CCUS applications (Favasuli & Sebastian, 2021).

Removal credits tend to trade at a premium to avoidance credits, not just because of the higher level of investment required by the underlying project but because of the high demand for this type of credits. They are also believed to be a more powerful tool in the fight against climate change (Favasuli & Sebastian, 2021).

Beyond the type of the underlying project, the price of carbon credits is also influenced by the volume of credits traded at a time. Also, when the underlying carbon project also helps to meet some of the UN's SDGs, the value of a credit from that project to potential buyers may be higher, and the credit can trade at a premium to other types of projects. For this reason, credits emitted by community-based projects may trade at a premium to projects that don't meet SDGs, such as industrial projects, which are typically larger-scale and can often produce large volumes of credits with more easily verified GHG offset potential (Favasuli & Sebastian, 2021).

In current carbon markets of voluntary offsetting, the price of one carbon credit can vary from a few cents per metric ton of $CO_2$ emissions to \$15/metric ton $CO_2$ equivalent (14.3 €/ ton of $CO_2$) or even \$20/metric ton $CO_2$ equivalent (19 €/ ton of $CO_2$) for afforestation or reforestation projects to \$100 (95.3 €) or even \$300/metric ton $CO_2$ equivalent (286 €/ton of $CO_2$) for tech-based removal projects such as CCUS (Favasuli & Sebastian, 2021).

Diagram 3 is indicative to understand why 2021 could well be remember as the year when carbon finance emerged as a talking point among a wide range of industries. S&P Global Platts (Platts, 2022) assesses the price of an array of carbon credits and currently produces 20 price assessments including both spot and forward (Year 1) prices. Each price assessment reflects the most competitive credit for each category, based on bids, offers trades reported in the brokered market, or on trading and exchange instruments (Favasuli & Sebastian, 2021).

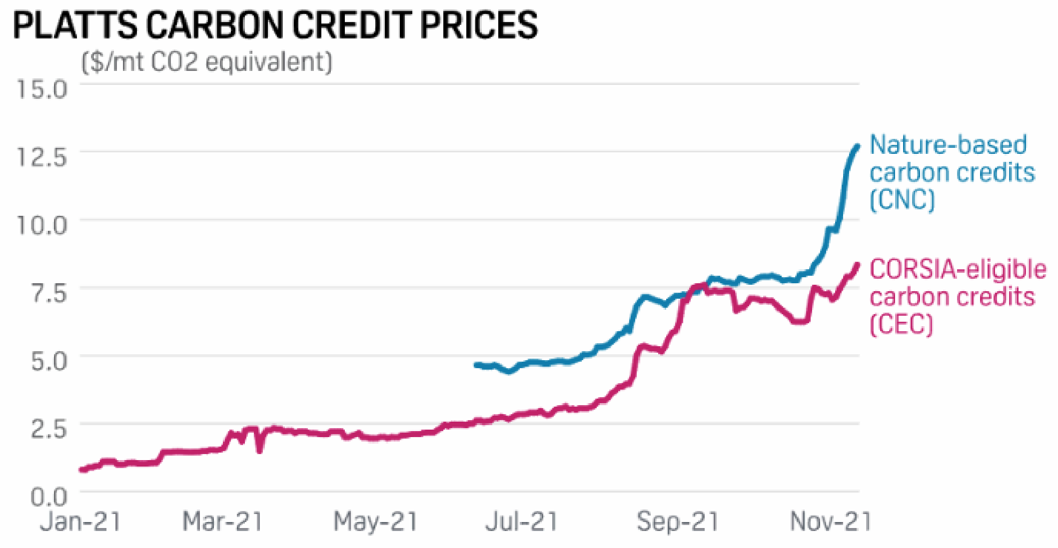


*Diagram 3: Evolution of prices of carbon credits in the voluntary carbon offsetting market (Platts, 2022)*

As shown on diagram 3 the increasing demand for carbon offset is a critical factor in understanding this year's 944% price increase in CORSIA compliant offsets and 174% for nature-based credits (Sanchez, 2021) that make carbon technologies such a pop-up talk point.

According to Sanchez (Sanchez, 2021) voluntary carbon offset market is going to intensify its activities soon. Projections for voluntary carbon offset markets point to demand reaching 2 gigatons of carbon dioxide by 2030 and up to 13 gigatons by 2050. That means that by 2030 voluntary carbon offsets could be contributing to 10% of the required 23 gigatons reductions.

Diagram 3 carbon credits rise is compatible with diagram 1 upward trend of prices of carbon allowances of the EU ETS leading to the conclusion that a tightening implementation of the legal framework of carbon trading leads to more expensive carbon credits to the voluntary carbon offset market which eventually leads to more opportunities for funding CCUS start-up firms, especially when it comes to technologies that meet most of SDG's 2030 agenda.

#### 4.2.7. Why however are carbon offset markets controversial?

Companies' major challenge when buying credits from carbon offset markets is the instrument reputation for not delivering the emissions reduction they promise. This reputation is an immediate concern for offset credit buyers that don't want customers, investors, or employees to associate their brand with greenwashing (Sanchez, 2021). Given the increased public awareness around climate change especially from young individuals, millennials and generation Z consumers who constitute a decent market share with great purchasing power, companies actually use voluntary carbon trading as a form of marketing, promotion and advertisement of their contribution on climate change mitigation. Even though, this may be perceived as a bit hypocritical if a company uses voluntary carbon offset markets only as a mean of promotion of their goods, at the end of the day aside from the profit-driven superficial incentives for carbon removal projects, the opportunity for CCUS funding still counts.

Also, another controversy is offsets' bad reputation. This bad reputation is due to the abundance of available standards, the intended use for the offsets and the complexity to measure its quality (Sanchez, 2021). Undoubtedly, such innovative and new technologies as CCUS cannot be treated without any suspicion from general public. But it should be the function of the market and independent evaluators of CCUS applications that have to gain the confidence of the public about funding something undeniably beneficial for climate change mitigation.

#### 4.2.8. EU ETS vs Voluntary Carbon Offset Markets

As discussed, EU ETS constitutes a pioneering system in carbon trading and after the past years learning period it currently transitions into its maturity phase with dual-faced beneficial results for all affiliated parties. EU ETS system is based on laws and mandatory trading for gaining carbon allowances and avoiding possible penalties for excess emissions by energy intensive activities. On the other hand, voluntary carbon offset markets as presented on this chapter is an optional choice for traders. Here, prices of carbon credits are set according to a company's will to fund a carbon removal application so there is now real time price benchmark as it is in EU ETS with its price evolution presented in diagram 1. So, there can't be any real actual comparison between them.

However, it is interesting to mention that EU ETS mainly affects energy intensive industries, aviation and maritime sector that are constrained by a legal framework for trading carbon allowances. In voluntary carbon offset markets, the major players are mostly companies that willing to establish a good reputation on climate awareness and promote their goods from different various sectors of economic activity.

All in all, we expect EU ETS to play a detrimental role for the funding of carbon removal activities, but we do also expect Voluntary Carbon Offset Markets to accelerate promotion and subsidies of innovative carbon removal solutions since the driving force behind this market are the environmental sensitivity and the reputation of big investment funds-companies without any barrier from law's directives.

# 5. Decision Making Model

Having the best product or even a great one is not enough to win in business. It will generate no value and be of no consequence at all unless the end user actually gets the product or service and takes advantage of it. For this to happen, the customer needs to acquire the product or service.

“Customer” is a general term that is needed to become more specific. To begin with, it is of high importance to clearly identify the key people and sources of information involved. The customer is not a monolithic entity but consists of multiple roles, whether embodied in one person, or several, that constitute a Decision-Making Unit (DMU).

The three primary roles in the DMU are:

1. End user: The person whose use of the product or service creates value for the customer.
2. Primary economic buyer: The person who will pay for a product or service and will determine whether the value the customer gets from the product is worth the cost.
3. Champion: The person who advocates for a product or service. This is the person who gets the process going and hopefully keeps it going until it is concluded.

Figure 26 below shows the key players of the above DMU.


*Figure 26: Key players involved in a Decision-Making Unit (Aulet , 2017)*

These roles reside in actual real people and not general, unspecific organizations. Many of these roles may exist in the same person, which is common in consumer product sales. The roles may be split across three (or sometimes even more) different people in business-to-business (B2B) service focused corporations.

The roles in the DMU are represented by professionals for the most part, but especially when it comes to influencers, they can be sources of information like *Customer Reports* or Oprah Winfrey’s television shows. In another recent development, today in some places, like the financial services, the decision is being taken out of human hands and instead made by algorithms and computers.

During the recently launched concept of $CO_2$ credits trading & offsetting, there is an imminent need for extra efforts to be done, so we facilitate the key-positions professionals to take the most suitable decision for their corporation and teams, that will also positively affect their individual career paths.

To complete this step, there is always a need to build Persona profiles for both primary roles in the DMU such as: the "economic buyer" and the "champion". Even if the economic buyer and the champion are the same person as the end user, they most likely may have different priorities when acting in a different role.

For each Persona, you have to identify primary (i.e., strongest) and secondary (i.e., strong but weaker than the primary) influencers, concerning the $CO_2$ pros and cons within a complicated manufacturing corporation, which leading team needs to handle in the most beneficial way not only for its own customers' perception but also for the environment and humanity's longevity. Moreover, for each Persona we should also identify who, if anyone, has veto power over the purchasing decision. Veto power can include governmental and company regulations. The purchasing department of a company is rarely an end user, an economic buyer, or a champion (although, if you are a low-cost solution, it is possible they might be a champion) and is usually only really holding veto power. Most important decisions are made by people with responsibility for the profit and loss, or at least the revenue, of a business or household.

Then Figure 27 is more explanatory of how the key players operate in this DMU process.

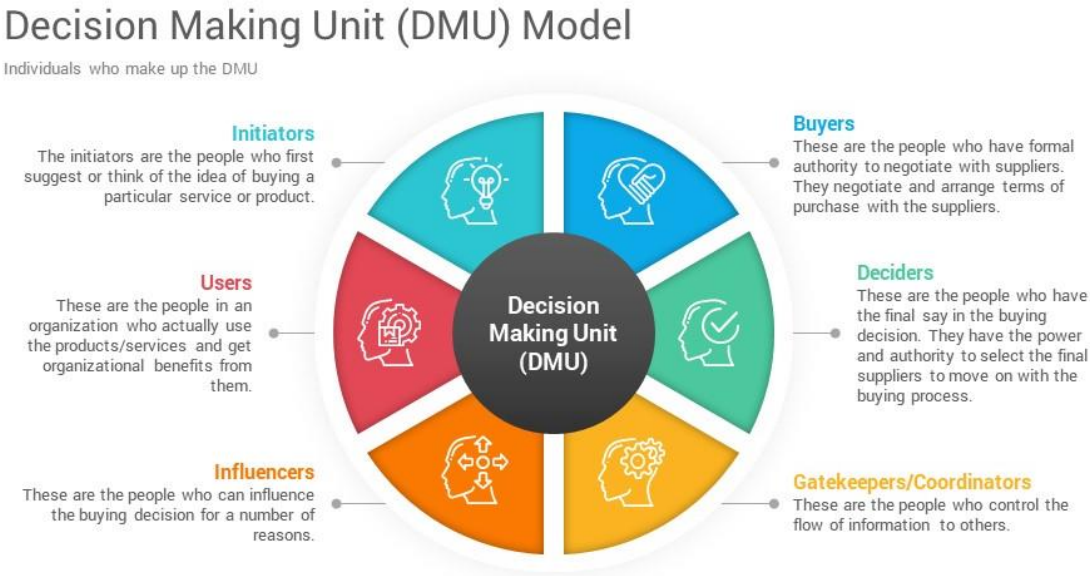


*Figure 27: Explanation of the role of the key players in the DMU*

Given the complicated organizational charts of professionals in our current world, a decision-making unit (DMU) is a team of people within an organization who play a role in the business-purchase decision-making process for products and services. It is sometimes referred to as the 'buying centre' of this organization, given their ability role to "kill" or "rebirth" substantial projects.

The term decision-making unit originates in B2B marketing but has now spread into consumer and service applications.

Typically, a decision-making unit may comprise:

- Specifiers – usually define the sort of product that is required, possibly using broad-brush-stroke outlines.
- Influencers – usually have a persuasive role in the decision-making process. They can set preconditions which may be as a result of their knowledge and experience. They may be consultants employed by the organisation to help the decision-making process. Informal influencers can include acquaintances, friends and family members.
- Buyers – responsible for purchasing, sourcing, and negotiating with suppliers.
- Gatekeepers – usually search for information, determine what type of information will be delivered to certain players and pass it on to decision makers further up the line. Can strongly influence the decision-making process.
- Deciders – e.g., senior managers who have the final say, make the final deal, ultimately responsible for choosing the supplier or the decision, placing the order having reviewed information passed on from those further down the line.
- Users – these can be both employees and customers. Because they use the goods and services, their feedback can exert influence on the specification of future products.

Not all of the above roles will be involved in some decisions, and it is also possible that one person may perform more than one role. Decision-making powers may not be evenly spread throughout the DMU: some may have more authority than others

As part of this research thesis, while going through all possible and plausible scenario of convincing the key decision makers of a heavily-manufacturing if not governmental organization we came up with a simplified algorithm that could be presented to those professionals and build up their confidence about the added value and suitability of partnering with specific CCU or CCS technologies. It is of high necessity to communicate to the Business Executives about both the tangible and intangible values of such a "$CO_2$-mitigation" collaboration given this particular Decision-Making Mechanism "DMM" tool, for both their corporate micro & macroeconomics, as well as their customers' perception and their corporate stock price/performance in the long run.

On figure 28, there is a real-life case scenario including numerical calculations based on the above decision-making model.

In this numerical case study, there is a corporate value loan of \$600 million with an annual interest rate of 5.75% and 60 monthly installments within a 5-years payment plan. Scope of this model is to demonstrate how ESG incentives may heavily influence the decision-making model from the results of figure's 28 algorithm.

Therefore, we take as input a specific oil-refinery plant emitting annually 3 million tons of $CO_2$. From the total emitted volume of 3 million tons of $CO_2$ the reference company is allowed to freely produce 1 million tons of $CO_2$. The remaining 2 million tons should get acquired through carbon allowances (i.e., mainly through EU ETS).

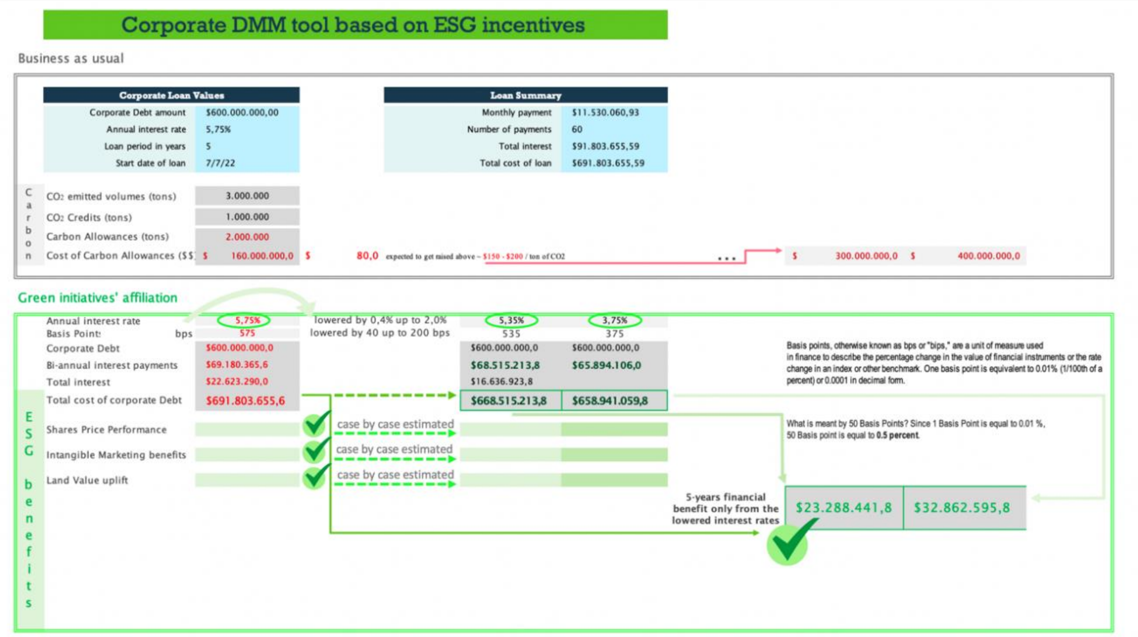


*Figure 28: Numerical calculations based on a case study scenario of the above decision-making model using Microsoft Excel algorithm (Solmeyea Ltd.)*

The price of the carbon allowances is 80\$ /t of CO2 as it is today, but price ranges are expected to reasonably increase up to 150-200\$ / t of CO2 given the rising trend of carbon prices that were presented in Part 3.

Then, on the ESG's incentives basis and taking the difference from a basic scenario (575 basis points and interest rate = 5.75%) with two other scenarios (scenario 1: 535 basis points and interest rate =5.35%, scenario 2: 375 basis points and interest rate = 3.75%) we managed to calculate the substantiated profit ranges.

The utility of the above case study scenario is to demonstrate the five years financial benefit exclusively resulting from the lowered interest rates, leaving room for further calculation of the additional benefits stemming from the Share Price performance, the intangible Marketing benefits, moreover the land value uplift.

In our case, a decision-making model could be composed of certain parameters:

- $CO_2$ emitted volumes – as part of the organizations' growth plan and production or services activity
- $CO_2$ credits – usually defined as is a tradable certificate - a permit that gives the holder the right to emit, over a certain period, carbon dioxide or other greenhouse gases (e.g., methane, nitrous oxide or hydrofluorocarbons)
- Carbon Allowances – bought on a voluntary basis, by any country or company interested in lowering its carbon footprint
- Land Value – the location where this production activity takes place, or any affiliated Land Asset that could serve the needs of $CO_2$ offsetting activities
- ESGs – Environmental, Social, and corporate Governance is an approach to evaluating the extent to which a corporation works on behalf of social goals that go beyond the role of a corporation to maximize profits on behalf of the corporation's shareholders
- Basis Points (BPS) – a common unit of measure for interest rates and other percentages in finance. One basis point is equal to 1/100th of 1%, or 0.01%, or 0.0001, and is used to denote the percentage change in a financial instrument
- Corporate bond / debt – usually issued by a corporation in order to raise financing for a variety of reasons such as to ongoing operations, M&A, or to expand business. The term is usually applied to longer-term debt instruments, with maturity of at least one year
- Share Price Performance – usually denotes the increase in the market price or Fair Market Value of the Common Stock or the increase in the price (or effective price) at which the Company sells shares of Common Stock
- Intangible marketing – the ability of a consumer to preassess the value of using a service or expressing positive comments about a corporate culture. Unlike a physical product, a service cannot be seen, tasted, felt, heard, or smelled prior to its purchase
- Local, national and EU GDP strengthening – a common unit of measuring the economic growth and progress, locally, nationally and internationally.

## 6. Results-Conclusions and CCUS comparison discussion

CCUS comparison is a challenging task since it needs to be adapted every time to the data and geographical characteristics of its respective areas of applications. In this paper we covered most of the following types of CCUS applications as the latter are summarized in figure 29.

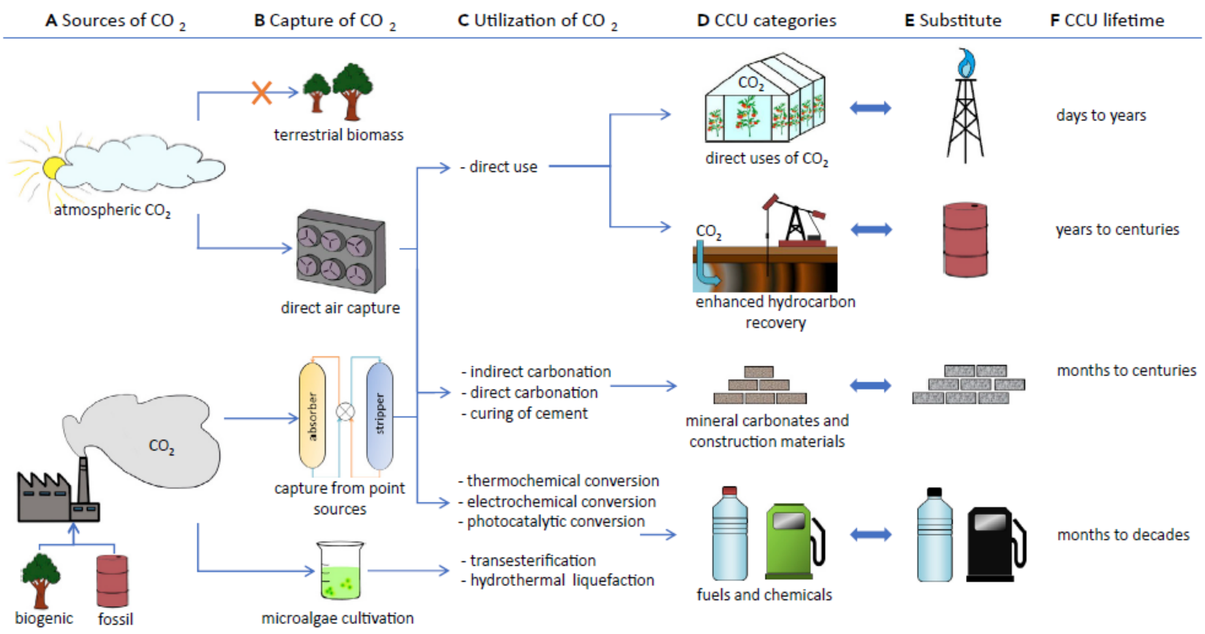


*Figure 29: An overview of CCUS most covered in this paper (de Kleijne, et al., 2022)*

In comparing CCS with CCU De Kleijne and his team (de Kleijne, et al., 2022) showed that per ton of $CO_2$ captured, CCS results in lower emissions than CCU. Although capture emissions are the same, emissions for compression and injection of $CO_2$ in geological formations are lower than most CCU technologies' emissions from conversion and ultimate release of $CO_2$. Based on this, only CCU technologies with low conversion emissions and permanent storage could compete with CCS. Although the avoided emissions of the product that CCU replace are not taken into account, De Kleijne is of the opinion that including these could still lead to the conclusion of higher ultimate emissions. So, in order to deal with residual flows containing $CO_2$ from essential industries as long as they exist, further research could focus on systematic comparison of CCS and CCU technologies in light of their product specific substitutes (de Kleijne, et al., 2022).

However, in comparing CCS and CCU applications geographic and geological limitations must be first taken into account. All CCS and CCU technologies are not compatible in every place in the world.

For instance, Greece is notorious for its intense seismic activity which makes very difficult the implementation of any CCS technology which involves permanent storage underground by mineralization of the injected carbon, because the risk of leakage during an earthquake is judged to be too high. So, in other words the most advanced companies in the field of CCS and DACC technologies; Climeworks and Carbon

Engineering can't operate easily in Greece due to an inelastic geological constraint. Therefore, Greece's innovation promoters in carbon removal solutions should mainly examine activities that involve CCU and thus invalidating their comparison with CCS.

The above geological limitation was important to be mentioned because it demonstrates that before any comparison really happens between CCS and CCU on the criteria discussed in Parts 1&2 the area of implementation plays a defining role on the variety of carbon removal solutions that are to be promoted. Also, it demonstrates the importance of funding further research on CCUS technologies since it's almost certain that none CCUS application will prove the winner in every area of the world. So, all carbon removal options must be examined and supported.

For CCU technologies the most promising ones that can compete with DAC in general are those that are Paris compatible in 2030. In order to be compatible with Paris Agreement a CCU technology mainly needs to have low GHG emissions from $CO_2$ capture and conversion, replace a GHG-intensive-substitute, and in most cases lead to permanent storage (de Kleijne, et al., 2022).

Now, summing up on the parameters that influence the financial viability and the profitability of CCUS we came up to the conclusion that it is extremely rare any firm or application in such an innovative scientific field to be able to be financed exclusively through equity and its own revenue streams. Subsidies and external funding are necessary for the early stages of a CCUS implementation. These early stages may include 2 up to 5 years of continuous financial support. The point that will define the closure of the need for external funding depends on the progress of the technology on this scientific field and the urgency of addressing climate change that will be reflected through laws and initiatives that promote CCUS applications.

However, as we demonstrated in this paper there is no excuse of a hold status for CCUS applications until they become financially sustainable by their own means given the severity of climate change on recent years. On the contrary, an initial subsidy for start-up applications of CCUS may lead the technology to mature in a faster way than would otherwise.

Through this diploma thesis, we came across with the main opportunities that influence positively the expansion of these CCUS applications. These opportunities are based on the will of the society and climate officials to promote activities that will contribute to the mitigation of climate change. These opportunities that we concluded can be summarized through the following points:

a. Legal and Economic environment (Decarbonization laws across Europe, EU ETS mandatory emission reduction directive, Voluntary Carbon Offset Markets)
b. Promotion of circular economy (making value from waste, $CO_2$ usage as a feedstock)
c. Contribution in global sustainable environmental longevity (benefits from the operation of CCUS, they may serve most of SDG's goals)
d. Public awareness about the severity of climate change

From all the above we could argue that the promotion of the contribution of CCUS in the fight against climate change and the public awareness about this problem and about the need for circular economies will drive the legislators through laws or through the anticipated tightening of EU ETS to make at least Europe a region with great investment opportunities in this field of operations. So, we can conclude that we expect financial opportunities to increase for CCUS compared to the current situation.

On the other hand, through this paper, we came also across with the main challenges that influence inhibitory the expansion of the well-known CCUS applications that we covered before. These challenges are mainly based on the juvenileness of the technology of carbon removal solutions that require in their beginnings a lot of resources. These challenges that we concluded can be summarized through the following points:

a. Low technology readiness (i.e., absence of scalability in most cases) that leads to no sustainable operational costs by their own means (i.e., levelized cost (€/t of $CO_2$) too high in the current situation to reach breakeven through their own revenue streams (i.e., income from trading carbon allowances in EU ETS, income from trading final outputs produced, income from trading $CO_2$ feedstock))
b. Possible need for creating new infrastructure for the implementation of some CCUS
c. High re-emission $CO_2$ percentage from LCA in some CCUS options which cancels out the benefits of implementation
d. Not inclusion yet of CCU from EU ETS (only CCS are included)
e. Absence of sufficient directives that will verify, evaluate, and persuade investors on a legal basis about the benefits from funding CCUS activities

From the above challenges the most severe according to author's opinion is the last point. That is because day after day as the technology matures levelized costs will be driven down and more efficient ways of implementing these CCUS applications will be invented without the need for new infrastructure or high energy conversion processes. However, the absence of transparency platforms and directives from independent organizations, as it is today, about the evaluation of the best possible CCUS options in every region hamper the gaining process of the confidence of the public on the beneficial of these projects and via this way hampers the acceleration on implementing these projects independent of the level of the technology readiness of each project.

Concerning now the selection process of promoting and funding a specific CCUS, as it is the case for the latter to start operations, in this diploma thesis we came up with some important criteria that will define the application that will prevail eventually in this selection process. We distinguished these criteria in Parts 1&2 on the comparison between CCS vs CCS applications and CCU vs CCU applications exclusively. The same in a more general manner apply also for the selection process between CCS vs CCU. These criteria can be summarized in the following points.

a. Geographic and Geological constraints (e.g., case of Greece with intense seismic activity)
b. Technology Readiness (i.e., scalability of CCUS implementation)
c. Capital and operating expenditures and Revenue streams
d. Quality and quantity of the benefits from each CCUS implementation (i.e., how much a CCU contributes to climate change mitigation)
e. Achievement of some SDG’s (i.e., quality of final products for CCU technologies)
f. Public acceptance and support (i.e., individuals, energy-intensive industries, companies, and governments)
g. Targeted and successfully executed decision making model

As we have presented in this paper there are CCUS that excel in some of the above criteria and fall behind in others. Of course, the selection process of the best CCUS is not straightforward based on the above criteria since not one application excels simultaneously in all of them. From what we have presented so far, we have advocated that Climeworks has the highest technology readiness and public acceptance, direct uses of $CO_2$ have the lowest capital and operating expenditures and Solmeyea followed by LanzaTech and e-fuels making serve the most SDG’s and share the best quality and quantity of environmental benefits if done in an efficient way. On the other hand, we have advocated that direct uses of $CO_2$ have by far the lowest quality and quantity of environmental benefits together with no goal achievement from the SDG’s. Finally, we could argue that due to the newness of the technology Solmeyea has the least technology readiness until now.

Concerning the targeted executed decision-making model, as we have presented in Part 5, it is not influenced only by the quality of work that is done from a CCUS entity and the amount of marketing promotion that is receiving. The political and social environment needs also to be positively inclined to the respective application in order to put the pressure on the decision makers to argue to finance it. So, the tangible and intangible incentives play a decisive role on putting the pressure on heavy industries, notorious for emitting large quantities of $CO_2$ in the atmosphere, to understand how they are better off internally by funding CCUS applications.

All in all, scope of this paper is not to judge which CCUS technology is found to be the best according to the author’s point of view. However, it is important each decision unit to be aware of the criteria that a CCUS needs to meet and improve according to each region’s needs. To conclude a CCUS entity that decides to go to business its carbon removal solution should be aware that the percentage of meeting the above selection criteria are probably going to define its financial future viability and that they should invest in research and resources to try optimizing them in order to be in a great place to attract investors. Challenges are there but the existing urgency and the opportunities are capable to transform carbon removal markets in an area of very interesting and beneficial economical activities that will involve would-be start up carbon removal firms in a vast and constantly discussed market in the near future.

## Epilogue

In this diploma thesis the most important technologies of carbon dioxide capture and utilization were examined. Undoubtedly, these technologies under the right circumstances can contribute significantly to the reversal of the climate change problem by complying with the technological requirements of our days.

Their comparison and the selection of the most suitable one for wide promotion became impossible to be judged as a safe conclusion, since the requirements of the place and the society in which the latter will operate favor different optimal technologies each time. This leads to the conclusion that such innovative technologies should all be supported both at university and at industry level, given the juvenileness of their maturity as business activities where no one will know which will ultimately prove to be the most appropriate.

From their side, these technologically innovative ideas should decisively support both their business model and their intended tangible and intangible benefits, so that they will be able to take advantage of the economic and legal environment of the coming years which is judged to be very favorable for their development.

Closing this paper, it is important to emphasize that beyond the scientific results and the continuous effort to improve the existing technologies, analyzed in this thesis, additional external effort is needed for their further expansion. The cultivation of environmental sensitivity in schools and the promotion of the severity of climate change problem by institution and non-governmental organizations, as well as, the adoption of clear sponsoring criteria of carbon removal solutions that will inspire confidence in the society that are being done for their benefit are vital in order to create the conditions at the society level that will allow such healthy innovative ideas to thrive at operational level and deliver their benefits for the longevity and sustainability of humanity.

# Επίλογος

Στην παρούσα διπλωματική εργασία εξετάσθηκαν οι σημαντικότερες εφαρμογές δέσμευσης και αξιοποίησης διοξειδίου του άνθρακα. Κατέστη εμφανές, ότι οι συγκεκριμένες τεχνολογίες κάτω από τις κατάλληλες συνθήκες μπορούν να συνεισφέρουν σημαντικά στην αναστροφή του προβλήματος της κλιματικής αλλαγής με την συμμόρφωσή τους στις τεχνολογικές απαιτήσεις των ημερών μας.

Η σύγκρισή τους και η επιλογή της καταλληλότερης για ευρεία προώθηση κατέστη αδύνατο να εξαχθεί σαν ασφαλές συμπέρασμα καθώς οι απαιτήσεις του τόπου και της κοινωνίας στην οποία η τελευταία θα δραστηριοποιείται προκρίνουν διαφορετικές βέλτιστες τεχνολογίες κάθε φορά. Κάτι τέτοιο οδηγεί στο συμπέρασμα ότι τέτοιες καινοτόμες τεχνολογίες πρέπει να υποστηρίζονται όλες και ταυτόχρονα τόσο σε πανεπιστημιακό επίπεδο όσο και σε επίπεδο βιομηχανίας δεδομένου της νεότητας της ωρίμανσης τους σαν επιχειρηματικές δραστηριότητες όπου κανείς δεν θα γνωρίζει ποια εν τέλει θα αποδειχτεί η καταλληλότερη.

Από την μεριά τους οι καινοτόμες αυτές τεχνολογικά ιδέες, θα πρέπει να στηρίξουν καταλυτικά τόσο το επιχειρηματικό τους μοντέλο όσο και τα επιδιωκόμενα υλικά και άυλα οφέλη τους ώστε να μπορούν να είναι σε θέση να εκμεταλλευτούν το οικονομικό και νομικό περιβάλλον των επόμενων χρόνων το οποίο κρίνεται πολύ ευνοϊκό για την ανάπτυξη τους.

Κλείνοντας όμως είναι σημαντικό να τονιστεί ότι πέρα από τα επιστημονικά συμπεράσματα και την συνεχή προσπάθεια βελτίωσης των υπαρχουσών τεχνολογιών που αναφέρθηκαν σε αυτή την εργασία χρειάζεται και επιπλέον εξωγενής προσπάθεια για την ανάπτυξή τους. Η καλλιέργεια περιβαλλοντικής συνείδησης στα σχολεία και η προώθηση από μεριάς θεσμών και μη κυβερνητικών οργανισμών της κρισιμότητας του προβλήματος της κλιματικής αλλαγής ,όπως επίσης και της προώθησης σαφών κριτηρίων χρηματοδότησης τεχνολογιών απομάκρυνσης διοξειδίου του άνθρακα που θα εμπνεύσουν με εμπιστοσύνη την κοινωνία ότι γίνονται προς όφελός της είναι ζωτικής σημασίας με στόχο να δημιουργηθούν οι προϋποθέσεις σε επίπεδο κοινωνίας που θα επιτρέπουν σε υγιείς τέτοιες καινοτόμες ιδέες να ευδοκιμήσουν σε επιχειρησιακό επίπεδο και να προσφέρουν τα οφέλη τους για την μακροζωία και βιωσιμότητα της ανθρωπότητας.

## References


1) (BCG), B. C. G., 2021. *BCG's Net-Zero Strategy.* [Online]
Available at: https://www.bcg.com/about/net-zero

2) (EASAC), E. A. S. A. C., 2018. Negative emissions technologies: What role in meeting Paris Agreement targets?. *Easac*, February, pp. 1-45.

3) (IPCC), I. P. f. C. C., 2021. *Chapter 4: Future global climate: scenario-based projections and near-term information ,* s.l.: s.n.

4) (TNO), N. O. f. A. S. R., n.d. *Transition to E-Fuels: A Strategy For HIC Rotterdam.* [Online]
Available at: https://www.tno.nl/en/focus-areas/energy-transition/roadmaps/towards-co2-neutral-industry/biomass-to-fuels-and-feedstock/transition-to-e-fuels-a-strategy-for-hic-rotterdam/

5) Administration, U. E. I., 2019. International Energy Outlook 2019.

6) Aulet , B., 2017. Determine The Customer's Decision-Making Unit (DMU). In: *Disciplined Enterpreneurship.* New Jersey: s.n., p. 10.

7) Azarabadi, H. & Lackner, K., 2019. A sorbent-focused techno-economic analysis of direct air capture. *Elsevier*, 14 May, pp. 1-17.

8) Bowker, M., 2019. Methanol synthesis from CO2 hydrogeneration. *ChemCatChem 11*, pp. 242-250.

9) Breyer, C., Fasihi, M. & Aghahosseini, A., 2019. Carbon dioxide direct air capture for effective climate change mitigation based on renewable electricity: a new type of energy system sector coupling.Mitigation and Adaptation Strategies for Global Change. *SpringerLink*, 13 February, pp. 43-65.

10) Catalysts, F. o., 2021. Twelve and LanzaTech partner to transform CO2 into polypropylene. *Elsevier* , November.

11) CNN, G., n.d. *Δακτύλιος στην Αθήνα: Μόνο ηλεκτρικά αυτοκίνητα θα εξαιρούνται του μέτρου.* [Online]
Available at: https://www.cnn.gr/ellada/story/284776/daktylios-stin-athina-mono-ta-ilektrika-aytokinita-tha-exairoyntai-toy-metroy
[Accessed 2021 October 2021].

12) Commission, E., 2022. *Carbon capture, use and storage.* [Online]
Available at: https://ec.europa.eu/clima/eu-action/carbon-capture-use-and-storage_en

13) Commission, E., 2022. *Development of EU ETS (2005-2020),* Brussels : s.n.

14) Commission, E., 2022. *EU Emission Trading System (EU ETS).* [Online]
Available at: https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets_en

15) Commission, E., n.d. *Questions and Answers - Emissions Trading – Putting a Price on carbon.* [Online]

Available at:
https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_3542
[Accessed 24 July 2021].

16) Cooke, C., 2021. Direct Air Capture & Negative Emissions. pp. 1-3.

17) Daniel, T. et al., 2021. Techno-economical Analysis of Direct Air Carbon Capture with CO2 Utilisation. *Elsevier*, 17 December, pp. 1-10.

18) de Kleijne, K. et al., 2022. Limits to Paris compatibility of CO2 capture and utilization. *One Earth*, 18 February, pp. 168-186.

19) Favasuli, S. & Sebastian, V., 2021. Voluntary carbon markets: how they work, how they're priced and who's involved. *S&P Global Commodity Insights* , 10 June.

20) Ferioli, F., Schoots, K. & van de Zwaan , 2009. Use and limitations of learning curves for energy technology policy: A component-learning hypothesis. *Energy Policy* .

21) Formula1, n.d. *How formula 1 will lead the charge to use biofuels.* [Online]
Available at: https://www.formula1.com/en/latest/article.how-formula-1-will-lead-the-charge-to-use-biofuels.lxWqy8GilwwMBsjKyPiFf.html#:~:text=F1%20already%20uses%20biofuels%2C%20but,to%20100%25%20advanced%20sustainable%20fuels.
[Accessed 22 November 2019].

22) Guerra, K., Haro, P., Gutierrez, R. & Gomez-Barea, A., 2022. Facing the high share of variable renewable energy in the power system: Flexibility and stability requirements. *Elsevier*, 22 January, pp. 1-18.

23) Gutknecht, V. et al., 2018. *Creating a carbon dioxide removal solution by combining rapid mineralization of CO2 with direct air capture.* Reykjavik, International Carbon Conference.

24) Hansen, J. et al., 2008. Target Atmospheric CO2: Where Should Humanity Aim ?. pp. 1-20.

25) Jones, B. A., 2021. Planting urban trees to improve quality of life? The life satisfaction impacts of urban afforestation. *Elsevier*, 13 February, pp. 1-11.

26) Judge, P., 2021. *Data Center Dynamics.* [Online]
Available at: https://www.datacenterdynamics.com/en/news/climeworks-opens-the-worlds-largest-carbon-capture-facility-in-iceland/#:~:text=Climeworks%20hopes%20to%20reduce%20the,of%20around%20%2475%20per%20ton.
[Accessed 9 September 2021].

27) Kaithwas, A., Prasad, M., Kulshreshtha, A. & Verma, S., 2012. Industrial wastes derived solid adsorbents for CO2 capture: A mini review. *Elsevier*, October, pp. 1632-1641.

28) Keith, D., Holmes, G., Angelo, D. S. & Heidel, K., 2018. A Process for Capturing CO2 from the Atmosphere. *Joule*, 15 August, pp. 1573-1594.

29) Kenyon, D., 2015. The technologies behind carbon utilization. *Global CCS Institute*, 21 May, pp. 1-4.

30) Lackner , K., Grimes, P. & Ziock, H., 1999. Carbon dioxide extraction from air: Is it an option? Proceedings of the 24th International Conference on Coal Utilization & Fuel Systems.

31) Lackner, K. et al., 2012. The urgency of the development of CO2 capture from ambient air. *Pnas*, 14 August, pp. 1-7.

32) Maghzian, A., Aslani , A. & Zahedi, R., 2022. Review on the direct air CO2 capture by microalgae: Bibliographic mapping. *Elsevier*, 10 February, pp. 3337-3349.

33) Melo , J., Ribeiro, M., Telles, T. & Amaral, H., 2022. Microalage cultivation in wastewater from agricultural industries to benefit next generation of bioremediation: A bibliometric analysis. *Science and Pollution*.

34) Melzer, L., 2012. Carbon Dioxide Enhanced Oil Recovery (CO2 EOR): Factors involved in Adding Carbon Capture, Utilization and Storage (CCUS) to Enhanced Oil Recovery.. *Center for Climate and Energy Solutions*, pp. 1-17.

35) Nations, U., 2022. *The SDGS in action.* [Online]
Available at: https://www.undp.org/sustainable-development-goals?utm_source=EN&utm_medium=GSR&utm_content=US_UNDP_PaidSearch_Brand_English&utm_campaign=CENTRAL&c_src=CENTRAL&c_src2=GSR&gclid=CjwKCAjwkYGVBhArEiwA4sZLuJiGO3VsajQpH8NehUiqb3BNXXetKJNR_QqZuRw4ww8-EKa7gvfCIh

36) Nemet, G., 2006. Beyond the learning curve: Factors influencing cost reductions in photovoltaics. *Energy Policy*.

37) Oliveira, T., Varum, C. & Botelho, A., 2018. Wind power and CO2 emissions in the Irish marke. *Elsevier*, pp. 1-11.

38) Oreggioni, G., Luberti , M. & Tassou , S., 2019. Agricultural greenhouse CO2 utilization in anaerobic-digestion-based biomethane production plants: a techno-economic and and environmental assesment and comparison with CO2 geological storage. *Energy Appl.*, pp. 1753-1766.

39) Org, E.-C., n.d. *The latest data on EU ETS carbon prices.* [Online]
Available at: https://ember-climate.org/data/data-tools/carbon-price-viewer/
[Accessed 9 May 2022].

40) Peters , R. et al., 2022. A Techno-Economic Assessment of Fischer–Tropsch Fuels Based on Syngas from Co-Electrolysis. *Processes*, 4 April, pp. 1-42.

41) Pietzcker, R., Osorio, S. & Rodrigues , R., 2021. Tightening EU ETS targets in line with the European Green Deal: Impacts on the decarbonization of the EU power sector. *Applied Energy* , 26 April, pp. 1-18.

42) Platform, E. Z. E. T. &. I., 2022. *Why CCS,* Brussels: s.n.

43) Platts, S. G., 2022. *Carbon Credits ,* s.l.: s.n.

44) Ramirez, A., Sarathy, S. M. & Gascon , J., 2020. CO2 Derived E-Fuels: Research Trend, Misconceptions, and Future Directions. *Reviews CellPress*, September, pp. 785-795.

45) Roberts, D., 2019. Could squeezing more oil out of the ground help fight climate change?. *Vox.*

46) Royal Society & Royal Academy of Engineering, 2018. Greenhouse gas removal. 12 September, pp. 1-136.

47) Sanchez, C., 2021. Analyzing Carbon Offset Markets' role in our journey to a net-zero world. *Smart Sustainability* .

48) Santos, R., Sgouridis, S. & Alhajaj, A., 2021. Potential of CO2-enhanced oil recovery coupled with carbon capture and storage in mitigating greenhouse gas emissions in the UAE. *Elsevier*, 11 October , pp. 1-12.

49) Serre, C., 2015. Rationale for ETS & Overview of state of ETS worldwide. *ICAP,* p. 26.

50) Sigfusson, B. et al., 2018. Reducing emissions of carbon dioxide and hydrogen sulphide at Hellisheidi power plant in 2014-2017 and the role of Cardfix in achieving the 2040 Iceland climate goals. *Energy Procedia*.

51) Society, A. P., 2011. Direct Air Capture of CO2 with Chemicals: A Technology Assessment for the APS Panel on Public Affairs.

52) Solmeyea, 2019. *Home Solmeyea.* [Online]
Available at: https://solmeyea.com/

53) Solmeyea, 2022. *Goals.* [Online]
Available at: https://solmeyea.com/goals/

54) Statista, 2021. *Distribution of electricity generation in Greece in 2021.* [Online]
Available at: https://www.statista.com/statistics/1235419/greece-distribution-of-electricity-production-by-source/#:~:text=Power%20production%20breakdown%20in%20Greece%202021%2C%20by%20source&text=In%202021%2C%2035.8%20percent%20of,electricity%20production%20was%20rene

55) Sun, X., Dong, Y., Wang, Y. & Ren, J., 2021. Sources of greenhouse gas emission reductions in OECD countries; Composition or technique effects. *Elsevier*, 24 November, pp. 1-12.

56) Usman, Iskandar, Sugihardjo & Lastiadi , H., 2014. A systematic approach to source sink matchnig for CO2-EOR and sequestration in South Sumatera. *Energy Procedia* .

57) Wartmann, S., Groenenberg, H. & Brockett, S., 2009. Monitoring and reporting of GHG emissions from CCS operations under the EU ETS. *Energy Procedia*, pp. 4459-4466.

58) Zepos & Yannopoulos, 2022. Greece's first Climate Law | A roadmap to carbon neutrality. *Newsletters - Energy,* p. 1.

59) Αραβώσης, Κ., Καρμπέρης, Α. & Σωτήρχος , Α., 2011. *Τεχνικοοικονομική Αξιολόγηση Επενδύσεων.* Αθήνα: Νομική Βιβλιοθήκη.

60) Καρέλλας , Σ. & Κακαράς , Ε., 2021. *Αντιρρυπαντική Τεχνολογία Θερμικών Σταθμών.* 1 ed. Αθήνα : Τσότρας.

61) Ρακόπουλος , Κ. & Χουντάλας , Δ., 1998. *Καύση - Ρύπανση Εμβολοφόρων Μ.Ε.Κ..* Αθήνα : Φούντας .