UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO

FACULTAD DE INGENIERÍA

Exploring the viability of carbon reduction technologies in Mexico: a comparative study

TESIS

Que para obtener el título de

Ingeniero Petrolero

P R E S E N T A

Alejandro Gutiérrez Mercado

DIRECTORA DE TESIS

Dra. Ana Paulina Gómora Figueroa

Ciudad Universitaria, Cd. Mx., 2025

PROTESTA UNIVERSITARIA DE INTEGRIDAD Y HONESTIDAD ACADÉMICA Y PROFESIONAL
(Titulación con trabajo escrito)

De conformidad con lo dispuesto en los artículos 87, fracción V, del Estatuto General, 68, primer párrafo, del Reglamento General de Estudios Universitarios y 26, fracción I, y 35 del Reglamento General de Exámenes, me comprometo en todo tiempo a honrar a la institución y a cumplir con los principios establecidos en el Código de Ética de la Universidad Nacional Autónoma de México, especialmente con los de integridad y honestidad académica.

De acuerdo con lo anterior, manifiesto que el trabajo escrito titulado EXPLORING THE VIABILITY OF CARBON REDUCTION TECHNOLOGIES IN MEXICO: A COMPARATIVE STUDY que presenté para obtener el titulo de INGENIERO PETROLERO es original, de mi autoría y lo realicé con el rigor metodológico exigido por mi Entidad Académica, citando las fuentes de ideas, textos, imágenes, gráficos u otro tipo de obras empleadas para su desarrollo.

En consecuencia, acepto que la falta de cumplimiento de las disposiciones reglamentarias y normativas de la Universidad, en particular las ya referidas en el Código de Ética, llevará a la nulidad de los actos de carácter académico administrativo del proceso de titulación.

ALEJANDRO GUTIERREZ MERCADO
Número de cuenta: 419049795

Dedication

This thesis is dedicated to the people who have greatly influenced my path and have always supported me. Their encouragement and wisdom have been the foundation of my growth, both in my studies and personal life. Their belief in me has given me strength during this rewarding journey.

To my family, who have taught me so much and always been there for me. I want to thank my father, **Emilio Alejandro Gutiérrez Molina**, and my mother, **María Araceli Mercado Peralta**, for their guidance and for the important values they have given me, such as hard work, honesty, and the love of learning. Your sacrifices and support have helped me follow my dreams. Thank you for cheering me on through tough times.

To my brother, **Daniel Gutiérrez Mercado**, your support has reminded me how strong family bonds are. Your encouragement has lifted me during hard times and reminded me of the joy we share in our successes. I appreciate the laughter and advice you give me.

To my thesis advisor, Dr. Ana Paulina Gómora Figueroa, thank you for your guidance and patience with this project. Your mentorship has helped me grow as a student and taught me the importance of careful study and exploring new ideas. I am very grateful for your helpful feedback.

To my friends, thank you for standing by me on this journey. You have understood when I was busy with research and reminded me to enjoy life, even during hectic times. Your friendship has made this experience meaningful and full of memorable moments. I feel lucky to have friends who celebrate my achievements with me.

To the Petrobowl Team, you have played a big role in my development and have taught me so much. Your spirit of collaboration and passion for learning have made my experience richer. Our conversations have opened my mind and deepened my commitment to our field.

This thesis is not just my work; it also represents the support and belief of all these wonderful people. Thank you for being part of my journey and for helping me become who I am today.

Table of Contents

Introduction

In recent years, climate change has become one of the most pressing issues our world faces. Record-breaking temperatures, melting ice caps, and devastating natural disasters are several key evidence that the effects of climate change are becoming increasingly severe. The growing global population's unsustainable use of hydrocarbons creates environmental challenges and geopolitical problems that humankind has never seen before. The complexity of climate science and the vast amount of data can also make it challenging for the general public to grasp the issue entirely.

Because of this, it is crucial to understand the science behind climate change and the potential solutions available. By understanding the issues at hand, we can work together to make informed decisions and take meaningful action to mitigate the impacts of climate change.

The transition to a low-carbon economy has become a global priority, with nations striving to meet ambitious climate goals, such as those set by the Paris Agreement, to limit global warming below 2°C above pre-industrial levels. In response to these challenges, CCUS and Negative Emission Technologies (NETs) have gained attention as vital tools for reducing atmospheric CO_2 and

advancing toward net-zero emissions. Despite significant advancements globally, the exploration and deployment of these technologies in Mexico remain limited, creating a gap in understanding their potential contributions to the country's climate strategy.

This research aims to fill some gaps in the literature on NETs due to the lack of comprehensive analysis, research funding, and insufficient exploration of the application of NETs in Mexico to assess the feasibility of implementing NETs and CCUS within Mexico's oil and gas industry, an essential sector to the nation's economy yet mainly responsible for considerable emissions. This research investigates four primary NETs: Bio-Energy with Carbon Capture and Storage (BECCS), Direct Air Capture (DAC), CO_2 Mineralization, and Enhanced Weathering, including the cost analysis, carbon capture efficiencies, energy requirements, land use, and scalability in the context of Mexico's unique environmental, economic, and policy panorama. Thus, this research should significantly impact the understanding of how this could assess the issue of CO_2 emissions by contributing to the academic literature and providing practical guidance for implementation in Mexico and other similar contexts. Given that the primary goal of climate mitigation is to reduce energy sector emissions by 80-100 percent, it is essential to implement a large-scale deployment of low-carbon technologies by 2050, such as Negative Emission Technologies (NETs). [1], [2] This thesis aims to address a significant gap in the literature regarding deploying NETs in Mexico through comparative analysis and case studies. Also, this thesis emphasizes the integration of renewable energy sources, such as biofuels, solar, wind, and green hydrogen, to support NET operations and enhance their effectiveness. By coupling NETs with renewables, the research explores pathways for Mexico to achieve sustainable carbon reduction, aligning with international climate goals. The findings of this research are intended to offer practical insights into the role of NETs within Mexico's energy transition strategy, highlighting the policies and frameworks necessary to facilitate large-scale adoption of NETs and setting a potential model for other emerging economies facing similar challenges.

Chapter I. Theoretical framework

1.1. Climate change

The atmosphere is mainly composed of three gases: Ar (0.93%), O_2 (20.9%), and N_2 (78.1%). The 0.07% missing is mainly composed by other gases such as water vapor (H_2O)[1], carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and carbon monoxide (CO). The 80% of its total mass is contained within the troposphere [3]. These gases trap some of the heat released by the sun, prevent heat from being released out of the atmosphere, and consequently, keep the Earth warm. This process is known as the greenhouse effect[2], and over 80% of the GHGs we produce remain in the atmosphere for hundreds of years. [2]

The ozone layer, in the stratosphere, acts as a protective shield against harmful UV and IR radiation on the Earth's surface. About 50 years ago, it became evident that this protective layer was deteriorating due to chlorofluorocarbons (CFCs), a class of synthetic chemicals emitted mainly by refrigerators and aerosols. This deterioration was caused by excessive chlorine atoms, a byproduct created by the photodissociation of chlorofluorocarbons. [4]. However, since the implementation of the Montreal Protocol in 1987, the use of hydrochlorofluorocarbons (HCFCs) has been successfully reduced by 98% globally compared to 1990. These harmful substances have been replaced with non-ozone-depleting alternatives. As a result, the ozone layer has been repairing itself and is projected to recover fully by the middle of this century. [5]

The term "climate change" commonly refers to the effects associated with global warming due to the Earth's continuous temperature rise. While various factors contribute to this phenomenon, the increasing concentration of greenhouse gases (GHG) in the atmosphere, including carbon dioxide (CO_2), results from producing materials, energy and other goods from fossil fuels. [3] As individuals, we all have a role in reducing these emissions. By making conscious choices in our daily lives, such as using energy-efficient appliances for public transport, changing consumption

[1] Water acts as a feedback mechanism due to its dependency on temperature, as temperature increases, the concentration of water vapor rises, amplifying its' warming effect.
[2] The greenhouse gas effect was first described in 1824 by French physicist Joseph Fourier in a paper delivered to Paris's Académie Royale des Sciences in 1824. [2]

habits, reducing meat consumption, among others; we can contribute to the global effort to combat climate change.

1.2. Natural processes

1.2.1. Carbon cycle

The carbon cycle plays a crucial role in regulating the Earth's temperature, both natural and human activities affect the carbon cycle. The carbon cycle is a series of natural biogeochemical processes that help the Earth balance carbon in the atmosphere, ocean, land, soil, and vegetation. It works by moving carbon between these different reservoirs, where it is stored for varying lengths of time (known as residence time). This carbon takes various forms in each reservoir, such buffered carbonate system in the oceans, organic carbon in algae in the oceans, and in vegetation over land. Carbon exchange has a direct impact on the concentration of CO_2 in the atmosphere, and both land and ocean act as carbon sinks. These natural deposits absorb the CO_2 from the atmosphere, reducing its presence in the air. [6] See Figure 1

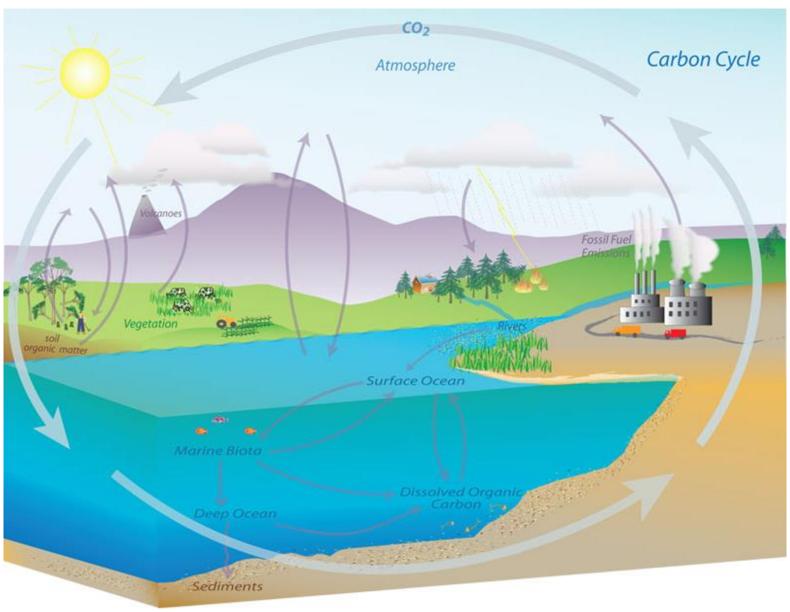

Figure 1. The Carbon Cycle. The carbon moves in and out of the atmosphere, ocean, waterways, and soils through burning fossil fuels, precipitation, fires, vegetation, volcanoes, and organic processes. [7]

These natural sinks are better described as “inadvertent” because they result from fossil fuel consumption and land use. The land sink grows mainly due to CO_2 fertilization of plants and forest regrowth after agricultural abandonment. One example is the Amazon tropical forest, one of the most significant natural carbon sinks on the planet. The vast expanse of jungle in the Amazon basin covers approximately 2.8 million square miles and accounts for over fifty percent of the world's remaining tropical rainforests. It is estimated that the Amazon region holds around 123 billion tons of carbon in both above and below-ground biomass. [8] Annually from 2001-2021, the rainforest has emitted an average of 120 million tons of CO_2e, and has removed 457.9 million tons of CO_2e, this results in an average net flux of 340 million tons of CO_2e stored per year. [9] In comparison, the Alberta Carbon Trunk Line (ACTL), the world's largest CCUS project located in Canada, has the capability to gather, compress, and store up to 14.6 million tonnes of CO_2 per year. [10] A massive difference in storage capability between a CCUS project and a natural sink.

The ocean sink mechanism works by the dissolution of atmospheric CO_2 and carbon gain by phytoplankton. (National Academies of Sciences, Engineering, and Medicine, U.S., 2019) The ocean is estimated to capture around 25 – 30% of anthropogenic CO_2 emissions annually, around 2.66 Gt of CO_2. [12], [13] The natural carbon sinks remove 31% of the carbon dioxide from the atmosphere, leaving a substantial amount to circulate and contribute to the harmful effects of global warming. [14]

One general misconception is that natural sinks will eventually stop absorbing CO_2 and start releasing it when atmospheric CO_2 levels decrease. However, these sinks are expected to continue absorbing CO_2 even during a period of declining atmospheric CO_2. This is due to an imbalance between the amount of CO_2 in the atmosphere and the capacity of these long-lived carbon pools in the ocean and land.

It is helpful to divide the carbon sequestered into two pools based on how long they retain carbon since some quickly reach equilibrium with the atmosphere, while others continue removing CO_2 over the next 10,000 years. This distinction is crucial because it underscores the long-term impact of our actions. Carbon in short-lived pools, such as surface ocean waters and rapidly decomposing land organic matter, fluctuates with atmospheric CO_2 levels. Carbon in long-lived pools, such as deep ocean carbon and woody remains, accumulates over time and responds more slowly to changes in atmospheric CO_2. This distinction affects the associated carbon sink's persistence, especially during declining atmospheric CO_2 concentrations, which is a reminder that our efforts in carbon sequestration have long-lasting effects on the environment.

Atmospheric, terrestrial, and oceanic carbon cycles have dispersed a vast amount of these anthropogenic emissions, locking the CO_2 away by dissolution in the oceans and the long-lived carbon pools in soils.

However, the carbon cycle, which had remained unchanged for thousands of years, has been significantly altered due to increased industrial activity and a rapidly growing population. For instance, changes in land use and management practices have reduced the ability of soils to store carbon in response to higher atmospheric CO_2. Additionally, ocean acidification has diminished the capacity of the oceans to absorb CO_2 from the atmosphere. As a result, natural carbon sinks that previously functioned properly have been impacted by the use of fossil fuels, leading to an accelerated increase in the concentration of CO_2 into the atmosphere. Unfortunately, this situation has worsened since the beginning of the Industrial Revolution. [14], [15]

1.2.2. Global energy and CO_2 emissions

In 2023, domestic fossil fuels[3] produced 88.6% (1.5% coal, 63.3% crude oil and 22.1% natural gas) of the energy used in Mexico collectively; 61% of those 22.1% of the natural gas was used for electricity generation. In contrast with the U.S., fossil fuels generate 81.8% of energy used. In the context of global oil trade dynamics, Mexico occupies a significant position, ranking 5th in crude oil imports and 13th in crude oil exports. [16] Between 2019 and 2023, the total global energy-related emissions surged by a concerning 900 million metric tons[4], reflecting a worrisome trend in environmental impact. [17]

[3] Domestic energy production includes fossil fuels that are drilled and mined for electricity generation or as fuels, along with energy generated from renewable sources. [16]

[4] The significant adoption of five essential clean energy technologies since 2019, such as solar PV, wind, nuclear, heat pumps, and electric cars, has played a crucial role in slowing down the growth of emissions. Without the widespread use of these technologies, the rise in emissions would have been three times greater. [17]

Globally, the energy sector accounts for roughly 34% of global GHG emissions, with the remaining 66% coming from industry, **a**griculture, **f**orestry and **o**ther **l**and **u**ses (AFOLU), transport, and buildings. [18].

It is necessary to recognize that both natural phenomena[5] and human activities also contribute to the emission of greenhouse gases but at lower proportions. Much of the excess in CO_2 emissions is due to increased global energy demand, particularly from high-income and fast-growing economies. At the same time, population growth and accelerated socioeconomic expansion come with significant environmental costs, such as the deterioration of land quality and the degradation of air and water supply. [6] For example, until 2018 China used coal to achieve energy independence. However, this is problematic since this carbon-intensive fossil fuel emits large amounts of CO_2. As of 2023, global energy-related CO_2 emissions increased by 1.1%, rising by 410 Mt[6] to reach a new record high of 37.4 Gt.[7] In comparison, there was an increase of 490 Mt in 2022 (1.3%). Emissions from coal contributed to over 65% of the increase in 2023. [19] See figures 2 and 3.

[5] These natural phenomena can refer to temperature variations due to solar radiation, volcanic eruptions, and the natural carbon cycle.

[6] Mega ton (millions of tons).

[7] Gt stands for Giga ton or billions of tons. This measurement includes CO_2 emissions from energy combustion, industrial processes, and flaring.

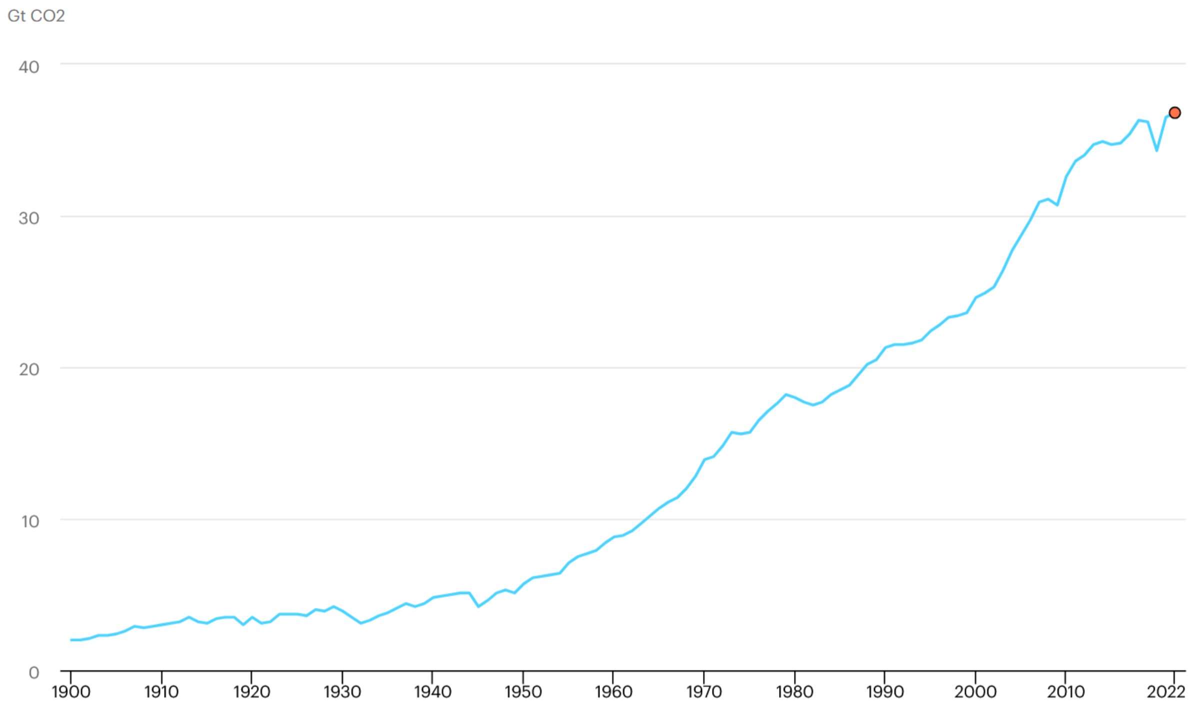

Figure 2. Global CO_2 emissions from energy combustion and industrial processes from 1900-2023, reaching a staggering 37.4 Gt of CO_2 in 2023, the highest recorded that year. (IEA (2024), Total increase in energy-related CO_2 emissions, 1900-2023, IEA, Paris https://www.iea.org/data-and-statistics/charts/total-increase-in-energy-related-co2-emissions-1900-2023, Licence: CC BY 4.0)

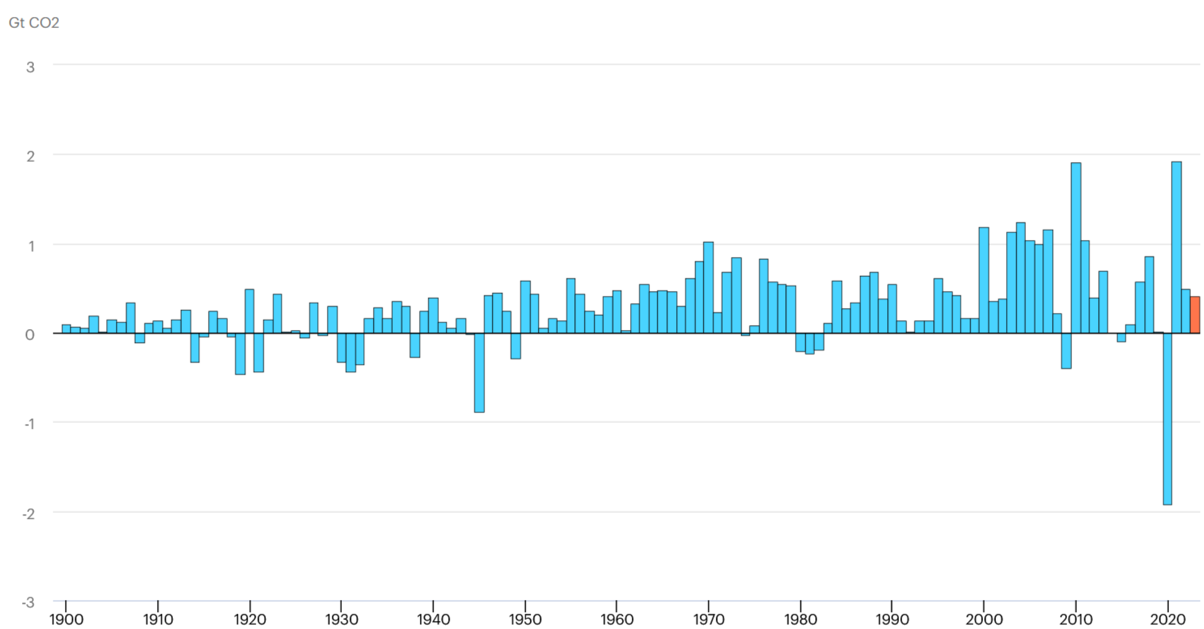

Figure 3. Annual change in energy-related CO_2 emissions, 1900-2023. The energy sector witnessed a historically low CO_2 emissions of -1.92 Gt as a result of the 2020 COVID-19 pandemic, marking the lowest level ever recorded. IEA (2024), Annual change in energy-related CO_2 emissions, 1900-2023, IEA, Paris https://www.iea.org/data-and-statistics/charts/annual-change-in-energy-related-co2-emissions-1900-2023, Licence: CC BY 4.0

Since the COVID-19 pandemics, global CO_2 emissions from energy combustion have increased by approximately 850 Mt, with coal being the largest contributor from 14.4 Gt, it has increased 900 Mt since then. Substantial increases occurred in China and India, partially offset by declines in advanced economies. In 2023, China experienced the largest global increase in emissions at around 565 Mt, reflecting the country's emissions-intensive economic growth in the post-pandemic period. Despite this, China remained a dominant force in global clean energy additions. [17] There is hope in the horizon, as current projections for achieving net zero emissions indicate that the biggest reduction in energy dependency will come from a decrease in the use of coal, reflecting the global shift towards lower carbon fuels. By 2050, coal consumption is expected to be 35 to 85% lower than today. It is important to note that oil demand also depends on road transportation. In fact, due to an increasing trend in the electrification of road transportation[8] in China, oil demand is expected to decline further by 2030. [20], reducing CO_2 emissions even further. See Figure 4

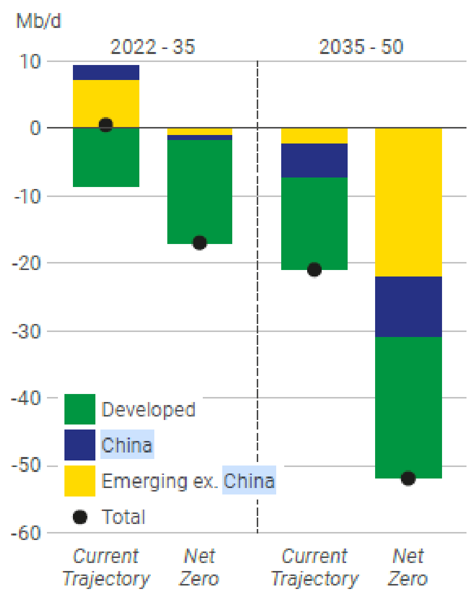

Figure 4. Change in oil demand by region. The graph shows the path that countries are taking to achieve the emissions reductions required to meet the 1.5°C target of the Paris Agreement. The left section illustrates the scenario for 2022-2035, while the right section represents 2035-2050. Achieving Net Zero emissions is the most effective way to rapidly decarbonize. By accelerating this process (Net Zero), we can significantly reduce the demand for oil. This is particularly applicable to China, where the electrification of road transport could expedite this process. [20]

[8] The reduction in oil consumption is primarily driven by the decreased use of oil in road transport, largely due to the increasing adoption of alternative fuels, particularly the electrification of cars and trucks.

In 2020, China's total CO_2 emissions exceeded the combined emissions of all developed countries. See Figure 5. By 2023, China's emissions increased by 15%, and the country alone was responsible for 35% of global CO_2 emissions. Additionally, in 2023, India surpassed the European Union to become the third-largest source of global emissions. Developing Asian countries account for approximately half of global emissions, up from two-fifths in 2015 to one-quarter in 2000, [17] implying that developed countries and developing countries in Asia must reduce global emissions by 40% or up to 70% by 2050. [2, p. 7] However, even if developing countries stop emitting CO_2, it would not be enough to solve the global warming problem. See Figure 6.

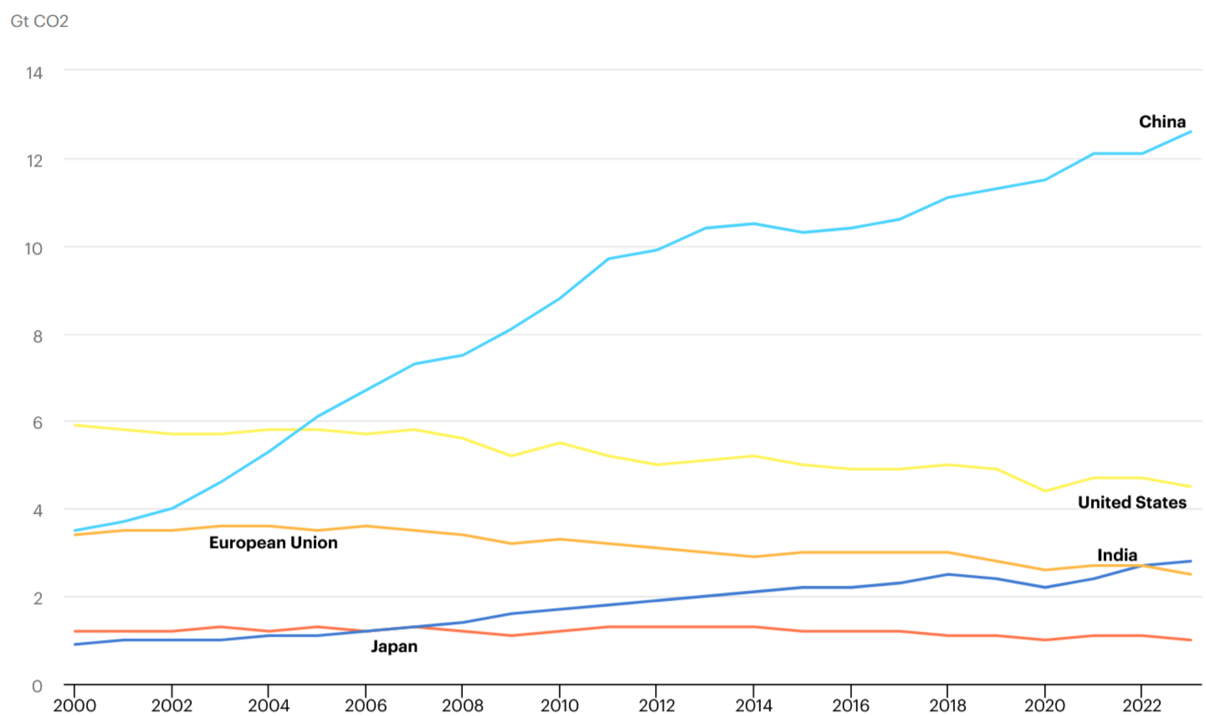

Figure 5. CO_2 total emissions by region, 2000-2023. By comparison, in 2023, China accounted for a total of 12.6 Gt of CO_2 emissions, while the United States accounted for 4.5 Gt of CO_2 emissions. IEA (2024), CO_2 total emissions by region, 2000-2023, IEA, Paris https://www.iea.org/data-and-statistics/charts/co2-total-emissions-by-region-2000-2023, Licence: CC BY 4.0

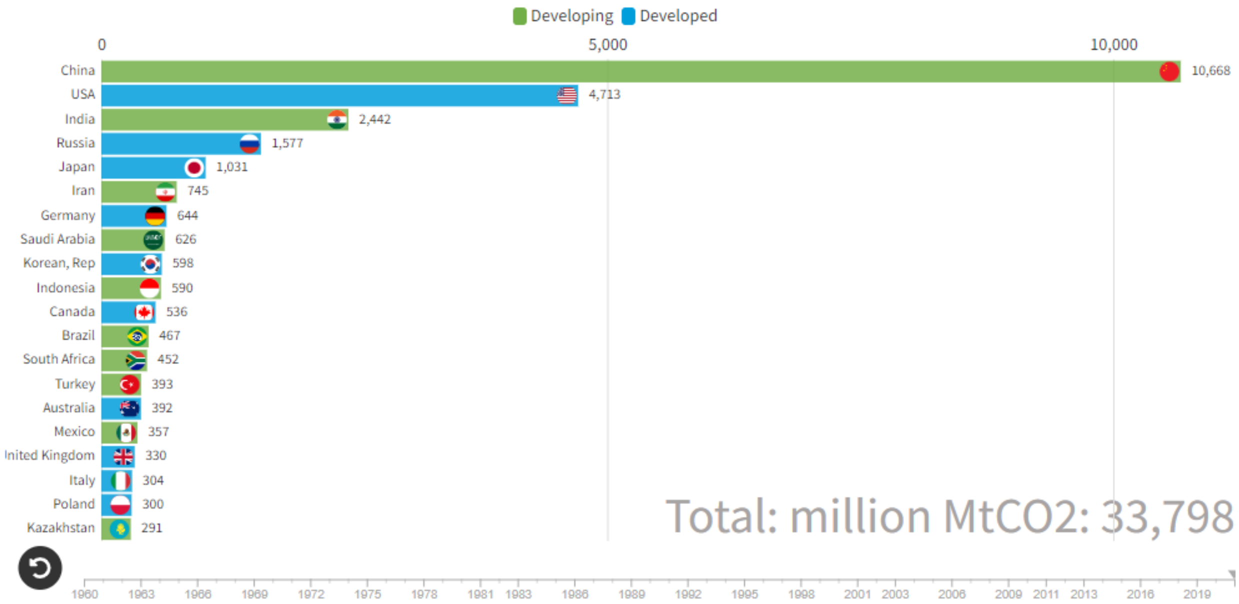

Figure 6. Historical CO_2 accumulation. The image depicts the evolution of global CO_2 emissions from 1960 to 2020. In 2020, more than half of global CO_2 emissions (63%) were from developing countries, with China being the leading developing country. [21]

Note that advanced economies continue to have relatively high per capita emissions, which is 70% higher than the global average in 2023. For instance, India's per capita emissions remain less than half of the global average, at around 2 tons. Per capita emissions in the European Union have fallen strongly and are now only around 15% higher than the global average and around 40% below China's, which per capita emissions exceeded those of the advanced economies as a group in 2020 and their emissions are 15% higher; 2023 represented the first time that they surpassed those of Japan, although they remain one-third lower than those of the United States. [22] See Figure 7.

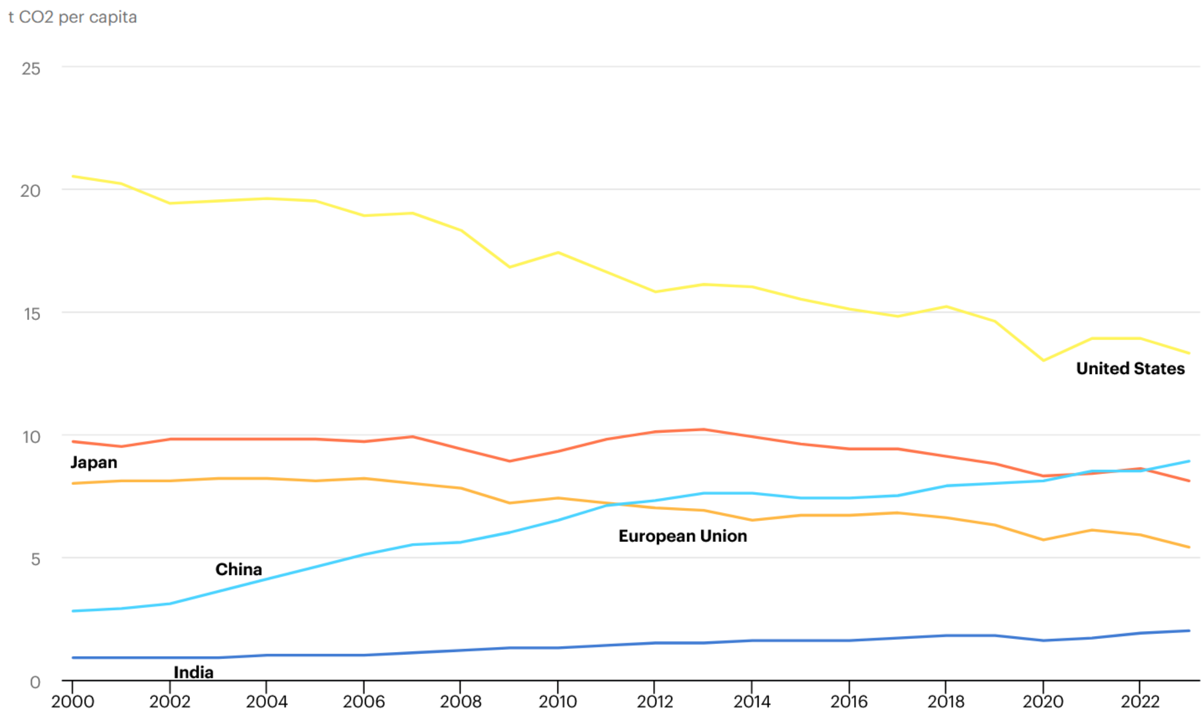

Figure 7. CO2 total emissions per capita by region, 2000-2023. In this comparison, the United States has higher emissions per capita than China. IEA (2024), CO2 total emissions per capita by region, 2000-2023, IEA, Paris https://www.iea.org/data-and-statistics/charts/co2-total-emissions-per-capita-by-region-2000-2023, Licence: CC BY 4.0

In 2019, historical accumulation of atmospheric CO_2 concentrations surged to 410 parts per million (ppm), marking unprecedented levels not observed in the past 2 million years. Additionally, CH_4 reached 1866 parts per billion (ppb), and nitrous oxide (N_2O) reached 332 ppb, surpassing levels recorded in at least 800,000 years. See Figure 8. [18, p. 8]

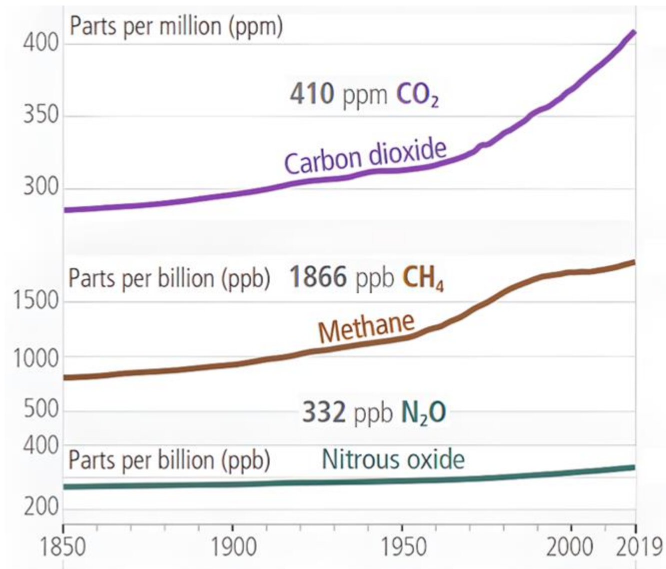

Figure 8. GHG concentrations in the atmosphere from 1850 to 2019. The values have been scaled in order to fit the graph and match their assessed contributions to global warming. Methane is scaled in parts per billion (ppb), having a higher contribution. However, despite this, CO_2 is known to have a greater impact in global warming. (Calvin et al., 2023)

Recordings of CO_2 emissions to the atmosphere come from the Industrial Revolution. 71 % of CO_2 emissions since 1750 come from geologic reservoirs of coal, oil, and natural gas, 2 % come from underground limestone reservoirs used in cement production, and the remaining 27 % originate from terrestrial ecosystems, mainly due to human activities such as deforestation, wetland drainage, and the conversion of forests and grasslands into agricultural lands for crops and pastures [11], which lead to an increase of of CO_2 atmospheric concentration from 280 ppm in 1750 to 427 ppm in 2023, setting a new record of 1.4 °C raise in May of 2024. [23], [24] See Figure 9.

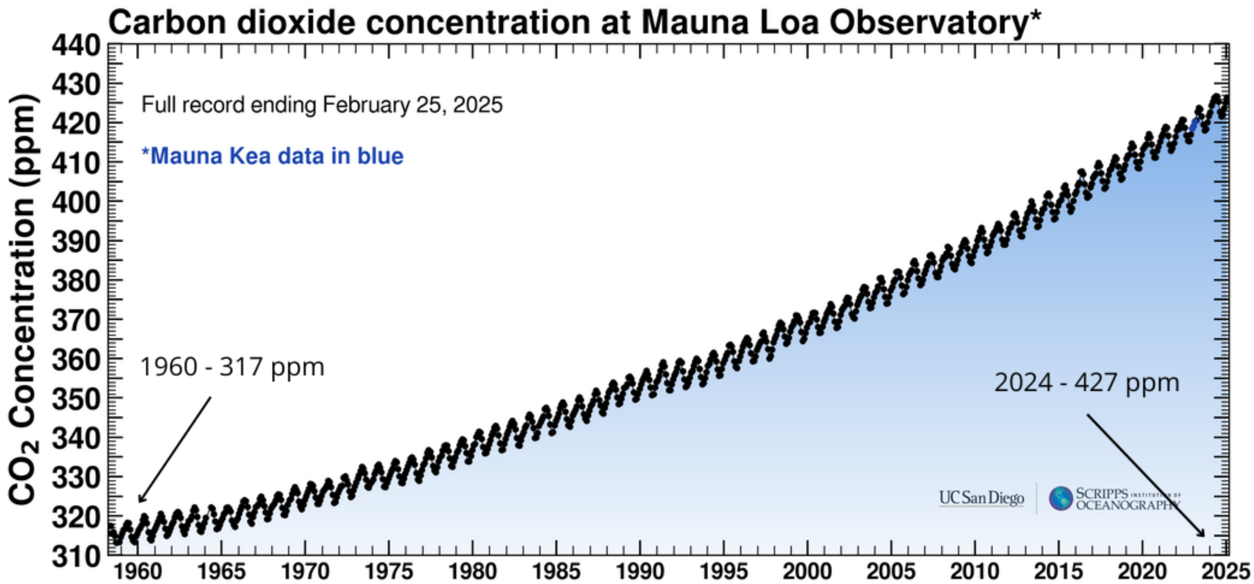

Figure 9. The graph shows the monthly average carbon dioxide measurements since 1958 in parts per million (ppm) recorded at the Mauna Loa Observatory Station, Hawaii, USA. In 1958, the atmospheric CO_2 levels were at 316.43 ppm, and in 2024 it was at 427 ppm, a 110.5 ppm increase in a span of 66 years. The seasonal cycle of highs and lows (small peaks and valleys) is driven by Northern Hemisphere summer vegetation growth, which reduces atmospheric carbon dioxide, and winter decay, which increases it. [24]

1.3. The consequences of climate change

Global warming has the potential to cause damage on a worldwide scale, impacting both population and environmental biomes. Until just a few years ago, we worried about the world in which our children and grandchildren would live. Today, we now face real-time survival conditions. It has led to several severe natural disasters, including increased frequency and intensity of hurricanes, typhoons, and cyclones, as well as more frequent and severe heatwaves, droughts, storms, and wildfires. For instance, in 2024, category 1 hurricane Beryl resulted in at least eight people dead and massive power outages across Texas and Louisiana, USA.[25] California has faced devastating wildfires caused by record-breaking heatwaves that have destroyed homes and natural habitats. On July 2024, there were 18 active wildfires across this state, many of which were still uncontained, Santa Barbara County being one of the most affected, with 26,176 acres (105.9 km^2) burned. [26] Additionally, the iconic Iztaccihuatl glacier Ayoloco in Mexico has completely disappeared due to rising temperatures [27], and hurricanes in Mexico have become more intense, causing widespread destruction and loss of lives. These events are stark reminders of the real and immediate consequences of climate change, for the environment and for human communities.

Scientists expect to see a couple of climate system changes over the next decade or a hundred years. Some rapid changes likely to occur in a decade include vanishing of glacial ice to a considerable extent, the disappearance of ice accumulated for over a year in the Arctic, and vast chances of conifer forests replacing the polar tundra. Some of the slower changes that are likely to occur in the course of the next hundred or thousand years include sea level rise, sudden shifts in the melting designs of the Greenland ice sheets, an increase in the flow of ice streams in Greenland and Antarctica, a considerable hike in the heated amplification of ocean, the vanishing of West Antarctic ice sheet, the acidification of the sea[9] and lastly, the decline of oxygen levels in the ocean. Climate change is having a massive impact on chilly areas like Antarctica and Greenland, where glaciers and snow caps are melting at an alarming rate. [3] In the last 100 years, approximately 50% of coastal wetlands have disappeared due to the detrimental impact of human activity, sea level rise, warming, and extreme climate events. [18] Rapid changes in climatic conditions, which are likely to take place on a massive scale in the near future, remain a troubling issue since the burning question of whether animals and plants can survive and adapt to the fast-changing conditions of the climate remains. Some species may survive, while others might perish under the prevailing climatic changes. [3] For instance, approximately half of the global animal species have already shifted towards the poles and to higher elevations inland. Hundreds of local species have been lost due to these changes. [18] In Mexico, there has been an escalating loss of ecosystems, with the country facing significant challenges in 2024, including persistent droughts and rising temperatures. For example, the state of Yucatán experienced unprecedented heat waves. The National Water Commission (CONAGUA) reported May 26th as the hottest day on record in Mexico, with a temperature of 92.8°F (33.8°C).[29], resulting in the death of howler monkeys in the jungle areas of the states of Tabasco and Chiapas. In the latter state, groups of dead fish were reported floating on the water’s surface in that same month. [30] Climate change inevitably results in changes in ecosystems and social infrastructure at large. Agricultural, coastal, transportation and health infrastructure are all affected by climate change. Furthermore, the only current solution for this is adaptability. In the realm of

[9] Currently, the ocean has absorbed enough CO_2 to lower its pH by 0.1 units, a 30% increase in acidity. [28]

public health, it is important to note that climate change indirectly contributes to the spread of diseases. This is due to its impact on ecosystems and weather patterns, which can affect the distribution and behavior of disease-carrying organisms, such as mosquitoes and ticks. Research indicates that 3.6 billion people currently reside in areas highly susceptible to climate change. It is projected that between 2030 and 2050, climate change will result in approximately 250,000 additional deaths annually, primarily from undernutrition, malaria, and diarrhea. [31] Furthermore, extreme weather events and shifts in temperature and precipitation patterns can affect the availability of clean water and food, leading to malnutrition and the proliferation of waterborne diseases. Dengue fever, for example, is common in tropical and subtropical regions around the world, including Southeast Asia, the Pacific Islands, the Caribbean, and parts of Central and South America. However, due to abundant rainstorms in Mexico, it reported a total of 23,856 confirmed infections in 2024, compared to 5,623 in 2023. The states of Guerrero and Tabasco are the main hotspots and are the most affected. [32] Also, some countries have a minor capability to adapt to climate change; Bangladesh, for example, being an underdeveloped country, is among the countries greatly affected by its vulnerability to rising sea levels. If the sea level rises to only 40 inches, millions of people would be rendered homeless and would have to be displaced. The South Pacific and Indian Ocean islands are very prone to storm surges. Coastal floods affect tourism, affecting the economies of countries that depend on them and local agricultural systems. [3]

Climate change has significant economic consequences, including a decrease in global domestic product (GDP) due to property damage from natural disasters, rising global temperatures, and increased water supply costs. For developing countries, losing 4% of their GDP is particularly challenging. This reluctance explains why many developing nations are hesitant to agree to binding greenhouse gas emission limits. Failing to prevent climate change could potentially result in a loss of up to 20% of global GDP annually. [2]

A study conducted by the Organization for Economic Cooperation and Development (OECD) in 2007 predicted that major cities such as Miami, New York City, Shanghai, and Tokyo could incur significant property losses due to climate change by 2070. The study estimated the losses to be around $3.51 trillion in Miami, $2.15 trillion in New York City, $1.7 trillion in Shanghai, and $1.2

trillion in Tokyo. These staggering figures highlight the potential impact of climate change on some of the world's most populous cities. See Table 1.

Table 1. Cities ranked in terms of values of assets exposed to coastal flooding in 2070. (Hanson, 2010)

Rank	Country	Urban Agglomeration	Exposed Assets Current ($Billion)	Exposed Assets Future ($Billion)
1	USA	Miami	416.29	3,513.04
2	China	Guangzhou	84.17	3,357.72
3	USA	New York-Newark	320.20	2,147.35
4	India	Kolkata (Calcutta)	31.99	1,961.44
5	China	Shanghai	72.86	1,771.17
6	India	Mumbai	46.20	1,598.05
7	China	Tianjin	29.62	1,231.48
8	Japan	Tokyo	174.29	1,207.07
9	China	Hong Kong	35.94	1,163.89
10	Thailand	Bangkok	38.72	1,117.54
11	China	Ningbo	9.26	1,073.93
12	USA	New Orleans	233.69	1,013.45
13	Japan	Osaka-Kobe	215.62	968.96
14	Netherlands	Amsterdam	128.33	843.7
15	Netherlands	Rotterdam	114.89	825.68
16	Vietnam	Ho Chi Minh City	26.86	852.82
17	Japan	Nagoya	109.22	623.42
18	China	Qingdao	2.72	601.59
19	USA	Virginia Beach	84.64	581.69
20	Egypt	Alexandria	28.46	563.28

As our planet continues facing the harsh reality of climate change, the future looks bleak for our coastal communities. By 2070, a staggering 150 million people worldwide will be at risk of coastal flooding. The value of assets at risk could reach $35 trillion, including lives lost and countless displaced people. (Hanson, 2010)

Therefore, to tackle the climate crisis and its effects on the planet, it is mandatory that both developed and developing countries work together to reduce their emissions and apply solutions to this shared problem.

1.4. Politics of climate change

The United Nations Framework Convention on Climate Change (UNFCCC) has made significant progress since its inaugural gathering in Rio de Janeiro in 1992. The Conferences of the Parties

(COP), held annually within this framework, hold a critical role in achieving the UNFCCC's mission of stabilizing greenhouse gas concentrations and preventing detrimental interference with the climate system while facilitating sustainable economic development. As such, the COP is tasked with convening and making vital decisions to fulfill this objective. As of now, the convention has been ratified by 197 countries, which is a testament to the international consensus on how we should tackle the urgent issue of climate change. [33]

Soon after, during the third Conference of the Parties (COP3), the Kyoto Protocol (1997) represented a significant international agreement. This was a substantial turning point in history, as it marked the first instance in which emissions from industrialized nations were limited. Furthermore, it represented the world's first global agreement founded on the creation of a groundbreaking carbon market. This innovative trading market allows for the exchange of public goods or property rights, such as grain, houses, machines, and stocks, in return for the use of the planet's atmosphere. Each trader is held to a set of emission limits, and those who exceed these limits are penalized and must purchase rights from those who remain under the limit, with minimal government intervention. This agreement established a fair carbon price and is currently implemented across four continents. However, the US, the world's second-largest emitter, has yet to ratify this agreement [2]. The Kyoto Protocol has resulted in emission reductions in some countries and has played a key role in developing national and international capabilities for reporting, accounting, and trading greenhouse gas (GHG) emissions. As of 2020, carbon taxes or emission trading systems covered over 20% of global GHG emissions. However, the coverage and prices have not been adequate to achieve significant reductions in emissions. [18]

In 2009, during the COP15 summit held in Copenhagen, an international agreement was achieved for long-term financing to limit the global temperature below 2 ºC compared to pre-industrial levels. It also introduced the concept of Negative Emission Technologies (NETs).[10]

The Paris Agreement adopted under the UNFCCC, was approved on December, 2015 at the COP21 summit and officially implemented in 2016, aiming to create a global strategy for fighting climate change beyond 2020. The long-term goal is to limit the global temperature increase to under 2ºC,

---

[10] NETs were mentioned to be required to avert catastrophic climate change in the IPCC's 5th Assessment Report, in 2013.

with potentially extending the target to 1.5ºC[11]. The agreement requires countries to present regular National Climate Contributions and update them to meet the long-term targets. It also includes provisions for emissions exchanges, advances in carbon pricing schemes, and the creation of a mitigation and sustainable development mechanism. Developed countries are urged to take the lead in providing finance, while other parties are called upon to give voluntary financial support. The agreement includes transparency frameworks and global stocktaking every five years on the implementation of the agreement, that is, ensuring that the Paris Agreement remains on track to achieve its long-term objectives and that countries are held accountable for their commitments under the agreement. It recognizes the need to accelerate the transfer of technology to developing countries and provides measures to establish principles for incentivizing it. The parties are urged to undertake adequate planning and implement measures for adaptation. For developing countries, financial and technical support is necessary to fulfill this task. [33]

In December 2023, 198 parties met to address and negotiate global climate concerns under the Paris Agreement at COP28, held in Dubai, UAE, where the parties agreed to speed up the transition away from fossil fuels to renewables such as wind and solar power since too little progress has been made against climate action, for reducing greenhouse gas emissions, enhancing resilience to a changing climate, and providing financial and technological assistance to vulnerable nations. The progress made in international climate change negotiations is a positive sign that we can work together to protect our planet for future generations. [33]

The International Panel on Climate Change (IPCC)[12], a group of esteemed experts assembled under the United Nations in 1988, evaluates scientific research on climate change, including causes and anticipated consequences. Their projections indicate that to prevent catastrophic temperature increases by the mid-century mark, we must remove more than 10 Gt of CO_2 from our atmosphere each year. If we can meet this objective**,** global temperatures will rise by a manageable 2ºC by 2050. [11] In their latest report of 2023 (AR6), they claim that urgent accelerated action to adapt to climate

[11] Research confirms that the 1.5°C threshold has already been breached, data suggests the global average temperature for 2024 was 1.66°C above pre-industrial levels. [34]
[12] In 1990, the IPCC published its first assessment report on the state of climate change, predicting a significant increase of 0.3 °C (0.54 °F) per decade, which would exceed any temperature rise witnessed in the past 10,000 years. This report played a crucial role in influencing public opinion, leading to a greater understanding of the severity of the climate crisis.

change is essential in order to keep global temperature below 1.5°C required by the Paris Agreement. They require deep, rapid, and sustained greenhouse gas emission reductions across all sectors in order to achieve this goal. By 2030, emissions should be cut by half to maintain the temperature at or below the above mentioned. The report claims that climate change has already caused substantial damages and irreversible losses in terrestrial, freshwater, cryospheric, coastal, and open ocean ecosystems. Also, the extent and magnitude of climate change impacts are more significant than estimated in their previous assessments. [18] Therefore it is encouraging a sustainable development from a political a societal standpoint, sharing of technologies, suitable policy measures, and adequate finance. Every community could reduce or even avoid carbon-intensive consumption if made available now. They introduced Representative Concentration Pathways (RCPs) as scenarios to assess regional climate changes, impacts, and risks. There are 1202 pathways classified according to their estimated global warming over the 21st century. These pathways range from those that aim to limit warming to 1.5°C with over 50% likelihood and no or limited overshoot to those that exceed 4°C. [18]

UN Sustainable Development Goals

The Sustainable Development Goals (SDGs) are a set of 17 global goals adopted by the United Nations General Assembly in 2015 as part of the 2030 Agenda for Sustainable Development. (*Sustainable Development Goals | United Nations Development Programme*, n.d.) The SDGs are a universal call to take action to end poverty, protect the planet, and ensure that all people enjoy peace and prosperity by 2030. The goals are integrated and indivisible, meaning that they are interconnected and should be implemented together as a whole. See Figure 10. While the SDGs made progress in many areas, they were criticized for not being comprehensive enough and for not addressing some of the root causes of poverty and inequality. The SDGs were designed to be more ambitious and to address a wider range of issues, including climate change, gender equality, and sustainable economic growth. The SDGs are a framework for governments, businesses, civil society organizations, and individuals to work together to create a more sustainable and equitable world. [35]

Figure 10. United Nations Sustainable Development Goals (SDGs) [36]

However, efforts to meet these SDGs have been hindered because of reduced food and water security caused by the climate crisis. [18]

For this reason, the international scientific community is warning us that the imminent climate changes are much more severe than Earth is currently experiencing. Scientists predict that if emissions continue to increase at the same rate, the CO_2 levels in 2100 will double and potentially even triple the pre-industrial levels. This alarming projection suggests that we are approaching a point of no return, with changes that will be irreversible for centuries or even millennia. [2]. In 2022 and 2023, some scientists have even claimed that we have already passed the point of no return on reducing climate emissions, pleading on the urgent use of carbon removal technology. [34], [37]. However, others claim this threshold is as close as the year 2035. [38] In light of this, society calls for immediate action to tackle the pressing challenge of climate change and mitigate further harm to our planet.

The cost of mitigating climate change depends on the speed at which we take action. The longer we wait, the more drastic measures we will have to take to reduce emissions of atmospheric CO_2, and mitigation efforts will be inevitably more expensive. Therefore, if we are worried about the expense of preventing climate change, there are better approaches to follow than procrastination. Moreover, we cannot predict with certainty when and which new technologies will emerge. Therefore, avoiding climate change by preserving the planet's climate system makes sense. It is crucial to prioritize keeping the planet's climate system, and we must do so regardless of any uncertainties.

The bottom line is that scientific research backed up by political influence, should deliver its focus on examining the costs of preventing and adapting to climate change with the evaluation of its benefits because slowing down climate change will eventually have some benefits worth achieving. “Adaptation” and “mitigation” methods have been applied to face this problem. Since 2014, government policies have significantly changed to raise awareness about climate adaptation. It has given rise to many development plans, such as preventive measures on coastlines to prevent sea level encroachment and measures to efficiently protect and manage lands and forests, fight water shortage problems, and increase the production of high-yielding and resilient crop plantations.

1.5. Global carbon reduction strategies: Carbon management, renewable energies and hydrogen fuel

It is important to consider both short-term and long-term approaches to addressing the climate crisis. Short-term solutions for reducing carbon emissions include carbon removal and storage technologies, which involve capturing carbon dioxide emissions from sources like power plants and either storing them underground or converting GHG into other useful products to prevent them from entering the atmosphere. In addition, long-term solutions involve transitioning to renewable energy sources such as wind, solar, and hydropower, as well as promoting the widespread adoption of hydrogen fuel as a clean energy alternative. These strategies are designed to overhaul the global energy infrastructure and diminish reliance on carbon-intensive fuels.

1.5.1 Transitioning from hydrocarbons to renewable energy

While it is crucial to urgently reduce CO_2 emissions, significantly cutting the use of fossil fuels poses a substantial challenge. Many industrialized nations rely heavily on fossil fuels for their economies, and the process of replacing the infrastructure for fossil fuel use would demand considerable time and resources. As an interim solution, some experts suggest employing negative emission technologies to decrease atmospheric CO_2 concentrations while still enabling the continued use of fossil fuels. [2] This approach would effectively lower atmospheric CO_2 levels without introducing additional CO_2 into the atmosphere. Nonetheless, it is important to eventually reduce the use of these fossil fuels in the short term, as recommended by the IPCC, [18] to facilitate the transition. This approach is viewed as a potential bridge to a low-carbon future, as it can help mitigate the impact of existing CO_2 emissions on the climate without significantly affecting economies reliant on this energy source. It acknowledges that solely avoiding further CO_2 emissions is not adequate to address the issue in the short term.

1.5.2. Renewable energies

As mentioned before, the long-term solution to reduce GHG emissions is transitioning towards alternative energy sources. These sources must be cleaner and renewable while supporting economic development and security without contributing to global warming. In 2016, the variability of renewable power sources was widely considered a significant obstacle to the transition towards renewable energy. [2] This variability in the context of renewable power sources refers to the fluctuations in power generation from sources such as wind and solar energy, presenting a challenge for integrating renewable energy into the power grid, as the availability of these energy sources, such as solar and wind, fluctuates based on weather conditions and time of day. [39] The efficient measures for regulating energy consumption include hydroelectric, geothermal, solar, wind, nuclear energy, and biomass resources. However, some of these measures lack sufficient capacity, and their widespread implementation is costly and raises environmental concerns. For example, hydroelectric energy lacks capacity and is significantly impacted by seasonal changes. This was evident with the recent severe and prolonged global droughts, particularly affecting China's hydropower generation, which declined by 4.9% due to below-average annual rainfall between mid-2022 and mid-2023—the most significant decrease in the last 20 years. [17] However, owing to the rapid advancements in this field, the issue of variability is now increasingly regarded as a problem that can be solved. In addition, by investing in and rapidly expanding renewable energy infrastructure, which could significantly increase the use of solar, and wind to replace traditional fossil fuel-based energy sources, we can reduce our reliance on fossil fuels and decrease CO_2 emissions. Furthermore, promoting and incentivizing research and development in the renewable energy sector can lead to the discovery and implementation of more efficient and affordable renewable energy technologies. This investment can foster innovation and accelerate the transition to a low-carbon future.

Renewable energies are electricity-generating technologies that derive either directly from sunlight, water, geothermal heat, or biomass. They are assumed to be available beyond the foreseeable future because they are naturally replenished and do not deplete over time (Jones, 2011). These energy sources are considered renewable instead of hydrocarbons, which we know to be finite.

Cleaner and renewable energies are vital to reduce emissions. As the world looks to decrease its reliance on fossil fuels, it is becoming increasingly clear that alternative energy sources must provide significantly more energy than current global usage. The projection is that the alternative sources should provide 5 to 10 times the current global energy usage, highlighting the scale of the transition needed. However, the potential of renewable energy to meet these future energy demands is immense, emphasizing the viability of the solution and inspiring confidence in the transition. This underscores a pressing need for innovative and efficient renewable energy technologies to meet future energy demands.[2]

By 2050 it is expected that energy demand will be 489 EJ[13], 21% lower than the 620 EJ consumed in 2024, and would be much more efficient. [41] This expected standard energy demand further underscores the necessity for significant advancements in energy production by these new energy sources. Meeting such projected demand will require substantial investment in research and development across various renewable energy sources to ensure a sustainable and secure energy future. [2]

The list of renewable energy technologies crucial for the energy transition I present in this work is partial. These technologies are interconnected and, in some cases, depend on each other. Therefore, discussions on one technology should also consider development in different areas. Some of these technologies, such as electric vehicles (EVs) and solar photovoltaic (PV) capacity, were projected to increase tenfold since 2020. This is seen in Table 2, as it describes the increase in solar PV, floating offshore capacity, and EVs, sold per year since 2015 and 2020, and it also predicted an exponential increase in a span of five years since 2020. [42]

[13] 489 EJ is equivalent to 489×10^{18} J or 135,833 TWh. In comparison, the world consumed 620 EJ in 2024, so by 2050, energy demand should be around 21% lower. [40]

Table 2. Global growth of new renewable energy technologies. [42]

Technology	2015	2020	2025
Number of passenger EV sold per year	300,000	2,000,000	20,000,000
Installed solar PV capacity (GW)	200	600	1,500
Floating offshore wind installed capacity (MW)	6.3	55.3	1,400

In 2022, electricity represented 20% of world final energy use. Further adding, no single renewable energy technology can achieve the challenge of a successful energy transition; rather, multiple technologies will have to work together. By 2040, it is estimated that wind and solar energy will account for 50% of the global electricity supply, and this proportion is projected to rise to nearly 70% by the mid-century, marking a twofold increase from current levels. This substantial growth is anticipated to effectively address the escalating energy demand. Furthermore, it is anticipated that the electricity sector will be nearly 90% decarbonized by 2050 and 82% of all electricity will come from renewable sources[14] and from fossil sources only 12%, but this can only be achieved by a net zero trajectory. [43] The following section will describe the selection of renewable energy technologies that have the potential to meet energy demand and ensure a successful global energy transition.

Floating wind turbines

Floating wind turbines[15] are an ingenious solution that unlocks abundant wind resources over deep water. They provide at least four times as much ocean surface space as fixed wind turbines, granting greater site selection flexibility, including the potential to tap into areas with higher wind speeds and minimize social and environmental impacts. In the coming years, significant technological advancements in floating wind are expected to reduce costs and increase applicability. It is estimated that floating wind will contribute approximately 2% of global electricity capacity, equivalent to 250 GW by 2050. [42] Additionally, floating wind presents an exciting opportunity for the oil and gas

[14] The projected energy mix from renewable sources includes hydropower, geothermal, biomass, solar, and wind. Additionally, 6% of the energy comes from nuclear sources, but this has decreased from its previous 9% share. Hopefully, there will be an increase in nuclear energy in the near future. [43]

[15] Hywind Tampen, located in Norway, has a capacity of 88MW and is currently the world's first and largest floating offshore wind farm. It was built specifically to power Equinor's offshore oil and gas installations. [44]

industry to transfer its skills and vessels into a new, burgeoning sector. Furthermore, floating wind can power oil and gas installations, reducing their CO_2 footprint. [45]

Solar photovoltaics

In the realm of solar power, solar photovoltaics (PV) has a lot of potential as it has emerged as the fastest-growing source of renewable electricity worldwide. With PV, electricity generation is projected to increase from 0.8 PWh in 2019 to 22 PWh in 2050 due to the significant decline in PV technology costs, which has led to an exponential increase in PV deployment. It is projected that solar PV capacity might double by 2025 and quadruple by nearly 3000 GW[16] in 2030 (see Figure 11), compared with offshore wind by that same year, it is expected that PV will account as the largest installed capacity (See Figure 12). So the latest PV technologies would make solar energy the most affordable power source in almost all markets. [42]

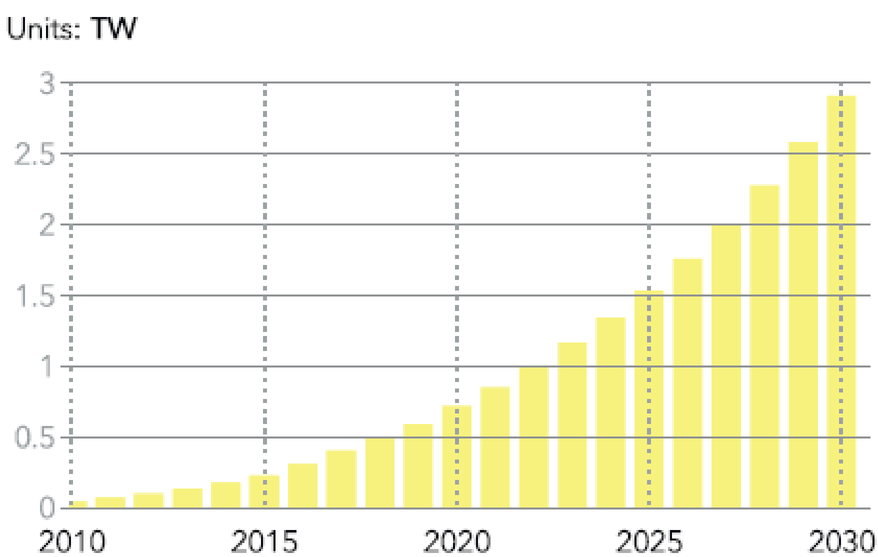

Figure 11. Global PV capacity. The image illustrates the increase in PV installation capacity. By 2025, the capacity will have doubled that of 2020, and by 2030, at 3000 GW it will have quadrupled. [42]

[16] Gigawatt (GW) is a measure of power that is equal to 1 billion watts. To put this prefix into perspective, 1 GW of power is the equivalent to 2.469 million photovoltaic (PV) panels, 310 utility-scale wind turbines or 100 million LED bulbs. [46]

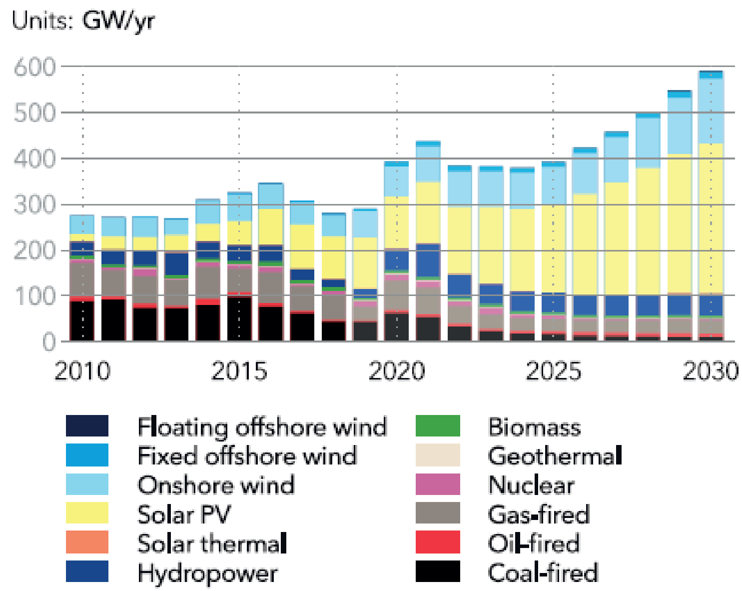

Figure 12. Cumulative addition of renewable energy technologies.The image depicts the rising use of various renewable energy technologies. PV is projected to become the most widely used and preferred technology in 2030, surpassing offshore wind and other technologies. [42]

Solar capacity will grow even more with cost reductions and the competitiveness of solar assets against traditional electricity generators. However, we should not focus solely on improving PV technology and cost; maintaining the value of solar generation as installed capacity increases is crucial. That is where energy storage systems, hybrid solar, and dynamic energy markets come in. By implementing these solutions, solar energy remains a competitive and sustainable energy source for years. In combination with Concentrated Solar Power (CSP) and Levelized Cost of Energy (LCOE) it is possible to effectively meet energy demands with minimal environmental impact. [2]

The impressive growth and move towards cleaner energy in the power sector have been influenced by policies and significant continual decreases in the expenses related to generating solar power. It is anticipated that the levelized cost of energy (LCOE)[17] for solar power will decrease by half by 2050, positioning solar as the most economical electricity source at around USD 21/MWh. [43]

[17] Levelized Cost of Energy (LCOE) refers to a measure used to assess the lifetime cost of generating a unit of electricity from a particular energy source. It takes into account all the costs over the lifetime of the energy-generating asset, including initial investment, operations and maintenance, fuel, and financing costs, and it is typically expressed in terms of dollars per megawatt-hour ($/MWh). [47]

Waste to fuel

Waste to energy (WTE) is a process for recovering energy from waste materials, particularly municipal solid waste (MSW), in the form of electricity and/or heat. The process is becoming increasingly popular worldwide due to the abundance of waste and technological advancements that enable efficient waste conversion into energy. Through the process of conversion, we can harness the energy potential of MSW and turn it into fuels such as methane and biodiesel. This not only addresses the issue of waste management but also presents a significant opportunity for sustainable energy production. [42]

Solid waste in landfills produces landfill gas (LFG), composed of 40 to 60% of methane (CH_4), and the rest is carbon dioxide CO_2, traces of hydrogen (H_2) and hydrogen sulfide (H_2S). Each year, over two billion tons of MSW is discarded globally; increasing by more than 60% by 2050 due to rapid urbanization. Therefore, methane mining in landfills worldwide has considerable potential (waste management alone is accountable for approximately 12% of anthropogenic methane emissions worldwide). LFG can be recovered by extracting it through a series of wells and can be used to generate electricity or refined to produce biomethane and curtail these emissions by 10-15%. Various technologies are now available for biogas cleanup, including pressurized water scrubbing, catalytic absorption/amine wash, pressure swing absorption, cryogenic liquefaction, and highly selective membrane separation. [42]

Thermochemical gasification can be used to produce gas from organic waste. This gas is called syngas and contains hydrogen and carbon monoxide. The syngas can then be converted into long-chain hydrocarbon molecules using the Fischer-Tropsch process. The Fischer-Tropsch (FT) process converts synthesis gas to long-chain, heavy paraffinic liquid. It produces water, CO_2, olefins, oxygenates, and alcohols as byproducts, generating significant heat. Different types of catalysts, such as iron-based or cobalt-based, and reactors, including fixed-bed, fluidized-bed, and slurry-phase, influence the product slate. Operating conditions, such as temperature, pressure, and desired product mix, also play a key role. The FT product is free of sulfur, nitrogen, metals, asphaltenes, and aromatics typically found in petroleum products. [48] These hydrocarbon molecules are used to create higher-end fuels such as synthetic diesel and bio-jet fuel. [42] Slurry-based and fixed-bed processes on the other hand, are commonly used to produce liquid fuels from biomass, and synthetic fuel (Synfuel) can be derived from this method. This approach has been successful in many European countries and is part of a well-received EU-funded project. It involves the production of green hydrogen and its conversion into synfuel by adding CO_2 in the FT process. The resulting synfuel is a combination of 62% diesel and 38% kerosene. Carbon dioxide for the FT process is obtained from biomass and the atmosphere through direct air capture, and it can also be stored. The study indicates that Germany has significant potential to increase its use of the TP process to produce syngas. [49] In the United States, companies like Fulcrum Bioenergy and Velocys are currently building facilities to produce synthetic fuels from biomass using this method. They are even using synfuels to create sustainable aviation fuel (SAF). [50] Furthermore, VTT Technical Research Centre of Finland has confirmed the viability of the FT process for biofuel production. [51]

However, when it comes to energy sources, such as biomass, biogas obtained from biogenic sources seems to pose a challenge as they compete with food production, and the former is less efficient per square foot compared to solar energy. [2]

Green hydrogen

Hydrogen is recognized as an efficient fuel due to many factors. For example, CO_2 emissions from vehicle exhaust pipes cannot be captured, but hydrogen can be extracted from primary energy resources. The generation of electricity through hydrogen from fossil fuels subsequently reduces carbon emissions. The hydrogen economy is on the rise, with global demand for hydrogen as an energy carrier projected to reach 24 EJ/yr by 2050. [42] Among the various categories of hydrogen production, green hydrogen stands out as the most sustainable and truly carbon-free option. See Figure 13. It is often perceived as a more centralized solution as the renewable energy system that can achieve the net-zero emission target for 2050, especially liquid hydrogen; however, it requires large-scale liquefaction units to become economically viable. [42]

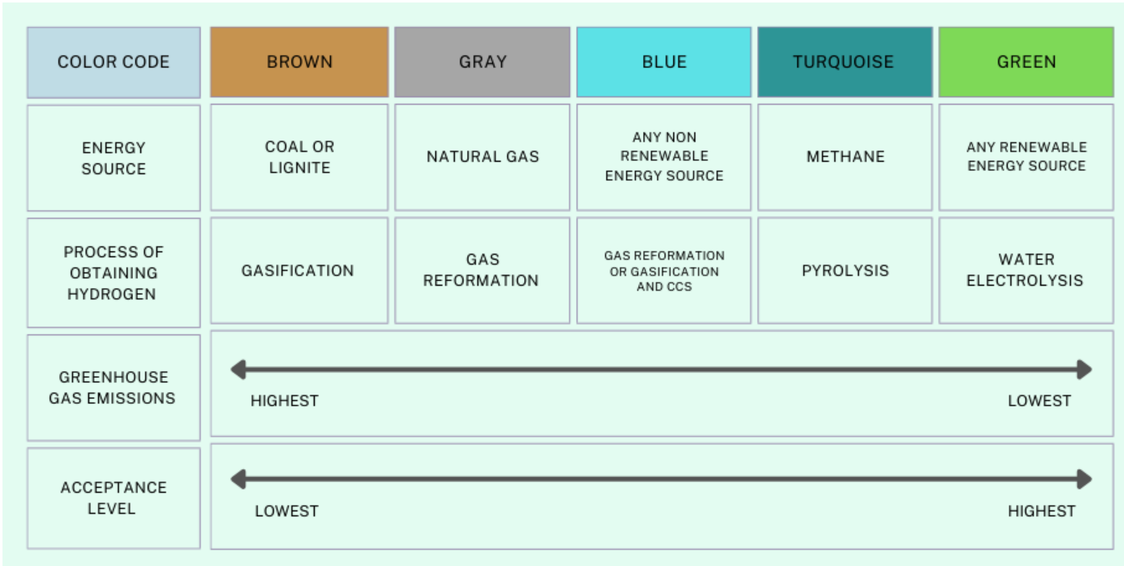

Figure 13. Hydrogen color code. The figure depicts the variety of hydrogen sources that produce a specific class of hydrogen. Green hydrogen is considered to be the most accepted type of hydrogen because of its low GHG emissions.[42]

This energy carrier often requires large hydrogen pipelines, which in most cases, is the least expensive onshore transport option. However, another challenge with green hydrogen is the need and requirements to change the existing infrastructure on the demand side. Green hydrogen production, when powered by renewable energy sources, has minimal environmental impact, it is produced through electrolysis, which involves splitting water (H_2O) into hydrogen (H_2) and oxygen (O_2) by applying an electric current. The field of green hydrogen technologies is advancing rapidly, with four leading technologies at the forefront: [42]

1. Alkaline Electrolysis (AE) is the most mature technology, utilizing a liquid electrolyte to enhance conductivity.
2. Proton Exchange Membrane (PEM) technology features a solid electrolyte, prompt response times, and typical pressurization, with slightly higher costs but comparable efficiency to AE.
3. Solid Oxide Electrolysis (SOE)[18] has reached commercialization and boasts high operating temperatures, high efficiencies, and the use of steam instead of liquid water.

[18] Solid oxide electrolysis (SOE) for green hydrogen production can operate in reverse, serving the function of a fuel cell.

4. Finally, anion exchange membrane (AEM) is the least developed technology; however, it shows promise due to its simple design and lack of critical raw materials despite facing issues with stability and limited lifetime. [42]

Since hydrogen has been considered a game-changer when it comes to global exchange of renewable energy, several efforts have been put into green hydrogen technologies, such is the case for PEM for high efficiency. [49] While AE and PEM are the most developed hydrogen technologies, SOE and AEM may also have a future role in different application areas. SOE, is likely to be applied in combination with a stable power supply and integrated with other processes in ammonia and synthetic fuel production. [42] AEM could potentially be used in applications where simplicity and raw material availability are key factors.

The use of green hydrogen is making significant progress in a wide range of pilot and commercial applications. Some examples are:

Pilot projects

- H_2 Mobility Initiative: The goal of this initiative is to set up a hydrogen refueling network across Germany. This involves setting up test stations to experiment with and enhance hydrogen refueling technologies for fuel cell electric vehicles (FCEVs). [52]
- HyDeploy: The blending of green hydrogen with natural gas in existing gas networks is part of this pilot project in the UK. The aim is to partially replace natural gas with hydrogen in order to reduce carbon emissions from heating and cooking. [53]
- Refhyne: The project at Shell's Rhineland Refinery in Germany includes one of the world's largest PEM electrolyzers. Its goal is to generate green hydrogen for refinery operations and potentially as a fuel for hydrogen-powered vehicles. [54]
- H21 Leeds City Gate: This project aims to investigate the possibility of transforming the natural gas network in the UK to rely entirely on hydrogen. The project involves evaluating both the technical and economic facets of such a shift. [55]

Commercial applications

- Hydrogen Fuel Cell Buses: Cities such as London, Los Angeles, and Tokyo have introduced groups of hydrogen fuel cell buses. These buses create no emissions and provide a feasible option to diesel-fueled public transportation. [56], [57]
- Hydrogen Refueling Stations: Japan and South Korea have established widespread networks of hydrogen refueling stations to accommodate the increasing fleet of hydrogen fuel cell electric vehicles (FCEVs).
- Power-to-X Projects: A number of European initiatives aim to transform excess renewable electricity into green hydrogen for application in different industries. For instance, Denmark's HyBalance project generates hydrogen for industrial purposes and as an alternative power supply. [58]
- Steel Production: The initiative HYBRIT in Sweden is striving to substitute coal with green hydrogen during the steelmaking process. The objective of the project is to manufacture carbon-free steel, leading to a substantial decrease in CO_2 emissions from the steel industry. [59]
- Hydrogen-Powered Trains: Alstom's Coradia iLint is the world's first hydrogen-powered train, first introduced in Germany. It provides a zero-emission alternative to diesel-powered trains on non-electrified rail lines. [60]

Green hydrogen encounters various challenges in terms of transport and storage. One primary issue is its low energy density, requiring larger storage volumes than traditional fuels. Additionally, hydrogen has a tendency to escape easily due to the small size of the hydrogen atoms, demanding specialized pipelines[19] and storage infrastructure to prevent leaks (see Table 3). [42] Moreover, the development of cost-effective and efficient storage methods, such as hydrogen tanks or underground caverns, poses a significant technological challenge. Ensuring the safety of hydrogen storage facilities and infrastructure is crucial, as hydrogen can be flammable under certain conditions. Its tendency toward auto-ignition[20], combined with a difficult-to-detect flame, makes small hydrogen leaks a serious potential risk that requires careful management. Finally, another problem associated with the transport and storage of hydrogen is its corrosive properties. Even small levels of impurities

[19] Pipeline design requirements may include stainless steel construction, internal coatings, corrosion protection, and in-line filters.

[20] This autoignition occurs because of hydrogen's low ignition energy and the fact that unlike most gases, hydrogen increases in temperature as it expands.

(ppm) such as CO_2, H_2S and water can significantly increase corrosion concerns. Many metallic materials, including steels (especially high-strength steels), stainless steel, and nickel alloys, suffer embrittlement in hydrogen gas environments. [42]

Table 3. Considerations for new and repurposed hydrogen pipelines. The table outlines essential safety requirements for repurposing and constructing new pipelines to accommodate hydrogen. Repurposing current infrastructure for hydrogen, as opposed to building new pipelines, can mitigate project risk and reduce commercial burdens by expanding capacity. It's important to note that these projects are still predominantly in the pilot stage. [42]

	Repurposed	**New**
Hydrogen	• Pipeline velocities • Pipeline cleanliness/hydrogen purity • Metering • Repair system design • Brittle fracture mechanisms in steel lines • Toughness and tensile strength parameters • Cleaning/purging of existing lines • Area classification of electrical systems • Update emergency response plans • Impact on compressors	• Pipeline material selection, steels, plastics, composites • Gas/Syngas composition • Pipeline routing and permitting • Public consultation • Metering • Pipeline sectioning • Autoignition risk on depressurization • Welding/jointing issues • Valve design and selection • Compressor design and selection

Cost competitiveness[21] is the main challenge for green hydrogen, as electrification competes with carbon-intensive energy carriers. The contest between gray, blue, and turquoise hydrogen, derived from low-cost fossil resources, and the low CO_2 prices influence brown, grey, and blue hydrogen production, suggest that hydrogen from fossil fuels might have a significant role in establishing hydrogen as a major energy carrier. However, as manufacturing processes are standardized and improved, and the efficiency of AEM and PEM is enhanced, the levelized cost of hydrogen (LCOH)[22] will decrease, making it more competitive. See Table 4. [42]

[21] Costs can be further reduced by larger capacity. International GW scale capacity can further reduce these costs.
[22] The Levelized Cost of Hydrogen (LCOH) is a measure of how much it costs to produce 1 kg of green hydrogen. It takes into account the estimated costs of the required investment and operation of the assets involved in its production. The LCOH strongly depends on assumed electricity costs, the number of full-load hours (FLHs), the cost of capital, and the investment costs for electrolyzers.

Table 4. Current and predicted main parameters of electrolyzer technologies involved in green hydrogen. When converting from SI to imperial units, AE and PEM emerge as the most promising technologies. However, additional research is necessary to further reduce costs. As AEM is still in the research and development phase, no current or future projections are available for its LCOH and CAPEX costs.

	Current/2030	**AE**	**PEM**	**SOE**	**AEM**
LCOH	USD/kg	4.1/2.5	5.93/2.5	7.87/3.23	-/-
CAPEX[23]	USD/BTU/hr	0.3136/0.1568	0.4704/0.1568	0.784/0.3136	-/-
Efficiency	BTU/scf	454.12/415.47	506.3/474.6	379.73/348.1	506.3 stack
Stack lifetime	hours	80,000/100,000	50,000/>80,000	20,000/>20,000	5,000
Operating pressures	psi	<580/<1015.26	<580/<1015.26	14.7/<290	<507

This transition is anticipated to take at least another decade and is dependent on government support to achieve cost parity. Investors in brown, grey, or blue hydrogen should be mindful of the risk that green hydrogen could become more competitive before their assets are fully utilized, particularly in regions with access to low-cost renewable energy for electrolysis, since electricity costs significantly impact the competitiveness of green hydrogen. [42] For example, hydrogen produced from natural gas typically ranges from 0.9-3.2 USD/kg. Alternatively, hydrogen derived from natural gas with CCUS falls within the range of 1.5-2.9 USD/kg, and hydrogen obtained from coal is the most cost-effective, with prices ranging from 1.2 to 2.2 USD/kg. [61] Moreover, a substantial amount of hydrogen production will depend on fossil fuels, and the production of hydrogen from fossil fuels is expected to increase until 2050. Beyond 2035, the availability of abundant renewable resources will result in a rise in the production of green hydrogen. Fortunately, there are other ongoing projects in Latin America and Africa, such as H2V Magallanes in Chile and the 15GW Aman Project in Mauritania, Africa, where green hydrogen production costs (LCOH) using solar PV at a large scale were in the range of 2-3 USD/kg (2021). [42] These projects serve as promising examples of the feasibility of large-scale green hydrogen production. However, green hydrogen production costs are still expensive compared to other energy sources. See table 5

[23] It refers to the purchase of new equipment or upgrading existing capital to produce hydrogen. It includes the costs of the equipment required. This will be strongly affected by the renewable energy system adopted, the electrolyzer technology selected (alkaline, PEM, SOE), and the characteristics of the auxiliary services involved, such as water treatment, the compression and cooling system, or hydrogen storage, among others. Therefore, the more precise the technology selection, the more reliable the result.

Table 5. Comparison of LCOE of different energy sources. The cost of producing various fuels can vary widely based on the production process, feedstock, location, and other factors. [62]

Energy Source	LCOE (USD/MWh)
Natural Gas (Combined Cycle Gas Turbine (CCGT)	40-80
Coal	50-120
Nuclear Power	80-130

In order to compare the LCOE of hydrogen with other sources, we must convert the LCOE of hydrogen to its equivalent USD/MWh LCOE with the following formula:

$$\frac{USD}{MWh} = \frac{\frac{USD}{kg}}{\frac{kWh}{kg}}(1000) - - - - - - - - - - - - - - (1.0)$$

The energy content of green hydrogen is approximately 33.3 kWh, and LCOE is in the range of 3 – 6 USD/kg [63]. Substituing these range of values in formula 1.0

$$\frac{USD}{MWh} = \frac{\frac{3\,USD}{kg}}{33.3\,\frac{kWh}{kg}}(1000)$$

$$\frac{USD}{MWh} = \frac{\frac{6\,USD}{kg}}{33.3\,\frac{kWh}{kg}}(1000)$$

We obtain

$$90.09\,\frac{USD}{MWh}$$

And

$$180.18\,\frac{USD}{MWh}$$

The LCOE (Levelized Cost of Electricity) for green hydrogen presently exceeds that of traditional fossil fuels such as natural gas, coal, and nuclear power. See Table 5. This difference is mainly attributed to the substantial costs linked with electrolysis and the efficiency declines involved in converting electricity into hydrogen.

1.5.3. Carbon management

This approach is a global carbon reduction strategy aiming to reduce carbon emissions by managing the carbon cycle, the natural process of carbon exchange between the atmosphere, oceans, soil, and living organisms. Carbon management involves measuring, monitoring and reducing carbon emissions through energy efficiency, such as smart buildings, reducing vehicle use and renewable energy sources, and capturing and storing emissions through carbon capture and storage (CCS) technologies. [64]

Carbon management can help slow down the rate of global warming and reduce the severity of its effects on the environment and human populations. One key benefit of carbon management is reducing individuals' carbon footprint and fulfilling emissions reduction targets worldwide as part of the Paris Agreement on Climate Change, see section 1.4. [2]

Another benefit is the potential for new business opportunities and jobs in the clean energy sector. As more countries and companies adopt carbon management strategies, there is a growing demand for renewable energy technologies, such as wind, solar power, and CCS.

Thus, to ensure a sustainable future, the world needs to further reduce global emission levels by 2050 [2], which is a challenging task. Even if we act quickly to reduce carbon emissions, it may not be enough to prevent climate change, since we are delayed for too long. Scientists have come to a consensus that limiting and reducing CO_2 emissions is necessary, but it is no longer sufficient to facilitate a Net Zero pathway. [65]

1.6. Negative Emission Technologies (NETs): Concepts and types

Negative Emission Technologies (NETs) and Carbon Dioxide Removal (CDR) are sometimes used interchangeably. CDRs are a much broader category that includes any technology and method specifically designed to remove CO_2 from the atmosphere either directly or indirectly. The methods CDR employs vary from natural solutions like afforestation/reforestation to technology-driven approaches supported by carbon capture and storage. However, NETs have to be seen as a subset of methods under the umbrella of CDR, aiming for net-negative emissions, which remove more carbon dioxide from the atmosphere than what is emitted. [66] NETs refer explicitly to a set of technologies, practices, and approaches for removing carbon dioxide from the atmosphere and storing it in various reservoirs such as vegetation, soils, geological formations, or the ocean. NETs aim to reduce the amount of CO_2 in the atmosphere, mitigating climate change, and helping to achieve net-zero emissions. It does not include natural CO_2 removal, which occurs through natural processes such as plant photosynthesis. NETs have been a part of the portfolio for achieving net zero emissions reductions for at least two decades. This inclusion occurred when reforestation, afforestation, and soil sequestration were brought into the United Nations Framework Convention on Climate Change (UNFCCC) as mitigation options. [11]

It is important to note that NETs cannot be implemented immediately to achieve significant reductions in GHG emissions. Nonetheless, NETs are necessary to limit global warming to 2ºC by 2100. However, implementing these technologies involves making important decisions regarding the methods, scale, and deployment timing. It is also necessary to consider the management of sustainability and feasibility constraints.

Various NET methods and implementation options exist, each carrying different levels of risk and timeframes. Depending on the scale and context of deployment, these methods may either yield additional benefits or lead to unintended consequences, which will require the development of appropriate NET governance and policies. Negative Emission Technologies (NETs) are classified as follows:

- Carbon Removal. Refers to various approaches that result in the long-term removal of carbon dioxide (CO_2) from the atmosphere. This can be achieved through a range of methods, including various technological, biological, geological, or other means. The goal of carbon removal is to reduce the concentration of CO_2 in the atmosphere and mitigate the negative impacts of climate change. Carbon Removal is further classified by the following approaches: [67]

Air (DAC)	Land	Ocean	Rocks
Solvent-based direct air capture	Thermal conversion of biomass	Macroalgae cultivation	Ex-situ mineralization of mined rocks
Solid sorbent direct air capture	Biological conversion of biomass	Biomass sinking	Mineralization of mine or industrial waste
Electrochemical direct air capture	Biomass to energy	Artificial upwelling or downwelling	In-situ mineralization (mafic or ultramafic mineralization)
Membrane-based direct air capture	Biomass direct burial	Ocean alkalinity enhancement	In-situ storage in sedimentary reservoirs
	Biomass sequestration in the built environment	Nutrient fertilization	Calcination of minerals with carbon capture
	Terrestrial ecosystem restoration and management	Electrochemical carbon separation	
	Agricultural and grassland carbon dioxide removal	Ocean ecosystem restoration	
	Carbon capture and storage (CCS) from biogenic sources		

- Point Source Capture. This refers to a set of technologies that have been designed to capture and divert significant sources of emissions, primarily carbon dioxide, and prevent their release into the atmosphere, thereby reducing the overall carbon footprint of the source in question. The following are methods used to separate and divert CO_2:

Amine Capture
Membrane separation

- Carbon Conversion: Innovative technologies that transform captured CO_2 into valuable products such as chemicals, fuels, building materials, plastics, and bioproducts. This process not only helps to mitigate the negative impact of carbon emissions on the environment but also provides economic benefits by creating new industries and markets for these products. This conversion is achieved by the following processes: [68]

Biological process
Electrochemical process
Thermochemical process
Mineralization process
Photochemical process

NETs stand out in climate mitigation efforts to decrease the amount of CO_2 emitted into the atmosphere. Unlike other methods that focus on reducing emissions, NETs directly and indirectly CO_2 removal from the air, even at lower concentrations, excluding emissions from carbon sinks [42] The current state of negative emission technologies (NETs) indicates that they are mature and readily available for large-scale implementation across various industry sectors. Moreover, it is anticipated that within the next decade, additional capture processes will attain commercial maturity.[42] The majority of the Negative Emission Technology companies are located in the United States. See Figure 14.[24]

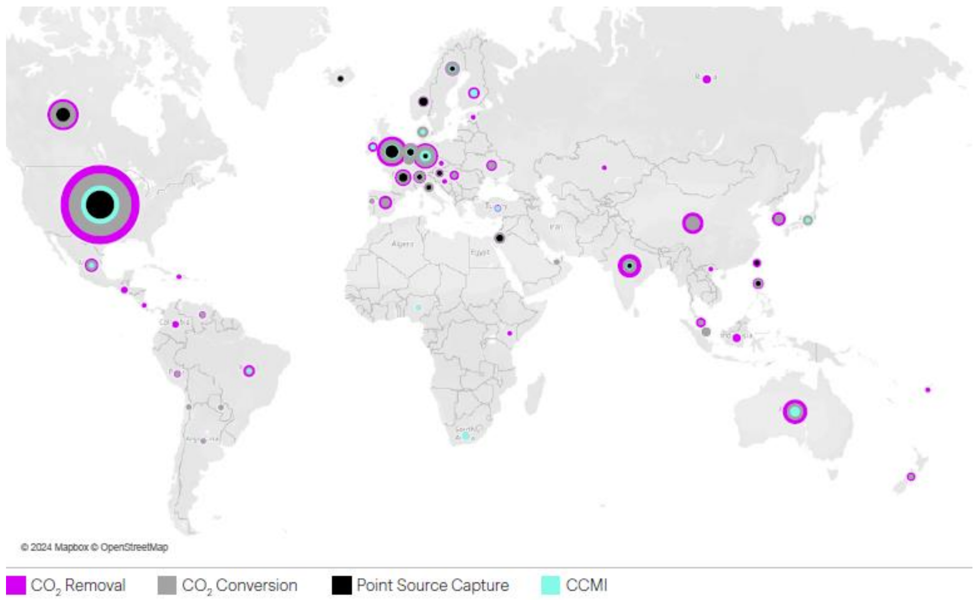

Figure 14. Location of NET manufacturer companies. Circular Carbon Market (CCM) tracked a total of 997 companies that manufacture a wide variety of NETs in 55 countries and have reported a total capital raised of 25.4 billion USD. [68]

The current costs specifically for carbon capture vary widely, ranging from 15 to 125 USD per ton of CO_2 for industrial processes that produce "pure" or highly concentrated CO_2 streams, such as ethanol production or natural gas processing. On the other hand, processes with "dilute" gas streams, like cement production and power generation range from 40 to 120 USD per ton of CO_2. Capturing CO_2 from Direct Air Capture (DAC) is the most expensive method but could still have a unique role in carbon removal. Some CO_2 capture technologies are available commercially, while others are still in the development stage, contributing to the wide range in costs. [70] However, these costs are

[24] México developed a CCU technology that converts polluting gas emissions into ethanol and ethaline, substances that are used to generate electricity as fuel, and plastic precursors. [69]

projected to decrease, [42] assuming that there is a relatively profitable opportunity to extract CO_2 from the atmosphere, generating business prospects and providing a potential solution for climate change.

Transport and storage costs vary significantly based on CO_2 volumes, transport distances, and storage conditions. In the United States, onshore pipeline transport typically costs 2 to 14 USD per tonne of CO_2, while onshore storage costs vary even more widely. Nevertheless, over half of the onshore storage capacity is believed to be accessible for under 10 USD per tonne of CO_2. Under certain instances, storage expenses can even be negative if CO_2 is used as an enhanced oil recovery process to increase revenue from oil sales. [70]

1.7. Fundamentals of carbon storage: CCS, CCUS

1.7.1. Carbon Capture and Storage (CCS)

Like other mitigation options mentioned in section 1.5, Carbon Capture and Storage (CCS) is considered a viable option to contribute mitigating and stabilizing the atmospheric CO_2 concentration since it can potentially reduce overall mitigation costs and increase flexibility in achieving greenhouse gas emission reduction. [71] It is important to note that these CCS technologies are widely applied to carbon capture technologies associated with biomass, as discussed in Chapter III.

Unlike NETs and CDRs, whose primary objective is to remove CO_2 already in the atmosphere, the primary application of CO_2 capture is predominantly used in significant point sources like fossil fuel power plants, fuel processing plants, and other industrial facilities, especially relevant in the production of iron and steel, cement, and bulk chemicals. An alternative approach to mitigate CO_2 emissions from these sources would involve using energy carriers such as hydrogen or electricity produced in large fossil fuel-based plants with CO_2 capture or by harnessing renewable energy sources, as mentioned in Chapter 1.5.

CO_2 has been collected from industrial process streams for almost a century. [72] CO_2 capture from process streams includes natural gas purification and the production of hydrogen-containing synthesis gas to manufacture ammonia, alcohol, synthetic liquid fuels, and steel. Conversely, industrial process streams contributing to uncaptured CO_2 include cement and steel production, as well as fermentation processes for food and beverage production. [71]

There are three fundamental methods for capturing CO_2 from fossil fuels and biomass in addition to industrial processes as mentioned above, and illustrated in Figure 15.

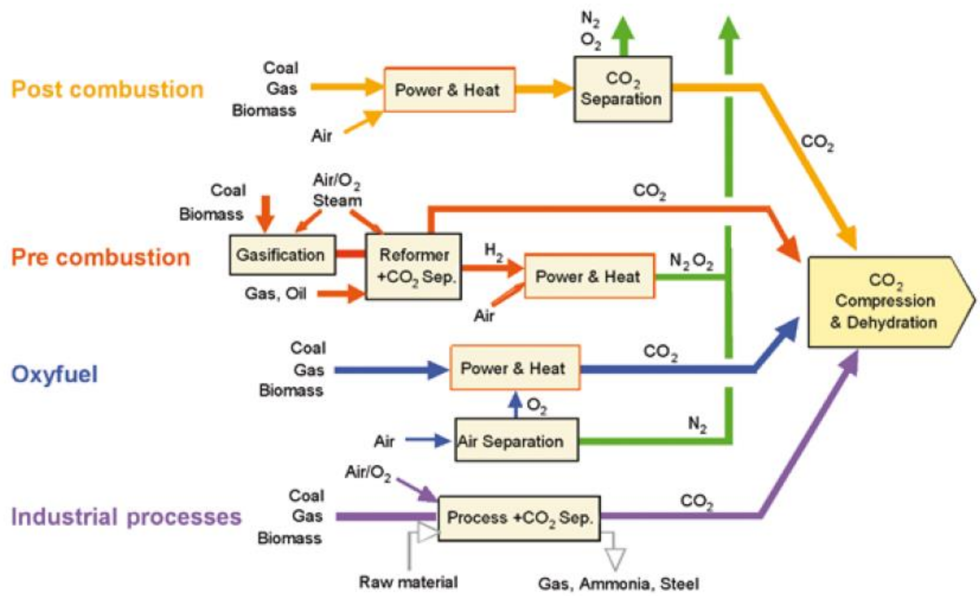

Figure 15. Representation of capture systems in diagram form is depicted. Oxyfuel combustion, pre-combustion, post-combustion, and industrial sources of CO_2 are denoted, along with fuels and products. [71]

Post-Combustion

Post-combustion capture involves the extraction of CO_2 from flue gases generated through the combustion of fossil fuels and biomass in the presence of air. Instead of being directly emitted into the atmosphere, the flue gas is directed through specialized equipment that isolates the majority of the CO_2. This separated CO_2 is then transported and stored in a reservoir, while the remaining flue gas is released into the atmosphere. Typically, a chemical sorbent process is utilized for the separation of CO_2 from the flue gases. [71]

Oxyfuel Combustion

In oxy-fuel combustion, pure oxygen is utilized for burning instead of air, resulting in a flue gas primarily composed of CO_2 and H_2O. This process leads to an extremely high flame temperature, which can be mitigated by recirculating CO_2 and/or H_2O-rich flue gas back to the combustor. Oxygen is typically obtained through low-temperature (cryogenic) air separation, and there are ongoing developments in methods such as membranes and chemical looping cycles to provide oxygen to the fuel. [71]

Pre-Combustion

In pre-combustion capture, a fuel undergoes a reaction with oxygen, air, and/or steam to create a mixture known as “synthesis gas” or “fuel gas”, comprising carbon monoxide and hydrogen. Subsequently, the carbon monoxide is treated with steam in a catalytic reactor (shift converter) to produce CO_2 and additional hydrogen. The CO_2 is then separated, typically using a physical or chemical absorption process, resulting in a hydrogen-rich fuel suitable for a wide range of applications such as boilers, furnaces, gas turbines, engines, and fuel cells. [71]

After using the processes mentioned above, CO_2 is compressed and transported to the site, where it is safely stored for the long term without entering the atmosphere. The captured CO_2 can be stored in depleted oil and gas fields in the ocean, deep saline aquifers, mineral carbonation or industrial processes. [42], [71]

By capturing and storing the CO_2 produced from burning fossil fuels in electric power stations or from cement manufacturing, we can maintain a low-emission (near-zero) facility. [73]. A power plant fitted with a CCS system (with access to geological or ocean storage) would require approximately 10-40%[25] more energy than a plant without CCS, primarily for capture and compression. [71] However, the overall outcome is that a power plant with CCS could potentially reduce CO_2 emissions to the atmosphere by around 80-90% compared to a plant without CCS. See Figure 16.

[25] This range includes three types of power plants, which include Natural Gas Combined Cycle plants (11-22%), Pulverized Coal plants (24-40%), and Integrated Gasification Combined Cycle plants (14-25%). [71]

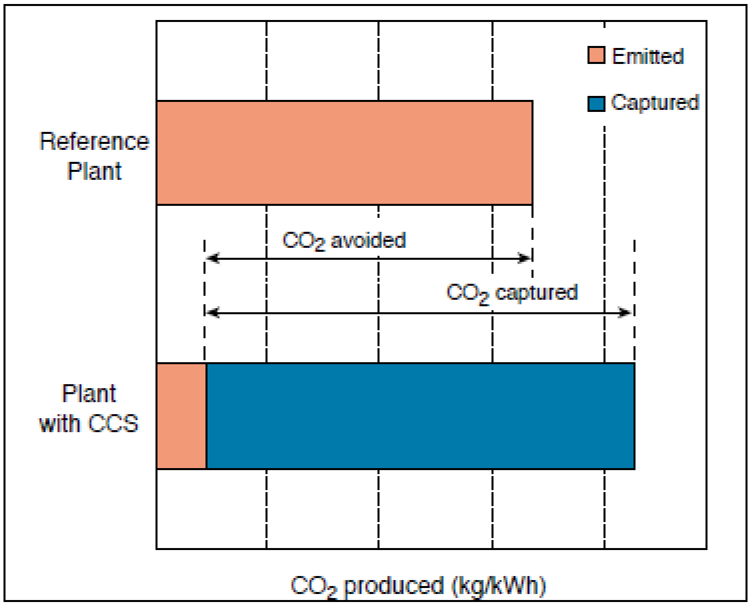

Figure 16. CO_2 emissions of a conventional power plant compared to others with a CCS system. A substantial amount of CO2 emissions can be avoided and simultaneously stored if a CCS system is implemented. [71]

Geological Storage

The capture of CO_2 in underground, onshore, or offshore geological formations uses methods created by the oil and gas sector. In certain circumstances, it has been shown to be financially viable for oil and gas fields and saline formations, providing a potential answer to our urgent environmental problems. [71]

When carbon dioxide (CO_2) is injected into appropriate saline formations or oil or gas fields at depths greater than approximately 2600 ft (800 m)[26], various physical and geochemical trapping mechanisms come into play, effectively preventing its migration to the surface. The presence of a caprock, in particular, acts as a crucial physical trapping mechanism. Coal bed storage, which may occur at shallower depths, depends on the adsorption of CO_2 on coal, and its technical feasibility largely depends on the permeability of the coal bed. Integrating CO_2 storage with Enhanced Coal Bed Methane Recovery (ECBM) may generate additional revenues from the recovery process.

[26] Below 2620 – 3280 ft (800 – 1,000 m), CO_2 becomes supercritical, with a density similar to that of a liquid (approximately 0.5–0.8 g/ cm3). This characteristic offers the opportunity to effectively utilize underground storage capacity and enhance storage safety. [71]

Drilling and injection technology, storage reservoir performance simulation, and monitoring methods from existing applications are being further developed for use in the design and operation of geological storage projects. [71]

Carbon dioxide storage in the ocean is a potential method for CO_2 management, which can be achieved through two approaches: injecting and dissolving CO_2 into the water column at depths typically below 3,280 ft using a fixed pipeline, a moving ship or depositing it onto the sea floor below 9,850 ft using a fixed pipeline or an offshore platform. In the latter method, CO_2 becomes denser than water, forming an underwater "lake" that delays its dissolution into the surrounding environment. The dissolved CO_2 eventually becomes part of the global carbon cycle and equilibrate with the CO_2 in the atmosphere. It is crucial to consider the environmental implications of dissolving CO_2 in the ocean, as studies have indicated that it leads to increased acidity, impacting marine ecosystems. Nevertheless, this challenge can be addressed by creating solid CO_2 hydrates or liquid CO_2 lakes on the ocean floor, and by using alkaline minerals such as limestone to counteract the acidic CO_2 [71] There are currently many offshore CCS projects in the North Sea, being Equinor the global leader with their first large scale CO_2 capture and injection project (the Sleipner) to storage and monitoring [27] offshore gas field in 1996. [74] Other projects include Snøhvit in 2008, Northern Lights (Longship) a partnership with Shell and TotalEnergies and currently one of the worlds largest CCS projects, and two more upcoming projects in 2026 and 2028. [75]

The widespread implementation of CCS depends upon several factors, including technical maturity, cost-effectiveness, potential for widespread use, technology transfer to developing nations, adoption of the technology timing, regulatory considerations, environmental impacts, and public perception, among others. [71]

CCS has historically been viewed as immature and risky, taking focus away from other decarbonization methods. However, there is now a renewed interest in these technologies as an effective tool for achieving net-negative emissions[28] and transitioning to a net-zero emission future.

[27] The commercial viability of the project was achieved with the introduction of a CO2 tax on offshore oil and gas activities by the Norwegian government in 1991. [74]

[28] As of 2024, there were 45 operational commercial-scale CCS facilities worldwide, capturing just under 50 $MtCO_2$ anually, indicating a significant increase in commercial CCS projects and investment. [76], [77]

The large-scale implementation of CCS technologies is essential for reaching the climate targets outlined in the Paris Agreement. The first step in any large-scale CCS project involves capturing CO_2 from industrial facilities. Mature CO_2 capture technology exists for applying CCS to nearly all industries, with recent focus shifting to major industries such as cement, steel, refining, hydrogen, and ammonia. [43], [71] See Figure 17.

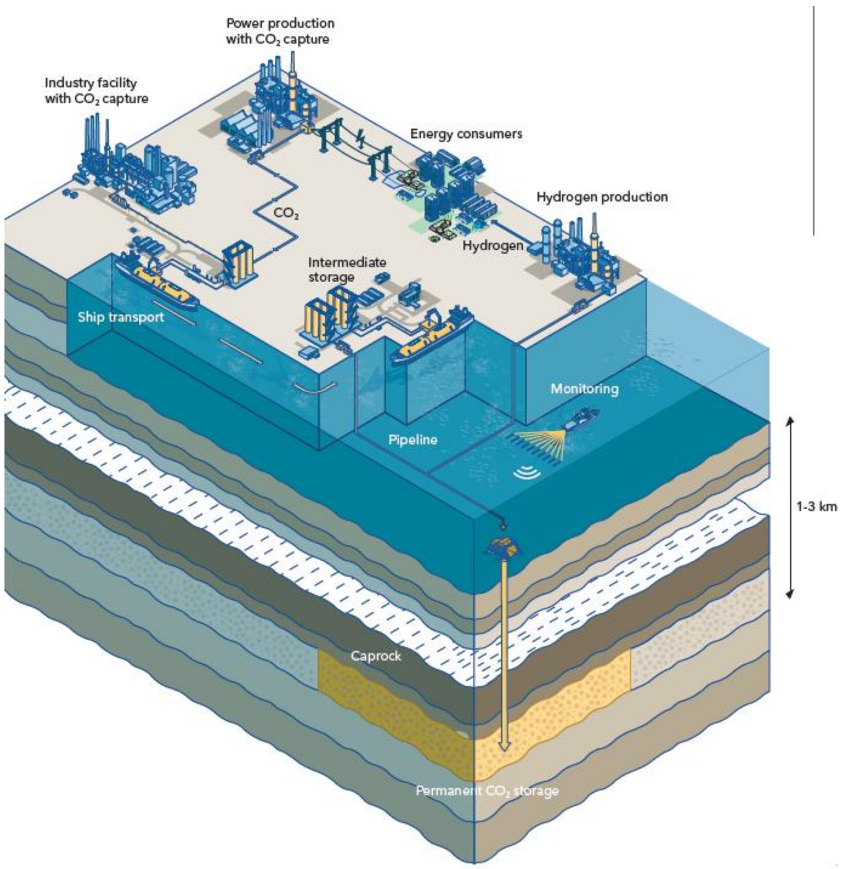

Figure 17. Ilustration of CCS from different industrial facilities and power prodcuction. [42]

Negative emissions technologies (NETs) will help offset emissions from hard-to-decarbonize sectors and play a crucial role in restoring the atmospheric carbon budget. Bioenergy with CCS (BECCS), direct air capture (DAC), and geological storage are critical methods for achieving negative emissions. It is estimated that BECCS and DAC will need to capture and store approximately 1.9 $GtCO_2$/yr by 2050. [42]

Disadvantages

The primary obstacle for implementing CCS is the high cost of capture and transportation of CO_2; although there are many suitable and secure sites for storing CO_2 globally, these sites must be located near capture plants. Identifying, evaluating, and obtaining permits for storage sites are a time-consuming process, taking up to 10 years. [42]

1.7.3. Carbon Capture Utilization and Storage (CCUS)

As previously mentioned, CCS (or CCUS) comprises capturing CO_2 emissions at their source, permanent storage, and utilization routes where CO_2 serves various purposes, including producing synthetic fuel and chemical products, concrete curing, algae cultivation, and Enhanced Oil Recovery (EOR). CCUS technologies are essential for transitioning energy systems globally to a sustainable path, but the implementation has been sluggish. Currently, there are only about 45 operational CCUS facilities worldwide across industrial processes, fuel transformation, and power generation. [76] However, there has been significant growth in momentum in the past few years. In 2020, governments and industry committed over USD 4.5 billion to CCUS, and there are over 700 projects at different development stages. [70], [76]

In our quest for net zero, we cannot disregard CCUS as being "too expensive." It represents a promissing set of technologies for cutting emissions in vital economic sectors and extracting CO_2 to offset unavoidable emissions, which is a crucial element in achieving net-zero goals. In certain sectors, particularly heavy industry, CCUS presently stands as the most cost-effective or only feasible approach for significant emissions reductions. [70]

Still, it is widely recognized that there is significant potential for cost reduction in CCUS. Historical evidence suggests that as the market expands, technology advances, financing costs decrease, economies of scale are achieved, and experience in building and operating CCUS facilities accumulates, the cost of CCUS should decrease. This trend is reminiscent of the cost reductions observed in renewable energy technologies over recent decades. Significant cost reductions have already been realized in large-scale CCUS projects. For instance, CO_2 capture cost in the power sector has decreased by 35% from the first to the second large-scale CCUS facility, and this downward trend is expected to continue as the market grows. [70]

Enhanced Oil Recovery (EOR)

When a reservoir becomes depleted, its output can be increased. Enhanced Oil Recovery (EOR) encompasses a set of sophisticated techniques designed to modify the original properties of oil, such as API gravity, viscosity, and wettability. [78]. EOR can be implemented at any point during the productive lifespan of an oil and gas reservoir, to restore the formation pressure and to enhance oil displacement and fluid flow within the reservoir. [78]

Reservoir engineers devise EOR processes to alter wettability to water-wet conditions, which facilitates the removal of oil adhering to the solid surface of the rock, thereby improving oil recovery. The three major types of EOR operations include chemical flooding, thermal recovery, and miscible displacement. [78] The latter involves using CO_2 as a miscible gas in EOR operations. The technique of injecting CO_2 gas into the reservoir is considered a miscible displacement process, as it allows the mixing of the injected gas and oil in the reservoir in all proportions to form a single homogeneous phase. This method helps maintain reservoir pressure, improve oil recovery, and reduce the interfacial tension between oil and water. CO_2 is commonly chosen due to its ability to reduce oil viscosity and cost-effectiveness compared to liquified petroleum gas (LPG). [79]

EOR by CO_2 applies to reservoirs deeper than approximately 2,625 ft, where the hydrostatic pressure reaches the CO_2 critical pressure (1,070.38 psi) and the corresponding crude oil density is less than 0.9 at 15 °C. [15] Under these conditions, the dissolution of supercritical CO_2 increases the mobility of the residual oil in the formation by increasing its volume and saturation and reducing its viscosity. From a carbon capture and storage (CCS) perspective, depths greater than 2,625 ft also enable high storage efficiency by storing CO_2 as a dense supercritical fluid. [15] Therefore, the only carbon storage method applied on a commercial scale to date is the injection of captured CO_2 into permeable rock formations, also known as geological storage. The produced CO_2 plus crude oil mixture obtained from EOR is further separated in surface facilities, yielding oil, hydrocarbon gas, and, after breakthrough, CO_2 product streams. [15], [71] EOR through miscible CO_2 flooding has been extensively applied in the Permian Basin in West Texas and southeast New Mexico, primarily using CO_2 produced from natural CO_2 reservoirs. This incremental oil recovery spans a wide range from 5% to 15% of the original oil in place (OOIP). [15], [80] The CO_2 can be stored at the end of the oil recovery process for climate change mitigation rather than being released into the atmosphere, as demonstrated in the Weyburn field Project in Saskatchewan, Canada.

Key differences

CCUS is primarily applied to industrial and power sector emissions, while NETs and CDRs can be broader, including natural and engineered solutions.

CCUS includes a utilization component (using CO_2 in industrial processes such as EOR), whereas NETs and CDRs are more about removing and permanently storing CO_2.

While these categories overlap, each has its specific focus and application in the broader effort to mitigate climate change.

1.8. Overview of carbon emission trends in Mexico

In Latin America and the Caribbean, Mexico is the second-largest economy behind Brazil. The second-largest steel producer and the eleventh-largest oil producer in the world. [81] Because of this, Mexico's CO_2 emission levels has been fluctuating over recent decades, linked to the country's economic growth, energy consumption, and industrial activities. CO_2 emissions in Mexico peaked at 520.3 $MtCO_2e$[29] in 2019 before declining slightly to 456.3 $MtCO_2e$ by 2021 and 479 $MtCO_2e$ by 2022, accounting for a 1.4% share of global CO_2 emissions. [82] See Figure 18.

[29] CO_2 equivalent (CO_2e) is used as a reference to measure the impact of the rest of GHG. This is because methane (CH_4) has a warming potential 28 times greater than CO_2, however, it is important to keep in mind that because of the amount of CO_2 in the atmosphere, CO_2 is the main contributor to global warming. [82]

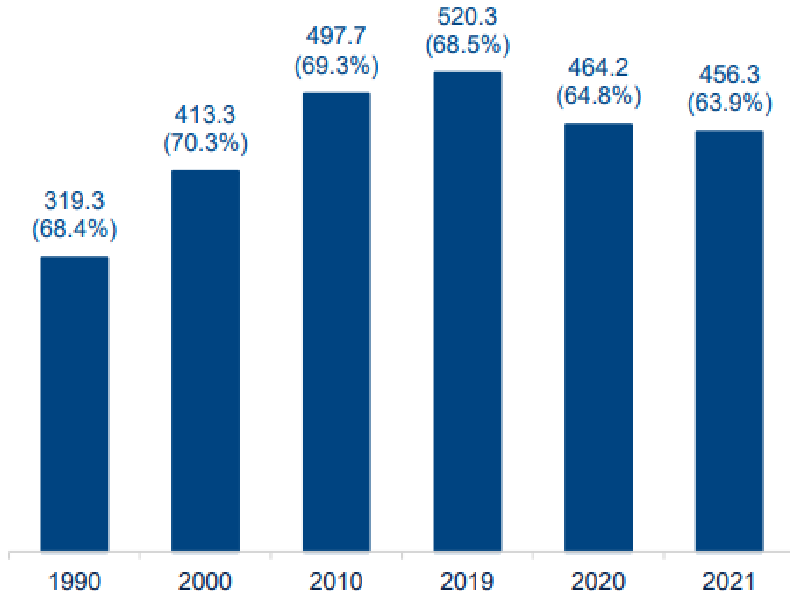

Figure 18. Mexico's brute CO_2 emissions from 1991 to 2021. It is represented by millions of tons of CO_2 equivalent and from the total percentage of GHG. [82]

- Pre-COVID trends: From 1990 up to 2019, CO_2 emissions increased due to rising energy demand, especially in the industrial and transportation sectors. [83]
- Impact of the COVID-19 pandemic. During 2020, Mexico experienced a sharp economic contraction of 8.6%, which resulted in a 5.6% decrease in CO_2 emissions [82]. This decline reflected global trends, as decreased industrial activity and transportation resulted in lower energy consumption. Still, this reduction is viewed as temporary, since emissions rebounded in 2021 with economic recovery. For 2022, the primary sources of CO_2 emissions were the burning of fossil fuels—including natural gas, coal, and oil—for electricity generation, industrial processes, and transportation. [81]

Sectoral breakdown of CO_2 emissions, see Figure 19.

- Energy production (33.3%): The production of electricity and heat, largely dependent on fossil fuels, mainly natural gas, is the second largest contributor to Mexico's CO_2 emissions [82]. Despite efforts to transition to cleaner energy sources, fossil fuels still dominate.
- Transportation (34.2%): The transportation sector is the largest emitter, with vehicles running on gasoline, diesel, and aviation fuels being significant contributors [82]. This sector

offers significant opportunities for emissions reductions through electrification and the adoption of cleaner fuels.

- Industry (11.9%): Industrial activities such as manufacturing, construction, and the petrochemical sector contribute heavily to emissions due to the combustion of fuels like natural gas and petroleum coke [82].
- Other sectors (14.9%): Smaller contributors come from residential, commercial, and institutional energy use, fugitive emissions (gas leaks), and waste management [82].

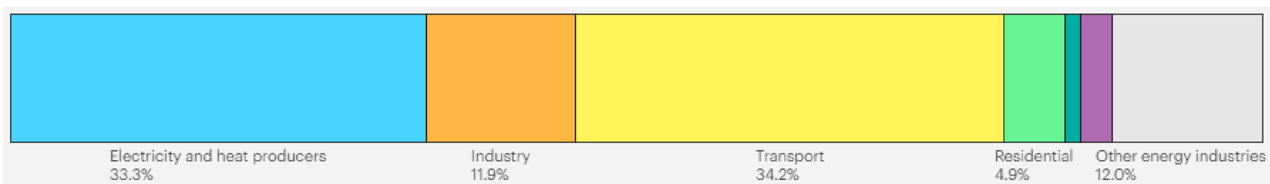

Figure 19. Mexico's CO_2 emissions by sector, 2022. Most of the CO_2 emissions account for the burning of fossil fuels to generate electricity and for transportation. [84]

1.9. Carbon reduction strategies in Mexico

In 2015, the Mexican government approved the Electric Industry Law (Ley de la Industria Electrica), which classifies CO_2 geological storage or biosequestration as a clean energy source, granting the same status as nuclear and renewable energy, and in that same year, Mexico presented CCS as part of its climate change mitigation strategy under the Paris Agreement.

Mexico is actively pursuing policies aimed at reducing its CO_2 emissions in line with international agreements, including:

- Nationally Determined Contributions (NDCs): Mexico’s 2022 updated NDCs pledge to reduce 40% of GHG emissions by 2030, compared to a business-as-usual scenario. This target includes a 35% reduction through domestic measures and an additional 5% contingent on international financing [81], [82].
- Clean energy transition: Mexico’s Energy Transition Law (Ley de Transición Energética) aims to increase the share of cleaner energy in electricity generation to 35% by the end of 2024. However, challenges remain, as the energy sector still relies heavily on fossil fuels [81], [82]

Carbon tax: Since 2014, Mexico has implemented a carbon tax on the carbon content of fuels, excluding natural gas, to promote the use of cleaner energy sources [81]

Mexico's future emission scenarios:

Projections by the EIA outline two main scenarios for Mexico's energy future: the Stated Policies Scenario (STEPS) and the Announced Pledges Scenario (APS). See Figure 20.

- STEPS: This scenario assumes that current policies and trends continue. Under this model, Mexico's fossil fuel dependence remains relatively constant through 2050, with some increase in renewable energy but insufficient to meet its climate targets [81].
- APS: Mexico will meet its climate commitments with a sharp reduction in fossil fuel use and an accelerated shift towards renewable energy, especially solar and wind [81] In this ambitious scenario, there is a substantial reduction in CO_2 emissions from the energy sector.

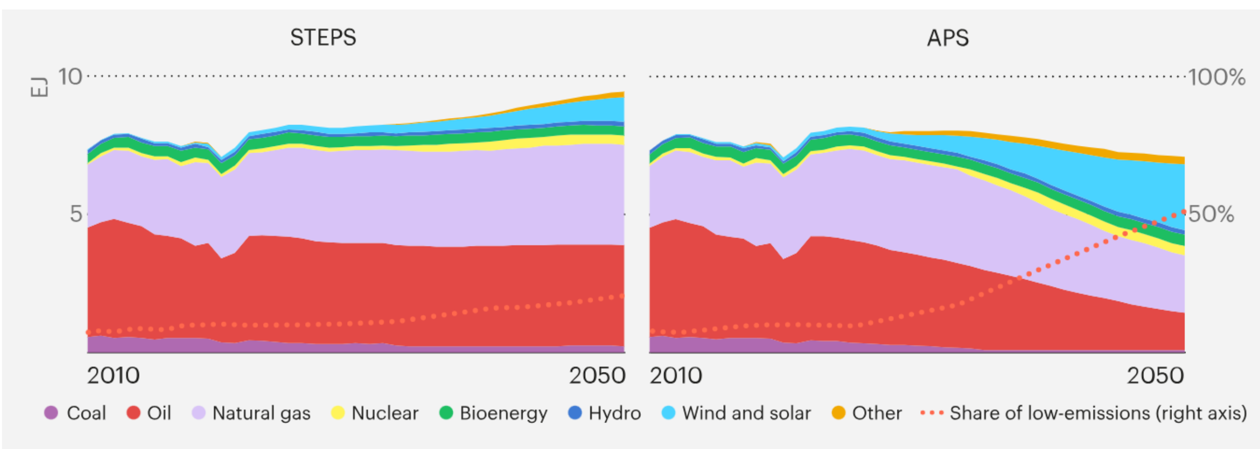

Figure 20. STEPS and APS models predicting the use of fossil fuels into the future. APS is the most ambituous and the primary goal to achieve effictive reductions. [81]

1.9. Previous studies on NETs

In 2018, the Intergovernmental Panel on Climate Change (IPCC), the U.S. Global Change Research Program (USGCRP), and the U.S. National Academy of Sciences (NAS) published that the only solution for averting catastrophic climate change is to remove CO_2 from the atmosphere. [85], [86] However, reducing atmospheric CO_2 levels solely through emission reduction, without NETs, is challenging because some fossil fuel and land-use sources, such as methane emissions from agriculture and CO_2 from air travel, are too complicated and expensive to mitigate. The same could be said for ignoring major mitigation options such as solar power, wind energy, or carbon capture at power plants. Furthermore, NETs are the only option for profound reductions in carbon dioxide concentration in the atmosphere (more than 100 ppm), surpassing what natural sinks can absorb each year. [11]

Combustion of a gallon (3.79 l) of gasoline releases approximately 10 kg of CO_2 into the atmosphere, and permanently storing it has the same effect on atmospheric CO_2 as any mitigation method that simultaneously prevents the combustion of gasoline. [11]

1.9.1. Understanding NETs development process

The development of new technologies typically progresses through four stages: Research, Development, Demonstration, and Deployment (RDD&D). [15] This process outlines the journey of most new technologies, from fundamental research to their eventual commercial application. See Table 6.

Table 6. Example of RDD&D process for carbon capture and storage projects. [15]

Stage	Description	CCS Examples
Research	This phase involves fundamental research and experimental proof of concept led by academic or industrial research organizations. It is a relatively low-cost exploration of a wide range of potential options. The goal is to develop a roadmap that outlines further fundamental and applied research requirements and provides a broad estimate of eventual deployment costs and commercial viability.	Amine-facilitated transport membrane for post-combustion CO_2 separation from flue gas.
Development	The company conducts applied research on process engineering and system integration. This research leads to laboratory and pilot-scale demonstrations of the process. As further implementation issues arise, additional fundamental research may be conducted. The company will also refine construction and operating cost estimates to determine commercial viability.	Hybrid combustion-gasification chemical looping using calcium compounds.
Demonstration	The first large-scale implementation of an industrial project is often financed through partnerships between the government and industry. This process involves	Air-separation plant using ion transport membrane to supply oxyfuel combustion.

	incorporating existing and tested technologies into a new application. The evaluation and enhancement of the project's design, construction, and operational processes are also taken into account. Additionally, the construction and operating costs need to be defined at a budget level.	
Deployment	During the initial stages of implementation, economic incentives such as capital grants or premium prices could accelerate progressive commercial implementation.	Transportation of CO_2 by pipeline; geological storage for enhanced oil recovery.

Developing a new technology is often a complex process since setbacks can occur, especially when transitioning from development back to research, due to obstacles encountered during applied research. This requires additional work to establish fundamental insights. Technology can also span across various stages, being proven in one application or industry but has yet to be in another. Furthermore, the integration of various proven technologies, a process that can be both challenging and beneficial, may require an additional demonstration stage. Although research and development work is usually transferable, repeating the demonstration stage is often necessary to account for location- or industry-specific aspects. [15]

As technology advances through successive stages, costs typically increase, and funding availability and competition control the progress of any project to the next stage. The key drivers of funding decisions are technical and commercial viability or the prospect of that viability in the early stages. Governments often incentivize the demonstration and deployment phases by encouraging initial projects that may be marginal from a commercial perspective, such as the premium pricing for early wind-power deployment in many countries. [15] Continued deployment often leads to reduced capital and operating costs as operating improvements and economies of scale are realized. See Table 7.

Table 7. Characteristics of the technology development process. [15]

Factor	Research	Development	Demonstration	Deployment
Academic involvement	High	Moderate	Low	Low
Industry involvement	Variable	Moderate	High	High
Costs	Typically low	Moderate	Moderate to high	High
Diversity of options	Very broad	Broad	Narrower	Narrow
Government involvement	General or targeted research funding	Focused technology-development funding	Market incentives	Market incentives

Considering the abundance of innovative technologies available to address climate change, and the extensive history of technological advancements in the past century, it is highly likely that the pursuit of such technologies holds significant promise in providing a viable solution to the challenge at hand. However, it is crucial to note that accomplishing this feat requires a unified political will and a sense of urgency across nations to create the ideal environment for the large-scale development of these technologies. [15]

Technology Readiness Level

The Technology Readiness Level (TRL) scale is a framework originally developed by the National Aeronautics and Space Administration (NASA) in the United States in the 1970s and later adopted by other organizations. The TRL provides a snapshot in time of the level of maturity of a given technology within a defined scale. The scale consists of nine levels, ranging from basic research and concept development to fully operational systems. See figure 21. This scale is one way to assess where a technology is on its journey from initial idea to market. [66]

The technology journey begins with defining its basic principles (TRL 1). As the concept and application area develop, the technology advances to TRL 2. It reaches TRL 3 when an experiment proves the concept. The next phase involves validating the concept, starting with a laboratory prototype (TRL 4), followed by component testing in deployment conditions (TRL 5), and full prototype testing in deployment conditions (TRL 6). The technology then moves to the demonstration phase, testing in real-world environments (TRL 7), eventually reaching a first-of-a-kind commercial demonstration (TRL 8) on the way to full commercial operation (TRL 9).

However, reaching TRL 9 is not enough to meet energy policy objectives; scale is often crucial. Beyond TRL 9, technologies need further development to be integrated into existing systems or to reach scale. The IEA has extended the TRL scale to incorporate two additional readiness levels focusing on market development: commercial and competitive technology that needs further innovation for integration into energy systems and value chains at scale (TRL 10), and technology that has achieved predictable growth (TRL 11). [66]

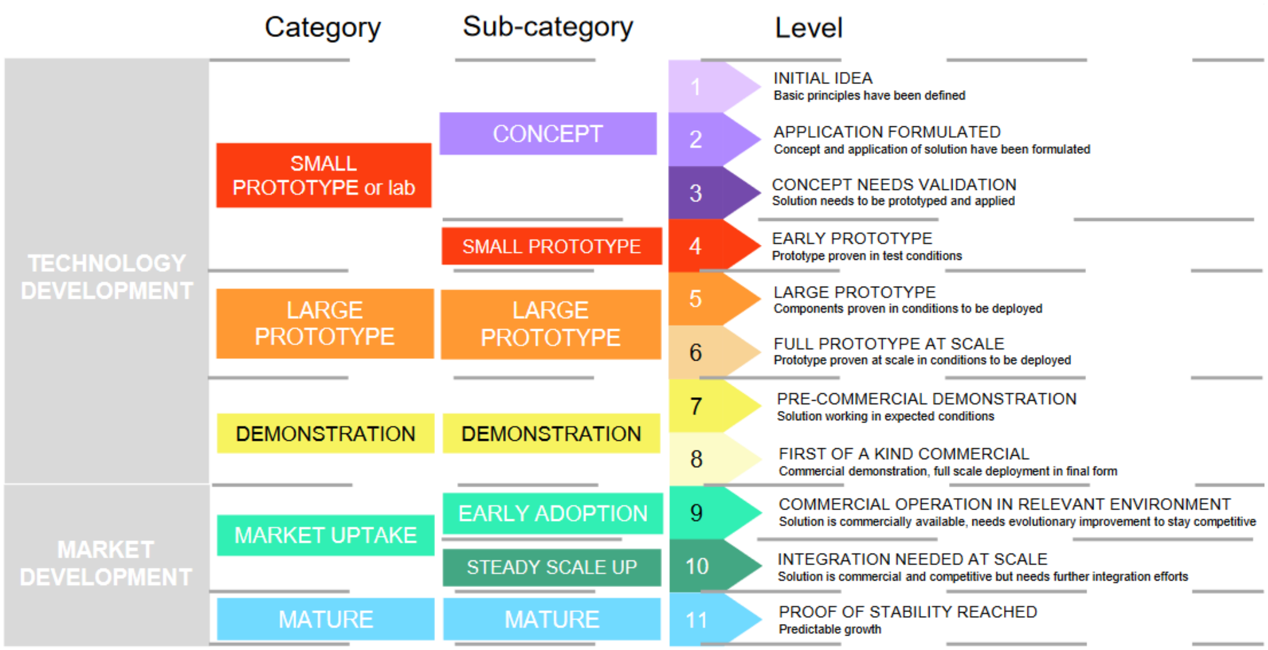

Figure 21. The figure depicts the maturity categories and TRLs along innovation cycles. [66]

Chapter II. Methodology

The methodology used for this study consists in the evaluation of the viability of various Negative Emission Technologies (NETs) in the Mexican context. The following section outlines the research approach, data collection methods, and analytical techniques used.

1. Research Design

This research uses a comparative analysis framework to assess the performance and applicability of four key NETs: Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Capture (DAC),

CO_2 mineralization, and Enhanced Weathering, allowing an in-depth evaluation of each technology's economic feasibility, scalability, environmental impact, and carbon sequestration potential within Mexico's unique environmental, economic, and policy landscape.

2. Data Collection

Data for this study were collected from various primary and secondary sources to ensure a robust and comprehensive analysis including:

- Literature Review: A thorough review of peer-reviewed academic papers, government reports, and industry white papers was conducted to compile existing knowledge about the technical feasibility, costs, scalability, and carbon sequestration potential of each NET. This review also included Mexico's natural resources specific data, energy landscape, and policy framework.
- Case Studies: Relevant case studies of BECCS, DAC, CO_2 mineralization, and Enhanced Weathering technologies implemented in other countries were analyzed to provide insights into success factors, challenges, and lessons learned that could be applied to the Mexican context.
- Statistical Data: Government databases, international energy reports, and environmental organizations were utilized to gather relevant data on Mexico's renewable energy potential, geological resources, industrial capacity, and CO_2 emissions.

3. Geographic and Sectoral Contextualization

The research also integrated a spatial analysis to determine the geographic suitability of each NET in Mexico by considering factors such as renewable energy potential, availability of natural resources, and industrial zones for carbon capture and storage. In addition, sector-specific implications were evaluated, such as how BECCS could integrate with Mexico's agricultural and forestry sectors or how DAC could be implemented in industrial hubs with high energy availability.

Limitations of the Study

While this research provides a comprehensive comparative analysis of NETs in Mexico, it is important to acknowledge certain limitations:

- Data availability: Some data, particularly Mexico-specific cost estimates for emerging technologies like DAC, were limited, which may affect the precision of the results.
- Technological uncertainty: The rapidly evolving nature of NET technologies introduces uncertainty in the long-term projections used in this study.

By employing a rigorous and multi-faceted methodology, this study aims to provide a balanced and comprehensive analysis of the potential for NETs contributing to carbon reduction emissions in Mexico.

Chapter III. Comparative analysis of Negative Emission Technologies (NETs)

3.1. Bio-Energy with Carbon Capture and Storage (BECCS)

Bio-Energy with Carbon Capture and Storage (BECCS) is a negative emission technology (NET) that integrates two critical components: bioenergy production and carbon capture and storage (CCS). It involves using trees and crops to extract CO_2 from the atmosphere as they grow and then using this biomass in power plants. The CO_2 produced from the combustion of this biomass is captured and stored in geological formations, allowing for the permanent removal of CO_2 from the atmosphere. [11]

This process is part of a broader category of biomass energy-based carbon removal pathways, including biomass combustion to thermal and electrical power with carbon capture and storage, biomass thermochemical conversion to fuel with biochar[30] soil amendment, and biomass fermentation to fuel with carbon capture and sequestration. [11], [87]

Bioenergy production paired with carbon capture and storage can result in negative net emissions because the carbon absorbed by growing biomass through photosynthesis is stored rather than released into the atmosphere. Obersteiner et al. (2001) first proposed this concept as a precautionary measure against climate risks, and Keith (2001) presented it as a potential method for mitigating

[30] Biochar is produced by slowly heating biomass by slow pyrolisis. It can be used to enrich soils and therefore remove CO_2 from the atmosphere. However, it is yet to be tested at a large scale. [66]

climate change. [11] Initially, BECCS technology was developed for hydrogen production and later adapted for generating electricity with negative emissions. [87] It is recognized as a crucial approach for removing carbon dioxide to maintain global atmospheric CO_2 concentrations below 500 ppm. [11] BECCS is cost-effective compared to other low-carbon technologies, leading to increased interest as a promising negative emission technology and a means to achieve the global warming targets set by COP21 of staying below 2°C and even 1.5°C. [87] Currently, there are promising developments in the implementation and research of BECCS, with various pilot projects and research initiatives underway. According to the IPCC, many scenarios that limit warming to 2°C consider BECCS as the most cost-effective option for achieving temperature objectives in the latter half of the century, playing a significant role in numerous low stabilization scenarios. [88] Climate change models from the International Energy Agency recommend implementing BECCS to remove at least 2 Gt CO_2 per year by 2050 to keep global temperature rise below 2°C. BECCS involves several key aspects:

Biomass feedstock

The choice of biomass is crucial in implementing BECCS, including the obtained from forest management, encompassing tree stems, branches, bark, logging residues, and sawmill waste. Additionally, biomass is present in agricultural sources such as purpose-grown feedstock, crop residues, and algae cultivation, as well as from municipal organic solid waste (MSW) collection. The growth of biomass absorbs atmospheric CO_2, resulting in an initial negative emission. [11] The sustainability of this biomass is vital to ensure that the net carbon balance is truly negative. Therefore, the decisions made when choosing biomass significantly impact the effectiveness of BECCS. The productivity of biomass supply options varies significantly based on the geography and the source of biomass.

Biomass transport

It is crucial to transport biomass from its source to the conversion facility or end-user for heat, electricity, or other fuel production. Once the biomass is converted, the resulting fuel needs to be distributed to end users. Besides costs, biomass transportation emissions should be considered in the assessments of net carbon emissions from biomass usage. Figure 22 illustrates emissions estimations from dry biomass transportation by truck, train, or sea freight, showing that truck transportation emits significantly more per kilometer compared to train and sea freight. [11]

Bioenergy production

Biomass can be converted into energy through various methods, each with different efficiencies and by-products that affect the overall carbon balance and energy output. [89] For this purpose, both thermochemical and biological processes have been developed. Thermochemical methods comprise pyrolysis, hydrothermal liquefaction, gasification, and combustion. [89] Pyrolysis uses heat on biomass in the absence of air or in the presence of hydrogen to create liquids and gases, which can be refined into fuels or directly combusted. It also produces carbon-rich biochar that can be combusted, gasified, or used as a soil enhancer. [42], [90] Hydrothermal liquefaction transforms biomass into primarily liquid products using high temperatures and high-pressure steam. Gasification partially oxidizes biomass using an oxidant to produce synthesis gas (syngas), which can be converted to liquid fuels through thermocatalytic processes or directly combusted for heat and power generation. Combustion fully oxidizes biomass to generate heat for power production. Biological techniques generate liquid and gaseous fuels through anaerobic digestion and fermentation to produce hydrogen, methane, and alcohol fuels such as ethanol. See Figure 23. These biologically derived fuels can be directly burned for heat and power or further processed into other fuels. [11]

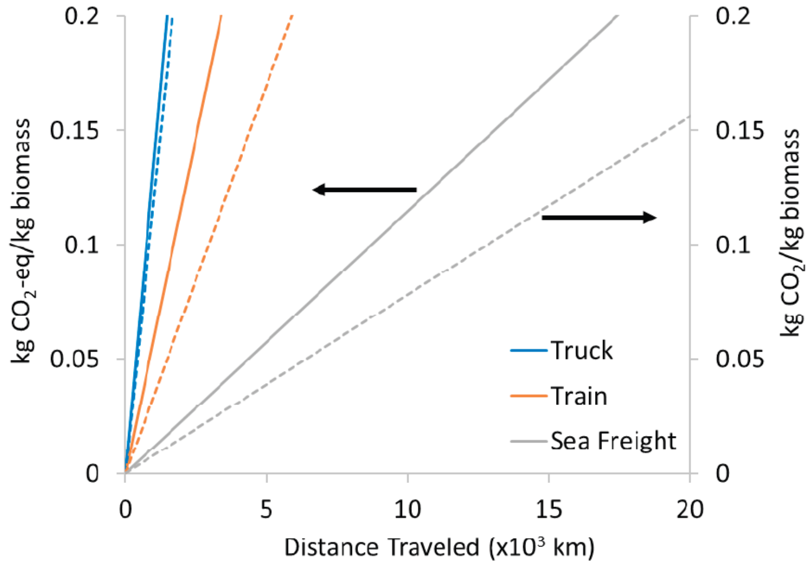

Figure 22. CO_2 and CO_2e emissions per dry biomass produced as a function of transportation distance by road, rail, or sea. [11]

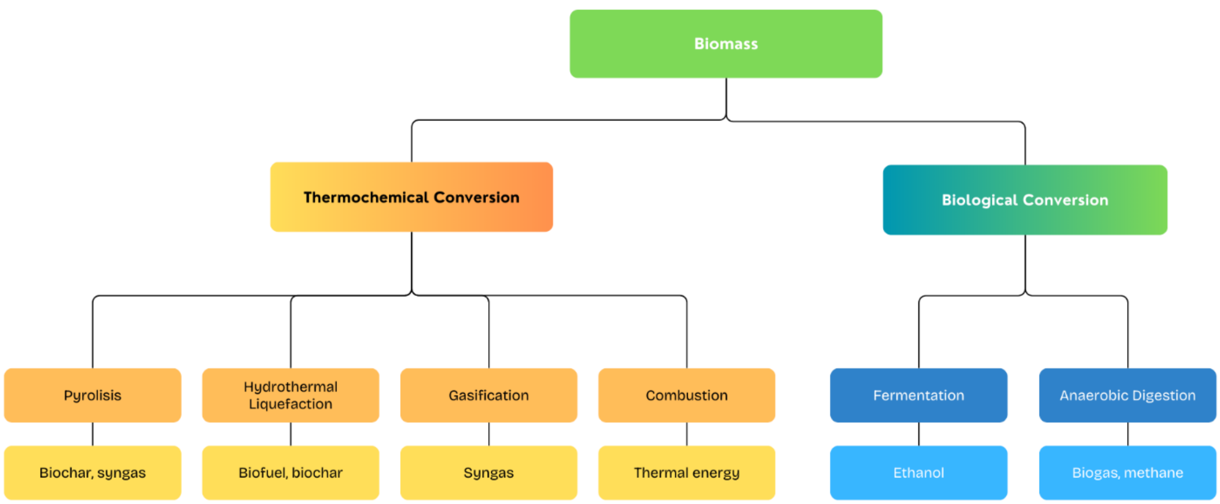

Figure 23. This figure illustrates the various thermochemical and biological processes that convert biomass into energy. Thermochemical processes include pyrolysis, hydrothermal liquefaction, gasification, and combustion. In contrast, biological processes include fermentation and anaerobic digestion. [11]

Carbon Capture and Storage

The technologies for capturing CO_2 from biomass thermal and electrical power generation for BECCS are described in Section 1.7. Post-combustion extracts CO_2 from flue gases produced by burning fossil fuels and biomass. Oxy-fuel combustion uses pure oxygen, yielding mostly CO_2 and H_2O. Pre-combustion capture converts fuel to synthesis gas, then processes it to produce CO_2 and hydrogen for use in various energy applications. They are currently under development for capturing carbon in conventional fossil fuel power plants (CCS). While extensive research is being conducted in all these areas for coal power plants, the various methods vary significantly in technological maturity. [11], [71]

Capturing carbon from fermentation processes, such as those used in ethanol production, can use the same technology being developed for carbon capture in fossil fuel plants. CO_2 is generated as a byproduct of the fermentation process and from the power plant that provides electricity and heat to the fermentation process. [11] The long-term storage stability of CO_2 is a crucial factor in the effectiveness of BECCS as a climate mitigation strategy. BECCS is considered the cheapest of the technology-based approaches, with capture costs ranging from 15 to 80 USD/tCO_2 [31][66], and has a cumulative carbon removal potential of up to 1,170 GtCO_2 for the year 2100, making it one of the most effective NETs for carbon removal. [66]

Economic Aspects of BECCS

Cost of Biomass

The availability and cost of biomass feedstock can vary widely depending on the region, type of biomass, and competition with other uses, such as food production. [11] The cost of biomass plays a crucial role in determining the economic feasibility of BECCS. It encompasses various components, which contribute to the overall cost structure.

Types of biomass feedstock. Agricultural residue costs are typically lower, primarily related to collection, transportation, and processing. However, their availability might be seasonal affecting the consistency of supply. Forestry residue costs are also relatively low but increase if transportation distances are significant. Purpose-grown feedstock costs are generally higher than residues costs but provide a more consistent and scalable biomass supply. Waste biomass is often inexpensive or even

---

[31] The cost of capturing carbon in biomass-based power generation is approximately USD 60 per tonne, whereas BECCS applied to industrial processes incurs a capture cost of around USD 80 per tonne. [74]

negative cost (where disposal fees are avoided), but processing and logistics add to the cost. [11], [91]

Regional variability. The price of biomass is affected by local agricultural practices, forestry operations, and land availability. In areas with plentiful agricultural or forestry leftovers, the cost of biomass may be lower because of shorter transportation distances and existing infrastructure. On the other hand, in regions where land is limited or specific energy crops are necessary, biomass costs can be significantly higher. [91], [92] For example, biomass costs are relatively low in countries like Brazil, where there is an abundant supply of sugarcane residues (bagasse). However, in regions where dedicated energy crops need to be cultivated, such as parts of Europe or North America, costs can be higher due to land use and agricultural inputs. [93]

Transportation cost. Transportation is a significant element of biomass cost, especially considering that the availability of biomass resources differ by country and region, requiring the transportation of biomass over large distances. [11] The distance from the source determines the cost of transporting biomass to a BECCS facility, the type of transport (such as trucks, rail, or barges), and the existing infrastructure. Even in areas with abundant biomass, and short expected distances transportation costs and emissions can still be significant. The results of transportation study expenses for densified biomass in the United States are shown in Figure 23, illustrating that barge transportation is significantly less expensive for long-distance domestic transportation. Truck transportation is cheaper for relatively short distances, while rail transport is more cost-effective than truck transportation for long distances. [11]

Economies of scale. Large-scale BECCS operations might benefit from economies of scale, where the cost of biomass gets cheaper as the scale of operation increases. This can result from purchasing in large quantities, improving how the biomass is transported, and more efficient processing technologies. However, reaching such economies of scale requires significant investment and coordination across the supply chain. [94]

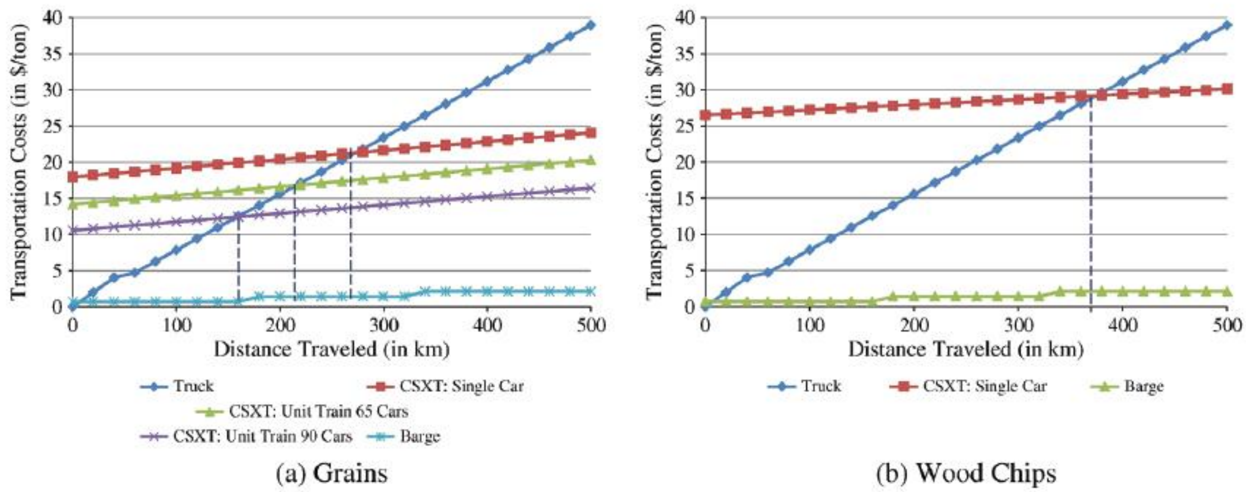

Figure 24. Transportation costs for (a) grains and (b) wood chips from Midwest to East and Southeast United States. [11]

BECCS in climate change mitigation

BECCS is considered one of the few negative emissions technologies (NETs) with the potential to remove CO_2 from the atmosphere. It should be seen as part of a broader portfolio of mitigation strategies, such as improving energy efficiency, using renewable energy, increasing forested areas, and implementing other negative emissions technologies. Its success hinges on globally coordinated efforts, supportive policies, and advancements in technology. [11], [95] Unlike other NETs like afforestation and reforestation, BECCS has been identified as an option with the highest storage permanence.

Commercial Status

The TRLs for BECCS cannot be measured directly, as it consist of various selected pathways, leading to variations in TRLs. For instance, gasification with CO_2 capture for power and heat is at TRL 3, indicating that it is still in the conceptual stage. In contrast, biomass co-firing in kilns with CO_2 capture for cement production has reached TRL 10, meaning it is commercially available but requires evolutionary improvements to remain competitive. [96] Overall, BECCS, particularly in biomass-fueled power generation, has been successfully implemented on a global scale. One notable example is the large-scale biological biomass-to-fuel technology, which has produced around 370 million barrels of ethanol. While few of these projects have integrated the fuel production process with CCS, the Illinois Industrial Carbon Capture and Storage (IL-ICCS) project stands out as the largest of its kind. [11] This bioethanol plant captures pure CO_2 from the fermentation process of corn-based ethanol production and stores approximately 1 million tonnes of CO_2 annually in deep saline formations located more than a mile underground. [97]

3.3. Direct Air Capture (DAC)

Direct Air Capture (DAC) refers to one of the technologies of the portfolio of CDR approaches designed to capture CO_2 directly from the atmosphere, concentrate it to store it in a geologic reservoir or use it for other purposes. [11], [66]

As mentioned in Section 1.6, DAC technologies fall into two main CO_2 separation processes:

- *Solid sorbents:* Solid DAC (S-DAC) systems based on solid filters operating through an adsorption/absorption cycling process that chemically binds with CO_2. The adsorption process takes place at ambient temperature and atmospheric pressure when the air is blown through a solid adsorbent contained within the air contactor. In contrast, desorption occurs through a temperature-vacuum swing process (regeneration), where a concentrated stream of CO_2 and water is released at ambient to low pressure (0.012 – 1.06 bar) and medium temperature (80-120 °C). Finally, the sorbent is cooled before it is restarted. (*DOE Explains. Direct Air Capture*, n.d.; International Energy Agency, 2022) A single adsorption/desorption unit has a capture capacity of several tens of tonnes of CO_2 per year (e.g. 50 tCO_2/year). It can be used to extract water from the atmosphere where local conditions allow.[32] An S-DAC plant has the advantage of a modular design and can include as many units as needed. [66]

[32] Early prototypes were able to remove around 1 tonne of water per tonne of CO_2

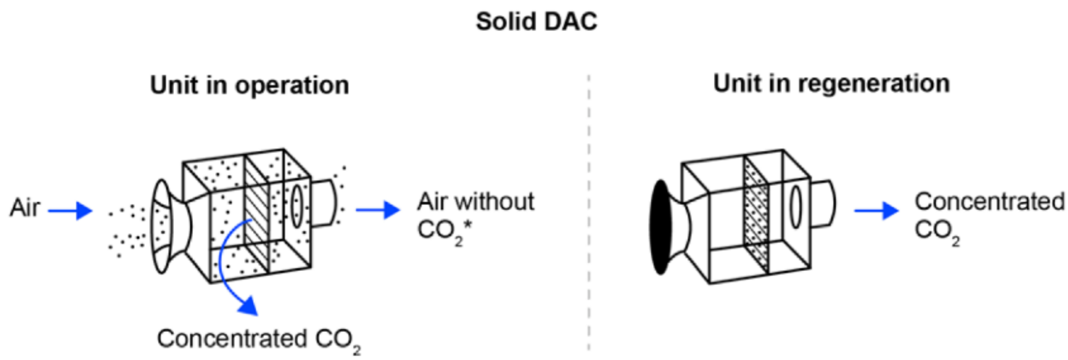

Figure 25. S-DAC system. Air is drawn into the collector, where a filter captures the CO_2, and once the filter is saturated, the collector is closed and heated to release the captured CO_2 in a process known as regeneration. [66]

- *Liquid solvents:* Liquid DAC (L-DAC) systems pass air through chemical solutions, which removes the CO_2 while returning the rest of the air to the environment. (*DOE Explains. Direct Air Capture*, n.d.; International Energy Agency, 2022) The system is based on two closed chemical loops. The first loop takes place in the contactor unit, which brings atmospheric air into contact with an aqueous basic solution (such as potassium hydroxide), capturing CO_2. The second loop releases the captured CO_2 from the chemical reaction with the pellets in a series of units operating at high temperatures (between 300°C and 900°C). [66] See Figure 26.

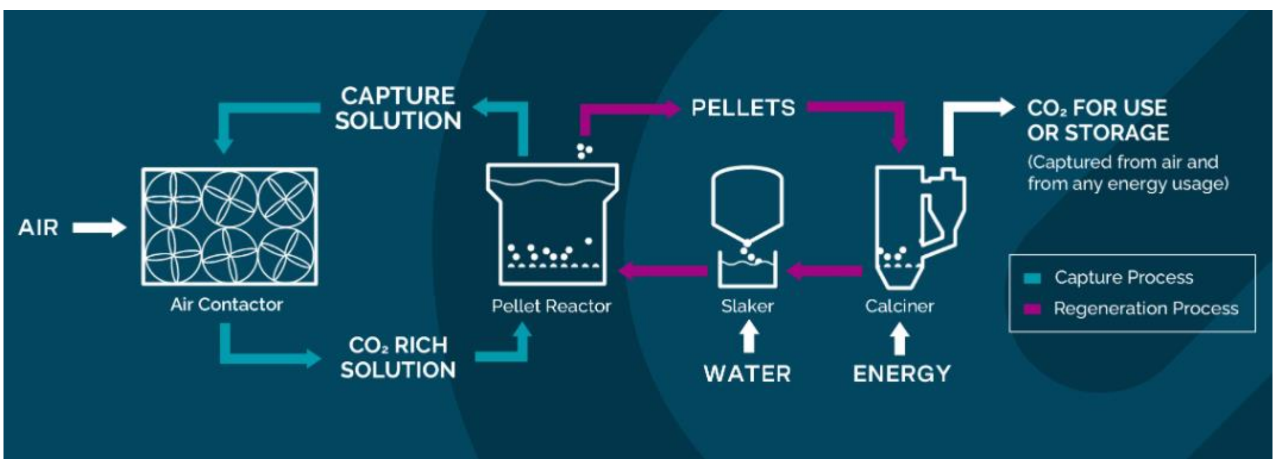

Figure 26. L-DAC system. The capture solution reacts with the CO_2 in the air to form a carbonate salt. The salt is then separated into small pellets that are then heated in a calciner to release the CO_2 in pure gas form. Processed pellets are hydrated in a slaker and recycled back into the captured solution. [99]

The TRL for DAC varies. The TRL ranges from level 5 to 6 for liquid DAC, indicating that it is primarily a prototype that still needs to be validated at scale. In contrast, Solid DAC has a TRL between levels 7 and 8, meaning the technology is in the pre-commercial demonstration stage. [64] Solid sorbents or liquid solvents do not need valuable arable land, therefore, DAC technologies do not compete for land use with the food or bioenergy industry.

DAC has been in operation since 2010, and the number of DAC installations has been growing ever since, and as of 2024, 27 plants were operating across Europe, North America, Japan, and the Middle East. [100] These are all small-scale, capturing a total of almost 0.01 $MtCO_2$/year[33]. Plans for at least large-scale (> 1,000 MtCO2/year) 130 DAC facilities are now at various stages of development.[34] [101]

In the IEA Net Zero Emissions by 2050 Scenario, DAC technologies capture more than 85 Mt of CO_2 in 2030 and around 980 $MtCO_2$ in 2050, requiring a large and accelerated scale-up from almost 0.01 $MtCO_2$ today. [66] In 2050, around 13% of all CO_2 emissions captured are DAC, and 64% are stored underground. Approximately 350 Mt, or 36% of the CO_2 captured from DAC, is used in combination with hydrogen to produce synthetic hydrocarbon fuels for aviation. DAC plays a significant role in providing one of the limited solutions available to reduce emissions in aviation transport, which remains one of the most challenging sectors to decarbonize. [66]

Geological CO_2 storage through DAC presents various benefits as a CDR method, such as requiring a relatively small amount of land and water and providing a high level of certainty regarding the storage's permanence and the measurement of removed CO_2. [66]

Governments and private investors have committed billions of dollars for the development and deployment of DAC technology. The United States alone has allocated significant funding for DAC hubs and a DAC Prize Program. Other countries such as Australia, Canada, Japan, and the United Kingdom are also providing R&D funding. Private and philanthropic investment in DAC technology

[33] Only 3 plants are capturing 1,000 metric tons of CO_2 per year or over, including Climework's Orca plant in Iceland, Global Thermostat headquarters plant in Colorado, and Heirloom's first large-scale dacility in California.
[34] 100 of these facilities are from 1 PointFive and Carbon Engineering (Now Oxy) 2035 project and 15 are currently in advanced development or under construction.

is growing, with leading companies raising substantial capital. Additionally, DAC is one of the technologies targeted for significant investment and is eligible for a Carbon Removal XPRIZE. [66]

Energy Requirements

DAC is highly energy intensive due to the CO_2 concentration in the atmosphere, and DAC plants are strongly dependent on operating temperatures (energy). While both L-DAC and S-DAC were initially designed to operate using heat and electricity, S-DAC can also operate using only renewable sources, which is very attractive from an environmental perspective. Based on the current commercial technology, the operating temperature is above 500°C only for very specific large-scale operations within the iron and steel sector. [66]

The lower temperature heat needs of S-DAC means it can be fuelled by renewable energy sources such as nuclear, hydropower, geothermal, solar energy, and biomass-based fuels; however, L-DACs' high-temperature configuration requirement relies on natural gas, and the produced CO_2 is captured within the process and not emitted. Theoretically, L-DAC could operate using low-carbon fuels such as biomethane or renewable-based electrolytic hydrogen for medium temperatures. [66] See Figure 27.

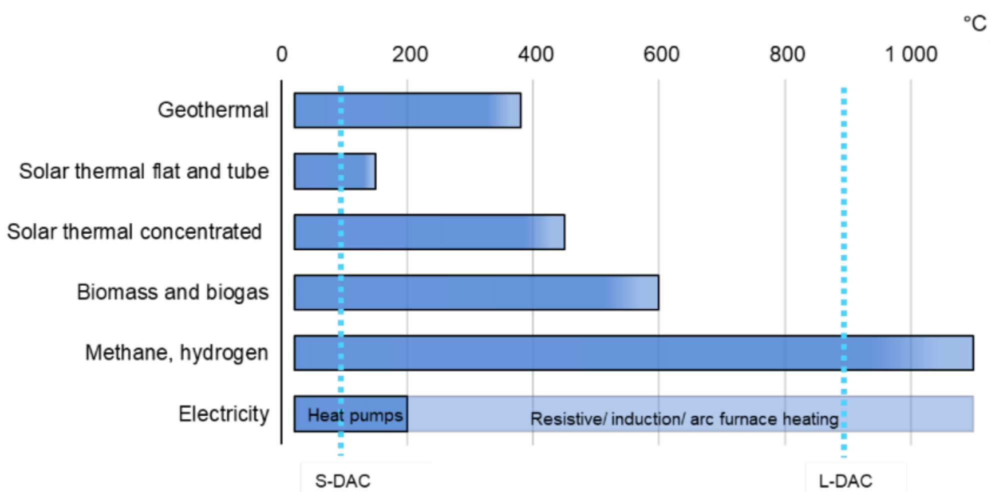

Figure 27. Operating temperatures of heat-generating technologies. The vertical dashed lines indicate the maximum operating temperatures for S-DAC and L-DAC respectively. [66]

However, accelerating the commercial availability of large-scale electric calcination technology is considered a high priority to enable L-DAC plants to operate purely on renewable energy. [66], [102] [66]

Optimal locations

A major advantage of DAC plants is that they can be virtually anywhere, for example near a suitable storage site for carbon removal, or an industrial facility seeking a supply of atmospheric CO_2 rather than fossil feedstock, this reduces the need for long-distance CO_2 transport. [66] However, for DAC to succeed, there must be a nearby suitable site where the CO_2 can be stored. If this is not the case, the costs associated with CO_2 transport can increase significantly. This CO_2 captured from the atmosphere through DAC can be stored geologically in deep saline aquifers, depleted oil and gas fields, and other rock formations, such as basalt, with deep saline aquifers having the largest storage capacity. When DAC is combined with a geologic storage mechanism, it is known as Direct Air Capture and Storage (DACS). [66]

Locations characterized by high renewable potential are best placed to host DAC plants, especially if characterized by substantial CO_2 storage potential where carbon removal is the objective. The Orca plant in Iceland uses geothermal power to generate electricity to power the S-DAC plant for CO_2 capture and subsequent storage through mineralization. (*Orca Is Climeworks' New Large-Scale Carbon Dioxide Removal Plant*, n.d.) Most geothermal plants are located along the west coast of the US and Mexico, Japan, the Philippines, South America, Eastern Europe/Asia and Southern China. Since DAC plants can also be powered by PV, the locations considered for these plants should be aligned with those of most PV potential; regions across the southwestern United States and Mexico, eastern South America, the Middle East, and eastern Australia are the most promising. [66]

Additionally, co-locating DAC facilities with existing assets and infrastructure where waste heat is available presents another option for powering DAC plants. Sources of waste heat include power and industrial plants, combined heat and power plants, synthetic fuel production processes, incineration processes, and cooling towers. [66]

Costs

The concentration of CO_2 in the atmosphere is significantly lower than in fixed sources, making the process of capturing CO_2 from the air much more expensive, since energy requirements increase for DAC compared to other CO_2 capture technologies. [103] See Figure 28. The costs associated with DAC are highly uncertain, the IEA Greenhouse Gas (IEAGHG) R&D Programme estimates the removal costs between 125 and 335 USD per ton of CO_2. [104]

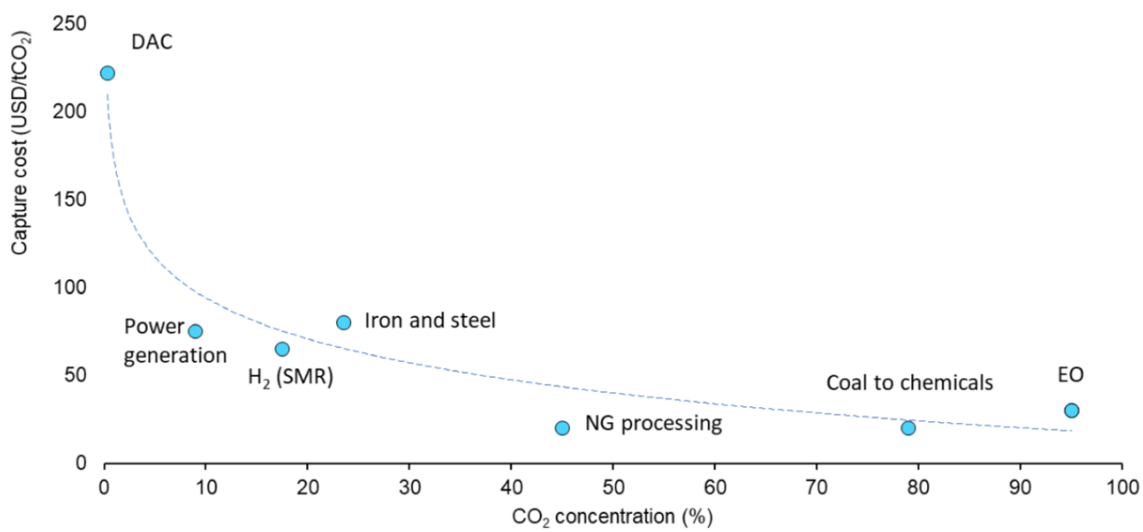

Figure 28. CO_2 capture cost at varying CO_2 concentrations. The empirical trend line shows the correlation between capture cost and CO_2 concentration. As CO_2 concentration from the source decreases, the capture cost increases. H_2 = hydrogen; SMR = steam methane reforming; NG = natural gas; EO = ethylene oxide. [101]

However, with low heat and electricity prices, the carbon capture expected costs could decrease to slightly above the industry goal of 100 USD per ton of CO_2, if the captured emissions are monetized through a carbon pricing system, the cost of capture could drop below that, making DAC competitive with other options for reducing emissions in specific industrial and transportation sectors. Studies from major technology providers suggest that capture costs will likely decrease significantly over the next 5 to 10 years due to widespread global deployment of DAC on a scale ranging from thousands to millions of tonnes capture capacity. [66]

The Carbon Negative Shot initiative was introduced by the Department of Energy (DOE) to encourage creativity in carbon dioxide removal methods to capture CO_2 from the air and storing it in quantities of 1 billion tons for under 100 USD per net metric ton of CO_2e. [98]

Europe and North America are well suited for hosting DAC plants due to their experience and potential for co-siting with existing industrial hubs, CO_2 transport, and storage infrastructure. Other cost-competitive regions for DAC deployment are North Africa, the Middle East, Russia, and Japan. The global DAC deployment rate aligned with the Net Zero Scenario could substantially decrease CAPEX, up to 49-65% lower by 2030 and 65-80% lower by 2050. Regional differences in CAPEX are expected, with lower costs in China, the Middle East, Russia, and North Africa. Additionally, gas and CO_2 prices vary across regions, contributing to the regional cost of carbon captured via DAC decreasing over time by 31-43% during 2020-2030 and 10-24% during 2030-2050. [66]

Several companies, such as Carbon Engineering, Global Thermostat, and Climeworks, aim to commercialize direct capture systems. Climeworks is the most advanced in market progress; it primarily sells its products to a relatively small market that requires high-cost CO_2 to enhance productivity and may cost more than 1,000 USD/t CO_2 if the greenhouse is far from the origin source. Because this market is small, it does not provide enough support for a diverse group of smaller innovators to explore different methods and technologies that could reduce the cost of direct air capture. For this reason, government intervention, such as incentives, is required to foster innovation and drive down costs in developing DAC systems, similar to what has been done for technologies like solar panels, hydraulic fracturing, and horizontal drilling. [11]

Scalability

The current challenge is to scale up DAC technology to impact climate change significantly. Eight large-scale 1MtCO_2/year plants should be built annually during the current decade. From 2030 to 2040, 50 plants are necessary annually, and almost 40 plants per year are indispensable between 2040 and 2050 to achieve the envisioned level of DAC deployment by 2050 in the Net Zero Scenario. Resource availability poses another challenge since delivering 1Gt of CO_2 removal would require 17-36 Mt of steel, concrete, copper, and aluminum to build 17-36 DAC plants, each capturing 1 Mt CO_2/year considering a material intensity 1:1. (1 Mt of materials per 1 Mt CO_2 captured annually), as well as 3-7 Mt of chemical commodities for liquid solvents and solid sorbents.

Additionally, capturing almost 1 GtCO_2/year from the atmosphere by 2050 could require up to 50 Gt of water and around 6 EJ of energy, per year. If in Mexico the energy were supplied only by PV, and considering that every square meter of solar panel produces an average of 200 W/day, one commercial solar panel produces 0.2 kWh/m^2, so in one day this would produce 4.8 kWhd/m^2, and in a year 1752 kWh/m^2. [105]

Converting to MJ/m^2:

$$\left(1752\,\frac{kWh}{m^2}\right)\left(3.6\,\frac{MJ}{kWh}\right) = 6307.2\ MJ/m^2$$

To find the area required and considering 6 $EJ = 6x10^{12}MJ$

$$A = \frac{total\ energy}{energy\ per\ unit\ area} = \frac{6x10^{12}MJ}{6307.2\ MJ/m^2} = 9.51x10^8\ m^2$$

Converting to square kilometers

$$(9.51x10^8 m^2)\left(\frac{1\ km^2}{10^6\ m^2}\right) = 951\ km^2$$

So roughly 951 km^2 of land would be required, significantly increasing its land footprint, thus challenging its main advantage. [66]

Permanence and leakage risk

To apply successful Direct Air Capture (DAC), the CO_2 must be either used as feedstock for producing chemicals, fuels, and building materials, or stored underground for permanent removal. In the IEA Net Zero Emissions Scenario, about 95% of the total captured CO_2 is intended for underground storage rather than for use, and by 2050, 630 MtCO_2 out of the 980 MtCO_2 captured via DAC, will be permanently stored. [66]

According to the Sixth Assessment Report of the IPCC, DACS is considered the Carbon Dioxide Removal (CDR) option with the highest storage permanence. [66]

Land Requirement

DAC systems have fewer requirements compared to BECCs and afforestation/reforestation. [11] Current estimations suggest that to capture 1 MtCO_2/year the L-DAC plant area should be approximately 0.4 km^2, while an S-DAC plant area should be between 1.2-1.7 km^2. Furthermore, the choice of energy source can significantly increase the S-DAC land footprint, ranging from 1.5 and 23 $km^2/MtCO_2$ annually for geothermal and solar PV, respectively. [66]

Environmental and social acceptance

The water requirements of DAC plants are small and limited compared to other NETs. For instance, L-DAC requires water for its operation, while S-DAC can also extract water from the air. In dry climates, S-DAC could provide water for other purposes such as hydrogen production. [66] To date, very few studies have investigated the public's perception of DAC among other technologies. With the little information that has been gathered, most of the public was concerned with the newness of DAC technology, furthermore, they did not fully understand the idea of capturing CO_2 from ambient air. So this suggests that DAC could face further public opposition due to a lack of engagement and understanding from the public, since many are skeptical of the CDR options because it seemed to take too long to deploy. [66]

Life Cycle Assessment (LCA) plays a crucial role in evaluating the overall environmental impact of CDR, and CCUS. It provides an analysis of the environmental consequences of these technologies across their entire lifecycle, that being from raw material extraction to end-of-life management. sources. The number of LCAs available for DAC is limited, and most research suggests that DACS is carbon negative. Additionally, DAC for CO_2 use can be carbon-reducing when it is powered by low-carbon energy sources. [66]

3.4. Carbon mineralization of CO_2

Although carbon mineralization is a natural geologic process that takes millions of years, scientists can now simulate and accelerate this process by intentionally exposing CO_2 to basalt or ultramafic rock formations. This results in the formation of solid carbonate minerals, such as calcite or magnesite, which permanently trap the CO_2. This method provides a long-term solution for CO_2 storage and has recently gained attention, particularly in the field of CCUS. Geologic storage of CO_2 in ultramafic and mafic formations has the potential to accommodate tens of billions of tons of CO_2 per year and ultimately store thousands of trillions of tons. [11]

The CO_2 mineralization involves the chemical reaction of CO_2 with alkaline silicate minerals rich (e.g. serpentine, and basaltic rocks) in calcium (Ca) and magnesium (Mg) such as olivine, to form solid carbonates such as calcite ($CaCO_3$), magnesite ($MgCO_3$), and dolomite ($CaMg(CO_3)_2$).

The generalized chemical reaction is summarized as follows:

$$CO_2 + Metal\ oxide\ (MgO, CaO) \rightarrow Metal\ carbonate\ (MgCO_3, CaCO_3)$$

However, the idealized reactions are as follows:

Brucite	$Mg(OH)_2 + CO_2 \rightarrow MgCO_3 + H_2O$
Olivine	$Mg_2SiO_4 + 2CO_2 \rightarrow 2MgCO_3 + SiO_3$
Pyroxenes	$CaMgSi_2O_6 + 2CO_2 \rightarrow CaMg(CO_3)_2 + SiO_2$
Serpentines	$Mg_3Si_2O_5(OH)_4 + 3CO_2 \rightarrow 3MgCO_3 + 2SiO_2 + 2H_2O$
Wollastonite	$CaSiO_3 + CO_2 \rightarrow CaCO_3$

These reactions are spontaneous and exothermic, with olivine, serpentine, and wollastonite among the most reactive minerals for CO_2 mineralization. [11]

This process of storing CO_2 via a chemical reaction with common silicate rocks and minerals has been considered for at least 30 years now. [11] Carbon mineralization methods can be broadly categorized based on their objectives, which include storing CO_2 in carbonate minerals or removing CO_2 from the air and storing it in carbonate minerals. However, the primary focus of this section will be to examine the different variations of mineralization associated with storage.

Types of CO_2 mineralization

In-situ mineralization: Also known as mineral trapping, involves injecting and circulating CO_2-bearing fluids, such as CO_2 dissolved in water, into geologic formations, which react with minerals underground and form carbonate minerals. The CO_2-depleted fluid can go back to the surface or remain in the subsurface by different means of trapping mechanisms from those of mineralization.

[106], [107] Another method involves injecting supercritical CO_2[35] into basalt rocks, which requires significantly less or no water at all. One example is the Wallulla Project, where the first supercritical CO_2 injection was conducted in flood basalt formations. [108] Other rock formations favorable to in-situ mineralization include iron-rich sandstone and glauconitic sediments. [106] Basalt rocks, in particular, have shown significant potential for in-situ mineralization its permeability and porosity can store great quantities of CO_2. Pilot studies have shown mineralization in just under two days. [106] Large basaltic formations[36] exist in several regions worldwide, and both onshore and offshore sites have been considered. Subsea tectonic spreading regions are ideal for injecting CO_2 due to their unique geohydrological activity. Injecting CO_2 away from the spreading region and entraining it in the flow could lead to the formation of various carbonate species such as magnesite, magnesium carbonate, dolomite, and carbonite. [107] In-situ mineralization investigations focus on basaltic lava and mantle peridotite due to their widespread distribution and fast carbon mineralization rates.

Ex-situ mineralization: This process involves reacting concentrated CO_2 with crushed alkaline feedstock, commonly ultramafic or basalt rocks, at the surface to form carbonate minerals. The feedstock includes crushed mine rocks and mine tailings, and can also be used with industrial waste. This mineralization can be carried out at industrial sites or mines. The interest in using industrial waste as a source for reactant mineral carbonation has increased because they are readily available, cheap, and often generated near large CO_2 emission sources. [107] The process occurs in high-pressure and/or high-temperature reactors[37], where alkaline rocks react with concentrated CO_2. See Figure 29. [110], [111]

[35] Supercritical CO_2 refers to CO_2 held at or above its critical temperature and pressure; in other words, it is CO_2 compressed to a density similar to water.

[36] The uppermost few kilometers of oceanic crust predominantly consists of basalt. Therefore, areas where the oceanic crust remains largely unburied by sediment present potential sites for mineralization. [109]

[37] The original development of ex-situ CO_2 mineralization of calcium and magnesium-bearing silicate minerals took place at Los Alamos National Laboratory (Texas) in the mid to late 1990s. [107]

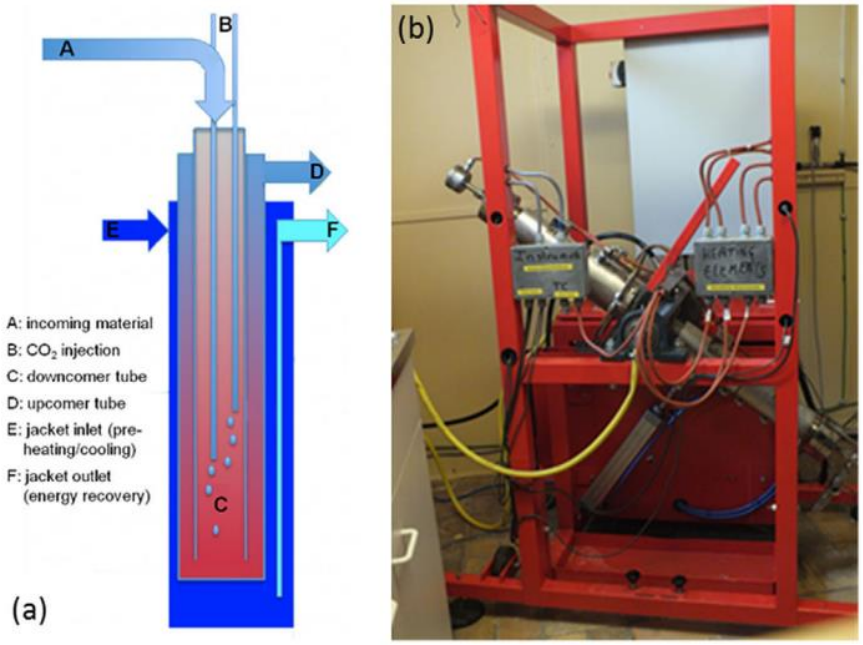

Figure 29. (A) Conceptual layout of "CO_2 energy reactor"; (B) lab scale energy reactor. Through the reaction of CO_2 and water with powdered rocks in the reactor, we can replicate the natural processes of rock dissolution and carbonate mineral precipitation that occur in the natural CO_2 cycle. At increased pressures and temperatures, the reaction occurs more quickly. Additionally, pulverizing the rock maximizes the reactive surface area of the initial material, further expediting the reaction. [112]

This process can be much faster than injecting CO_2 underground since the crushed rocks have more surface area. However, removing high volumes of CO_2 quickly requires large quantities of fresh rock to be extracted, making it one of the most energy-intensive and expensive CDR approaches, and is about ten times more expensive than in situ mineralization, with mined rock mineralization currently costing around 600 USD per ton CO_2. [109], [110] Another approach is to capture and convert carbon dioxide emitted from burning fossil fuels to create carbonate materials for construction, such as bricks. The estimation is that this approach would capture 1 Gt of CO_2 annually, representing one step forward to decarbonization.

Co benefits

There are not many benefits associated with both ex-situ and in-situ CO_2 mineralization because this technology is still in its infancy. In one particular example, because of the limited research on in situ peridotite carbonation due to the observation of natural feedback mechanisms between physical and chemical processes, such as the reaction-driven cracking in which volume expansion due to carbonation causes fractures, which in some cases maintain or enhances permeability and reactive surface area. See Figure 30. Engineered methods control these feedbacks and can have other valuable applications such as oil and gas extraction from tight reservoirs, in situ solution mining, and production of geothermal power. In some cases, ex-situ mineralization mitigates environmental hazards; for example, the carbonation of chrysolite asbestos reduces the significant health hazard of using natural fibrous asbestos as a mine tailing. Additionally, the carbonation of alkaline industrial waste can significantly reduce the risk of chemical contamination. [11]

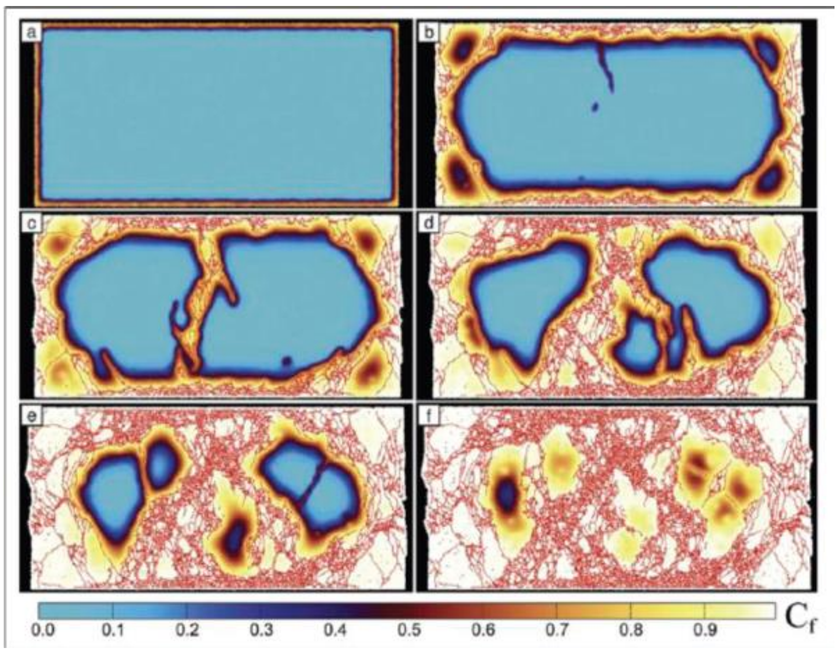

Figure 30. Two-dimensional numerical model of reaction-driven cracking of rock surrounded by fluid. The rock (blue) reacts with CO_2 rich fluid (black) that forms solid products (white), with volume increase and associated stress concentrations inducing fractures. [11]

Scalability

CO_2 mineralization has a high potential for large-scale deployment, mainly due to the abundance of minerals such as olivine, serpentine, and basaltic rocks worldwide. However, this is currently difficult for ex-situ mineralization because its scalability is limited by the need for sufficient quantities of reactive minerals at the surface, compared to the subsurface, and it is also limited to its high cost of processing and transport. [112] On the other hand, the scalability of in-situ projects is limited mainly to the size and availability of basalt formations near CO_2 emission sources.

Land requirements and environmental impact

In contrast to ex-situ mineralization, in-situ mineralization has a lower land-use impact because it leverages underground geological formations for storage. The surface footprint is only limited to CO_2 injection wells, monitoring stations, pipelines if needed.

The main advantage of CO_2 mineralization is that it provides a permanent solution for storing CO_2, especially through in-situ mineralization, since CO_2 is converted into stable carbonate minerals, eliminating the risk of it being released back into the atmosphere. This method has virtually zero leakage. [109] However, with ex-situ mineralization, large-scale mining operations for reactive minerals may be necessary, leading to habitat destruction and deforestation in some cases. Additionally, if fossil fuels are used for energy in the mining, transport, and processing of minerals, the overall potential for reducing emissions through CO_2 mineralization is reduced. This emphasizes the importance of using low-carbon energy sources to minimize environmental risks.

Natural mineralization systems have much lower Ni and Cr concentrations compared to the U.S Environmental Protection Agency (EPA) limits for safe drinking water. [11] Thus, there is a potential risk of groundwater contamination if the injected CO_2 or other chemical reactants used in the process migrate into nearby aquifers.

Commercial status

CO_2 mineralization has a relatively high TRL, ranging from 4 to 9, depending on the specific technology variant. For instance, the CO_2 mineralization process used for sequestration in inert carbonate materials, particularly in cement and concrete production, is at TRL 9, indicating that it is currently in commercial operation. [64], [113]

CARBFIX

Carbfix serves as a notable example of a commercially successful CO_2 mineralization project, which was initiated in 2007 and is located in Reykjavík, Iceland. This project typically injects CO_2 sourced from point emissions or nearby direct air capture (DAC) facilities. See Figure 31. A standout feature of Carbfix is its utilization of the Hellisheiði Geothermal Power Plant. [114], [115] Here, geothermal gases are dissolved in condensate from the power plant's turbines within a specially designed scrubbing tower before being injected into underground basaltic formations. The primary energy requirement associated with the Carbfix technology pertains to the energy needed to pressurize CO_2 and supply water to the injection wells. Depending on geological conditions, this energy requirement ranges from 40 to 80 kWh per tonne of CO_2. Since 2014, a total of 100,000 tonnes of CO_2 have been injected, with an average of 29.3 tonnes of CO_2 injected each day. [115]

Figure 31. Carbfix's innovative geodesic dome facilitates the blending of CO_2 emissions from a nearby power plant with groundwater, subsequently enabling the injection of this mixture into the underlying volcanic basalt rock for effective carbon sequestration. [114]

3.5. Enhanced weathering

It is also known as accelerated weathering, artificial weathering, or mineral carbonation. It can be described as a class of carbon mineralization known as surficial mineralization. This is a carbon sequestration process where alkaline minerals contained in crushed rock powder react with atmospheric or concentrated CO_2. [106]

Weathering is a natural process that takes place when acid rain dissolves minerals, which then react with CO_2, mineralizing it, and forming solid carbonates. Nevertheless, the process is accelerated by spreading fine-powdered silicate minerals such as olivine on vast areas, such as farmland, forestland, and coastlines, which then react with atmospheric CO_2, trapping it in stable solid carbonates. [66], [111], [116] Olivine powder dissolves in seawater along coastlines, converting dissolved CO_2 in surface water into bicarbonates and carbonates. This process helps absorb additional atmospheric

CO_2 into the ocean, acting as an "antacid" for the ocean and raising the water's pH, reducing local ocean acidification. [106] Enhanced weathering is a passive, naturally occurring form of mineralization that takes place on the Earth's surface over long time scale (years or even decades).

This technology is currently in the prototype stage, with a TRL of 4 to 6 [117], and is still pending demonstration. It has high permanence similar to in-situ mineralization, offering significant cumulative carbon removal potential, estimated from 100 to 367 $GtCO_2$ by 2100, and 50-200 USD/tCO_2 capture costs. [66].

Energy requirements

A case study conducted in the United Kingdom found that the energy requirements range from 764,320 to 11,945,909 BTU per tonne of CO_2. Notably, the mining, grinding, crushing, and transport of minerals to deployment sites are highly energy-intensive, collectively, accounting for 77-94% of the overall energy requirements. [118]

Scalability

Enhanced weathering is considered promising for large-scale carbon sequestration because the reactive materials needed for mineralization, such as silicate minerals like olivine or basalt, are abundant globally, so it is technically feasible to scale up operations. However, it would require overcoming the high energy requirements and costs associated with mineral processing and their transport, also it is necessary substantial financial investment. [119]

Co-benefits and environmental impact

The effectiveness of large-scale enhanced weathering is still uncertain. The chemical reactions of ground rock in natural soils or seawater are complex and difficult to predict. Some studies have suggested that olivine in seawater may quickly stop combining with CO_2 in certain environments, or that using the wrong type of olivine may actually add CO_2 to the atmosphere through secondary reactions involving iron. Some byproducts of mining, grinding, and applying rock may harm natural ecosystems or human health. These details need to be addressed before enhanced weathering is used on a large scale. [119]

On the other hand, in a study done at Nafferton Farm in northeast England, researchers found that spreading crushed 4 mm basalt particles can have several benefits for soil health and agriculture. Basalt and wollastonite contain essential nutrients like magnesium, calcium, and potassium. When these rocks weather, they release nutrients, reducing the need for fertilizers and improving soil health, providing nutrients to crops. Using crushed basalt as a soil amendment can also release important nutrients like calcium, magnesium, potassium, phosphorus, sulfur, copper, iron, manganese, molybdenum, and zinc, which are necessary for plant growth. Additionally, the slow release of nutrients from silicate rock amendments can reduce the risk of nutrient leaching and surface run-off, which can contaminate water sources. One of the most significant benefits of using crushed silicate rock as a soil amendment is its ability to neutralize acidic soils, improving plant nutrient availability and potentially increasing crop yield. [120]

3.6. Comparative Matrix

A comparative matrix has been developed based on the previously gathered data concerning BECCS, DAC, CO_2 mineralization, and enhanced weathering. This matrix aims to elucidate the distinct strengths and limitations of the NETs covered in this study, which is a vital framework for assessing their relative feasibility and sustainability across diverse contexts.

Table 8. The following table was generated with all the research carried out in the previous chapters.

Criteria	BECCS	DAC	CO_2 mineralization	Enhanced weathering
Cost	High — Initial and operational costs are due to land, water, and biomass.	Very high— Significant operational costs, primarily due to energy requirements.	High — Costs related to mining, processing, and transportation of minerals.	High — Mining and spreading minerals across land areas are costly.
Energy requirements	Moderate — Bioenergy produced offsets some energy costs but remains resource-intensive.	Very high — Highly energy intensive, requiring renewable energy sources for feasibility.	High — Mining and processing require considerable energy.	Moderate to high — Mining and mineral processing can be energy intensive.
Land use	High — Land for biomass may compete with food production and biodiversity.	Low — Land footprint for capture facilities; however, energy infrastructure is required.	Medium — Mining sites impact land use but less directly.	High — Requires land for extensive mineral application potential ecosystem impact.
Carbon Sequestration Potential	High — Dependent on sustainable biomass resources and efficient capture.	High — Theoretically large, though constrained by cost and energy.	Very high — permanent storage in mineral form.	Very high — Stable, long-term storage in carbonate minerals.
Technological Maturity	TRL 3 – 10 (mostly commercial)	S-DAC; TRL 7 – 8 (commercial) L-DAC; TRL 5 – 6 (prototype)	TRL 4 – 9 (commercial application)	TRL 4 – 6 (prototype scale)
Scalability	Moderate — dependent on biomass and land availability.	High (in theory) — Currently limited by energy requirements and costs.	Low to moderate — Scaling is challenging due to high costs.	Low to moderate — Land and mineral availability are limiting factors.
Environmental Impact	High — Potential conflicts with agriculture, water, and ecosystems.	Minimal (direct)— probably indirect impact due to energy use.	Low to medium — Mining impacts can cause local ecological disturbances.	Low — Land use may disrupt ecosystems.
Permanence	High — CO_2 is stored in geological formations.	High — Long term storage in suitable geological formations.	Very high — CO_2 binds to minerals permanently.	Very high — Carbon stored as stable carbonate minerals.
References	[11], [87], [96]	[99], [121]	[11], [107], [109]	[118], [119], [120]

Chapter IV. Case study: Application in the mexican context

This chapter assesses the viability of implementing NETS within Mexico's oil and gas industry by exploring each technology's potential, challenges and opportunities. It highlights how they can be integrated in the oil and gas operations while addressing carbon reduction goals.

4.1. Viability of carbon reduction technologies in the context of Mexico's oil and gas industry

According to Mexico's NDC pledge, the decarbonization of the energy sector cannot be possible without CCS and renewable deployment, therefore, CCUS/CCS, NETs, and CDRs become a practical and likely technology to consider to tackle carbon emissions.

CCUS in Mexico

- In 2015, the World Bank and Secretaría de Energía (SENER) began collaborating to conduct three key studies on CCUS. In 2018, the Comision Federal de Electricidad (CFE) constructed a CCUS plant and a pilot CO_2 capture project at Poza Rica Combined Cycle Power Plant. This natural gas combined power plant used post-combustion amine-based technology for CO_2 capture. [122] The same project aimed to establish the parametric foundations for what could later regulate the behavior of a commercial-scale CO_2 capture system for enhanced oil recovery in one of the region's oil fields. [123]

- During 2014 and 2015, PEMEX analyzed candidate fields for applying CO_2-enhanced oil recovery processes, selecting the Cinco Presidentes field to carry out the first CCUS pilot project. This project aimed to assess the response of fields in southeastern Mexico to CO_2 injection, aiming to increase oil production while permanently storing the CO_2 underground, contributing to CO_2 reduction. The CO_2 would be supplied by the Cosoleacaque petrochemical plant, where it is obtained as a byproduct. A total of 34 MMMcf of CO_2 was injected. [122]

Bio-Energy with Carbon Capture and Storage (BECCS):

Opportunities:

Mexico holds significant potential for bioenergy, contributing 4.8% to primary energy and 8% to final energy use, with wood being vital in the residential sector. The production of bioethanol can reduce CO_2 emissions by at least 35%. [124], [125] Integrating BECCS into refineries or processing plants can be beneficial. For instance, waste biomass from sources such as sugarcane or palm oil[38] can be converted into biofuel. This process not only captures CO_2 emissions but also helps reduce overall emissions and supports local economies by offsetting emissions from extraction and processing. [127] Integrating BECCS into oil and gas operations allows companies to leverage existing infrastructure while diversifying energy sources, potentially creating new revenue streams through the sale of biofuels and carbon credits.

Challenges:

Implementing BECCS in oil and gas facilities requires significant modifications to infrastructure for capturing, compressing, and transporting CO_2 for storage. [128] Companies must invest in pipelines for CO_2 transport and secure geological formations for long-term storage. Furthermore, BECCS involves high land and water usage, which could conflict with areas already impacted by extraction activities. [11]

Direct Air Capture (DAC):

DAC is a valuable asset for the oil and gas industry because it allows facilities to be located near oil fields. This is particularly beneficial in regions like Baja California, where abundant renewable energy sources such as geothermal, wind, and solar power can help meet high energy demands. [129]

[38] A life cycle assessment conducted by the University of Manchester revealed that in Malaysia, aside from the scenario where palm oil waste is converted into biofuel, utilizing palm oil waste for BECCS could generate approximately 7,730 GWh of energy annually. Additionally, this approach could eliminate 11.98 million tons of CO_2 each year from available palm oil waste, which represents around 10% of Malaysia's total emissions from electricity generation. [126]

Opportunities:

As global pressure mounts for oil and gas companies to commit to net zero emissions, DAC can serve as a crucial technology in meeting these targets. It offers a pathway to balance out unavoidable emissions from fossil fuel extraction and processing. With further investment and research being conducted in DAC technology and through the concept of economies of scale, this can drive down costs and make it economically viable to be implemented in Mexico. [66]. Additionally, CO_2 captured using DAC can be utilized for Enhanced Oil Recovery (EOR) increasing the recovery factor, which enhances oil production while simultaneously storing the CO_2 [121]. By using CO_2 from DAC, we ensure that the injected CO_2 does not contribute to overall emissions.

The oil and gas industry could implement DAC technology to capture atmospheric CO_2, offsetting emissions from ongoing activities such as drilling, refining, and transportation. [130] Furthermore, oil and gas companies could use DAC to capture CO_2 for either storage or utilization, generating carbon credits, which could contribute to meeting internal carbon reduction targets or be sold on the carbon market, providing an incentive for the deployment of DAC technology. [131]

Challenges:

As mentioned in Chapter III, DAC is very energy-intensive and requires significant amounts of electricity. To ensure that the process is net carbon negative, the electricity must come from renewable sources. Without a strong renewable energy infrastructure, the feasibility of implementing DAC in Mexico remains uncertain. Furthermore, the current costs associated with DAC may be prohibitive for many local companies unless substantial government incentives, such as carbon pricing mechanisms, are provided. Establishing DAC facilities in remote areas may also pose logistical challenges, including the need for extensive energy transmission and the creation of CO_2 transportation networks, such as pipelines. [66]

CO_2 mineralization:

Mexico is an ideal candidate for CO_2 mineralization due to its significant volcanic activity and extensive coverage of basaltic rock. Laboratory studies have already been conducted to assess its effectiveness. [132] The country is located along the “Ring of Fire,” which is characterized by numerous volcanoes and volcanic formations, creating suitable geological conditions for finding basalt, peridotite, and olivine. Several regions in Mexico have large basalt deposits, particularly in the Trans-Mexican Volcanic Belt, which stretches across central Mexico. [133] See Figure 29. Utilizing these local basalt deposits for CO_2 mineralization could help Mexico achieve its climate goals by providing a viable method for attaining negative emissions, thereby contributing to the overall decarbonization strategy.

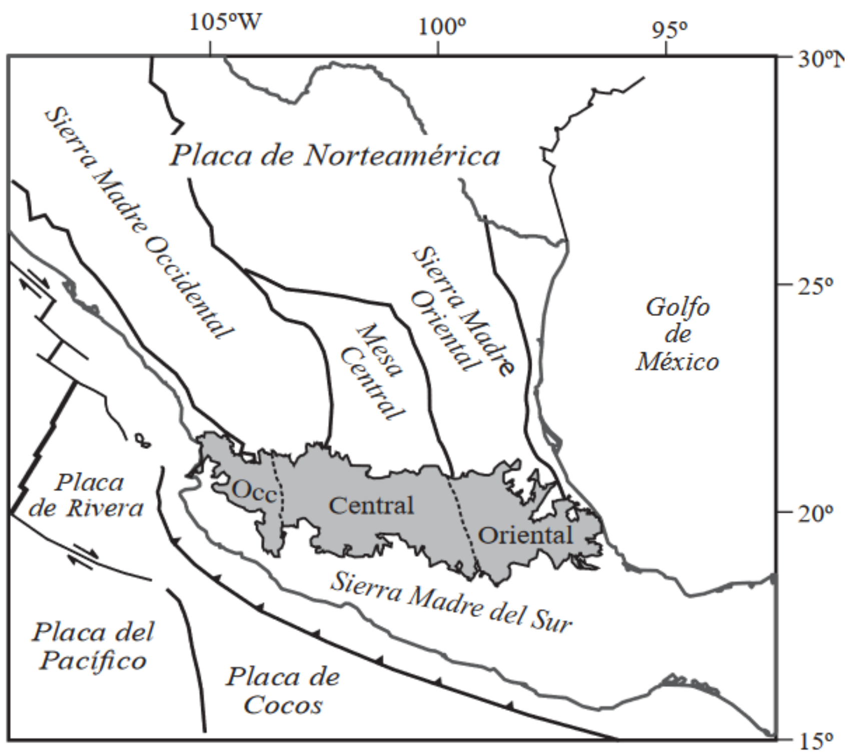

Figure 32. The Trans-Mexican Volcanic Belt (TMVB) is located in the country's center. It has a longitude of approximately 1000 km, and the western part of this geological province is much closer to the Gulf of Mexico, where most oil and gas activity occurs. [133]

Opportunities:

The oil and gas industry has significant experience in drilling and subsurface operations, which can be utilized for injecting CO_2 into basalt formations. Existing infrastructure, such as wells and pipelines, could potentially be repurposed for CO_2 injection, storage, and transportation, thereby reducing the capital costs associated with constructing new facilities. Additionally, the oil and gas industry can partner with mining companies to utilize existing mineral resources more efficiently, creating joint ventures that optimize operations for both industries.

Challenges:

Further in-depth research on underground basalt in Mexico is necessary to evaluate the feasibility of in-situ CO_2 mineralization. Collecting samples from deeper, less superficial zones, which tend to be better preserved, can achieve a more accurate characterization. This is particularly important as basalt samples in Mexico are primarily found in outcrops like volcanic structures and mountain ranges. [134], [135] In contrast, ex-situ mineralization involves significant energy consumption and transportation of minerals to mineralization site, which may limit its practicality in oil fields. Additionally, the Trans-Mexican Volcanic Belt (TMVB), located in the central part of the country, is densely populated, with oil and gas operations situated far from this area. Furthermore, scaling up mineralization efforts near oil facilities could potentially disrupt nearby communities and ecosystems.

Enhanced weathering:

Enhanced weathering is particularly relevant for reclaiming land affected by oil and gas extraction, as it can improve soil health while providing the dual benefits of carbon capture and increased agricultural activity.

Opportunities:

The integration of enhanced weathering techniques with land reclamation initiatives—specifically the application of minerals such as olivine to previously utilized land—represents a significant opportunity for oil and gas companies to mitigate the environmental liabilities associated with extraction operations. This approach not only has the potential to improve ecological restoration efforts but may also enhance the company's reputation and foster more positive community relations.

Enhanced Weathering in Mexico

There is significant interest in implementing enhanced weathering projects in Mexico, with companies like Silica Earth targeting regions near sugarcane plantations that have acidic land and abundant rainfall. This approach aims to combat climate change by using specific materials that can react with CO_2 to form stable carbonates. The key elements for this process include Magnesium (M), Calcium (Ca), Sodium (Na), and Potassium (K) in the form of silicates, rather than oxides.

To assess the suitability of materials using XRF1[39] results, the following criteria should be met: the combined mass percentage of MgO, CaO, Na2O, K2O, and SiO2 should be at least 20%, with higher percentages indicating better effectiveness.

Prioritized Materials:

1. Basalt and tezontle are identified as primary materials for surficial mineralization.
2. Other viable materials include calcium silicate and wollastonite, which can be sourced from operational mines. Ideally, these materials should be byproducts of mining operations and readily available.
3. If not sourced from mines, the materials should be in a semi-compact state for easy extraction.

The materials must meet the following criteria:

- Fine-grained particle size, or crushed to that size for effective use.
- An ideal specific surface area (SSA)[40] to promote faster degradation.
- Low variability in chemical composition and particle size.
- A high capacity to produce water-soluble forms of silica that are available for crops.
- Cost-effectiveness.

This technology holds the potential to remove up to more than 100 million tonnes of CO_2 per year in Mexico, enhancing agricultural yields and providing economic benefits to low-income communities through the sale of carbon credits. [138]

4.2. Advantages and disadvantages

[39] An X-ray fluorescence (XRF) spectrometer is a device that analyzes the chemical composition of materials using X-rays. In geochemistry, it is used to analyze rocks, minerals, sediments and fluids. [136]

[40] Specific surface area (SSA) is a physical property of a material that measures the total surface area of a material per unit of mass. It's a key factor in many chemical and physical processes that occur at the surface of solids. [137]

NET	Advantages	Disadvantages
BECCS	-Could repurpose bio-waste from operations. -Supports regional economies if integrated with biofuel production.	-High water and land use are challenging near extraction sites. -Requires extensive infrastructure investment.
DAC	-Can be placed virtually anywhere. -Suitable for areas with high renewable energy. -Allows direct air capture in remote locations.	-Energy-intensive and currently expensive to implement. -Limited feasibility without nearby renewable energy.
CO_2 mineralization	-Long-term carbon storage with stable mineral forms.	-Energy-intensive (particularly ex-situ mineralization) and logistically complex. -Mineral transport and application costs are high.
Enhanced weathering	-Offers reclamation benefits on degraded oil and gas lands. -Could capture CO_2 while improving soil.	-Expensive to implement on a large scale. -Requires extensive mineral application and monitoring. Long term exposure of mineral to CO2 to be sunk (once spread on crops)

Implementing Projects

CCUS, alongside NETs and CDRs, will play a significant role in achieving the greenhouse gas reduction objectives outlined in the agreements signed by Mexico to mitigate the impacts of climate change. Therefore, the Secretaría de Energía (SENER), Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT), Petróleos Mexicanos (PEMEX), Comisión Federal de Electricidad (CFE), Universidad Nacional Autónoma de México (UNAM), Instituto Politécnico Nacional (IPN), and Centro Mario Molina (CMM) collaboratively designed and established the CCUS Technology Roadmap. This official document provides a comprehensive framework for implementing CCUS in the country, encompassing norms, legislation, scientific knowledge, and systematic planning for CCUS deployment. [139]

As previously seen in Chapter 1.9., the energy and transport sectors are the country's main contributors to greenhouse gases. However, the objective is to implement CCUS and NET/CDR technologies in the sectors with the greatest focus on emissions. For these projects, it is necessary to consider the type of industry, types of greenhouse gases emitted, and where the emissions will be stored. The transport sector emissions will be drastically reduced using alternative fuels such as biofuels, synfuels, and electrification.

The assessment of Mexico's Technology Route Map reveals that emissions from the energy sector, particularly oil and gas operations, are concentrated in the country's southeastern region, especially along the continental platform of the Gulf of Mexico and further south inland. In contrast, the electricity generation industry, also part of the energy sector, is more dispersed throughout the central and northern regions. The cement industry, which significantly contributes to CO_2 emissions, is predominantly situated in the central area. See Figure 33.

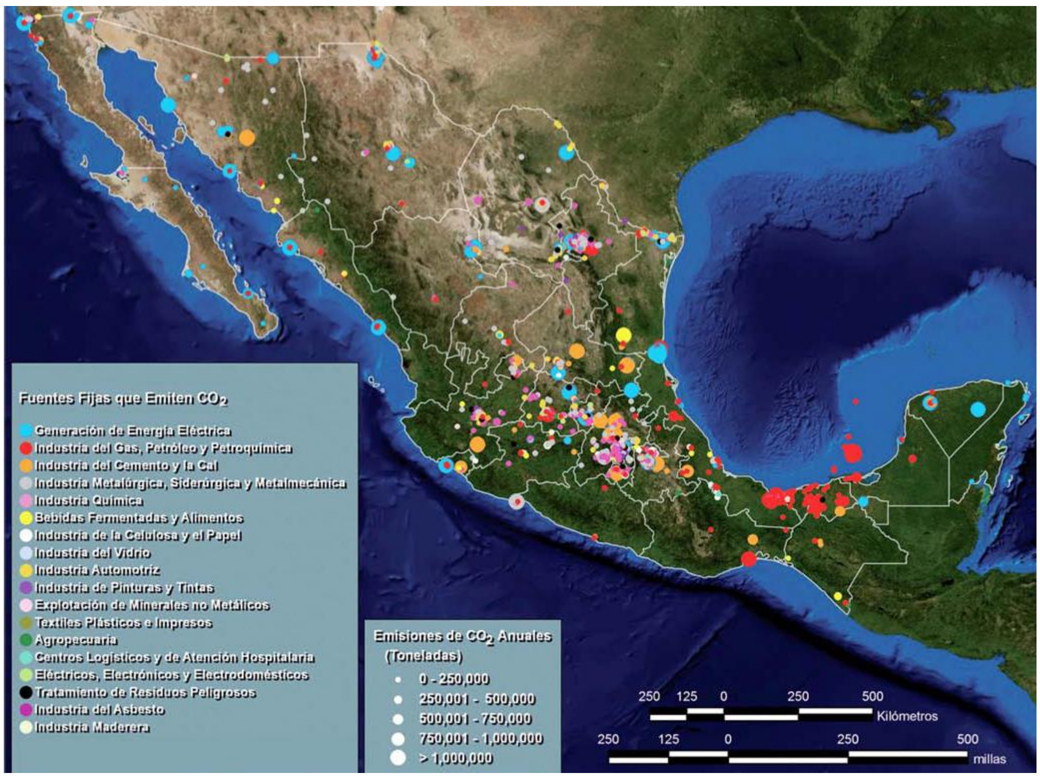

Figure 33. Main fixed source GHG emissions in México. This map indicates the main hotspots of GHG emissions in diverse sectors, with electricity, oil and gas, and cement production being the main contributors. [139]

Chapter V. Results and findings

Comparative Assessment of Carbon Reduction Technologies:

The analysis of the data collected for this work suggest that Biomass Energy with Carbon Capture and Storage (BECCS) has the potential to sequester significant quantities of CO_2 while generating bioenergy. This technology is up-and-coming in regions with abundant biomass, making it particularly viable for agricultural areas in Mexico. The cost of implementing BECCS ranges from 15 to 80 USD per ton of CO_2, which is relatively affordable; however, fees may vary based on biomass availability and logistical considerations. BECCS is highly flexible, as it can be deployed wherever biomass is accessible to harness its potential. It can also be integrated with fossil fuel-based power plants by co-firing biomass and applying carbon capture and storage techniques. This potential is especially evident in the central and southwestern regions of the country, where biofuel production is feasible.

Direct Air Capture (DAC): While DAC has higher costs (125-335 USD/tCO_2), its scalability and ability to capture CO_2 directly from the atmosphere make it attractive. DAC's coupling with CO_2 mineralization, discussed below, is also crucial for long-term sequestration. On the other hand, it is currently unreliable for capturing fixed-source emissions since capturing CO_2 from a concentrated source, for example, an industrial plant with around 5-15% concentration, is far more energy and cost-efficient than capturing from air, which is less concentrated at around 0.042%. It can, however, have a secondary use, co-locating it with an industrial facility or a refinery using waste heat or renewable energy to power the process. DAC can be best deployed with the combination of renewable energy to offset its energy demands, especially solar and wind, which are abundant in Mexico. Additionally, the CO_2 captured from DAC can be used for enhance oil recovery processes.

Accelerated Weathering: This technology leverages natural processes to store CO_2 permanently. However, its effectiveness is limited by high costs (600 USD/tCO_2). If costs were to lower, and taking into consideration regions near sugarcane plantations with acidic land and abundant rainfall, states such as Veracruz, Guadalajara, Nayarit especially close to Tepic and around the Volcano of Colima, and Tabasco are potential areas for enhanced weathering projects.

Carbon Mineralization: In the case of carbon mineralization and taking into consideration results from sample collection data analysis in [134], it was found that the seven basalt samples taken from Tlaxcala, Puebla and Hidalgo exhibit a promising composition to mineralize CO_2. The study indicated that mineralization is viable. For this reason, the best region to implement carbon mineralization projects would be the country's center, specifically the TMVB belt where basalt formations are rich. Figure 33 shows several electricity generation plants, cement production plants, and oil, gas, and petrochemical facilities within the TMVB belt. If CCS projects, such as post-combustion technologies, are initiated within these plants, as seen previously in the country, carbon mineralization can occur.

The Role of Renewable Energies in Supporting Carbon Reduction Technologies:

Biofuels: Biofuels are sustainable and can provide energy to run NETs like BECCS. By utilizing biofuels derived from local biomass, such as agricultural waste, Mexico can promote circular economy practices while reducing dependency on fossil fuels.

Solar and Wind Energy: With some of the highest solar irradiation levels and considerable wind resources, Mexico can leverage these renewable sources to power NETs, reducing the operational carbon footprint. Solar energy, in particular, has shown great promise in supporting the energy needs of DAC units, which require significant electricity input. With its variability, wind energy can complement solar energy, ensuring a more consistent energy supply for NETs. Although both have the potential to support NETs, solar energy is a better option than wind since Mexico has some of the highest solar photovoltaic potential globally, [140] see Figure 34. Additionally, Solar PV is widely deployed across Mexico, with existing projects and grid integration compared to wind energy projects, which are concentrated in only a few states. PV technology can be spread widely in Mexico's central and northern regions.

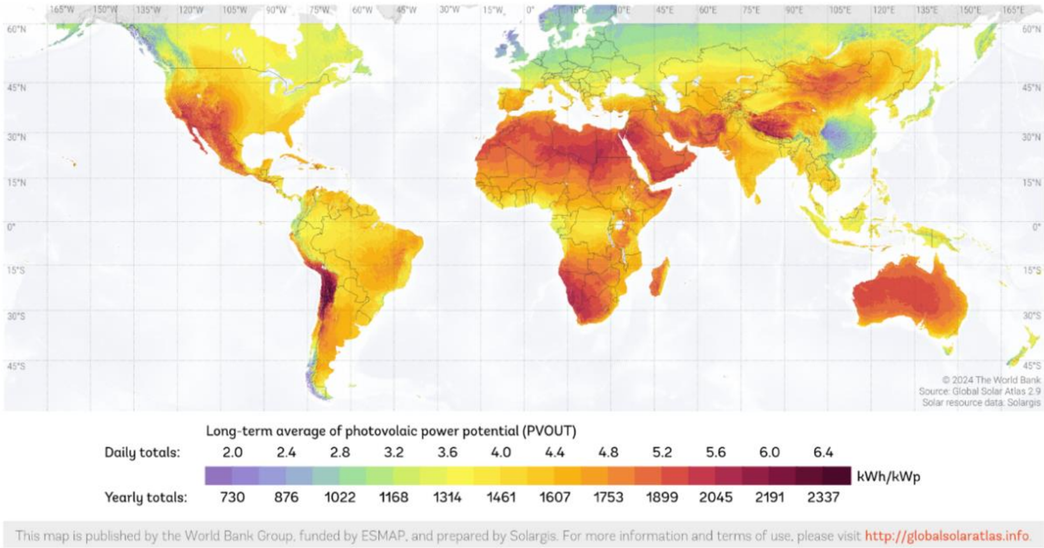

Figure 34. Photovoltaic Power Potential. [141]

Green Hydrogen: Green hydrogen production via electrolysis can be powered by renewable energy, offering a zero-carbon fuel for NET operations. Hydrogen can serve as an energy carrier in industrial applications, thus complementing DAC and BECCS by providing flexible energy support in areas with limited grid connectivity. The best regions in Mexico for green hydrogen production are those with abundant renewable energy resources, water availability, and proximity to industrial hubs or export routes. Key areas include the Pacific Northwest (specifically Baja California and Sonora), the Isthmus of Tehuantepec (covering Oaxaca and Veracruz), the Yucatán Península, and the industrial northeast. Notably, Sonora is emerging as a major player in this field, with both the government and private sector investing in projects such as the Sonora Plan, which is already underway in developing green hydrogen production initiatives.

Coupling DAC with CO_2 Mineralization:

As demonstrated by the Carbfix mineralization project in Reykjavik, Iceland, and the DAC plant, Mammoth, the combination of DAC technology and CO_2 mineralization offers a powerful solution, for long-term storage for the CO_2 captured by DAC. Implementing this combination in Mexico's suitable geological formations could be effective, as mineralization permanently immobilizes CO_2, eliminating the risk of re-emission and contributing to Mexico's long-term net-zero ambitions. Considering the region selected for carbon mineralization coupled with DAC, the permanence of carbon storage improves, making this pairing especially relevant for Mexico's long-term carbon sequestration strategy. However, the downside is that it would be much more expensive to capture CO_2 from DAC than directly from a carbon capture plant such as post-combustion used in combined cycle plants in the country.

CCUS

As outlined in Section 4.1, Carbon Capture, Utilization, and Storage (CCUS) is essential for Mexico's decarbonization strategy, especially in hard-to-abate industries and sectors dependent on fossil fuels. Natural gas is the predominant fuel in the power generation sector, surpassing coal and diesel, making CCUS a vital technology for reducing emissions in this area.

According to recommendations from the International Energy Agency (IEA) and international best practices, implementing CCUS technology is crucial for a successful energy transition. It ensures a stable energy supply while helping to meet greenhouse gas reduction targets. CCUS is particularly well-suited for natural gas processing facilities and can be integrated into PEMEX and CFE operations, such as Enhanced Oil Recovery (EOR) processes, allowing CO_2 capture and storage, thereby decreasing overall emissions.

Adopting CCUS presents a financially attractive option for the oil and gas sector to facilitate emission reductions. Therefore, it should be implemented in Mexico's southwest region and offshore areas of the Gulf of Mexico, where oil and gas operations are concentrated.

The following figures represent regions where carbon reduction technologies and renewable technologies will be highly effective if implemented by analyzing the technologies discussed above and using the map from Figure 33 to locate the fixed source of emission.

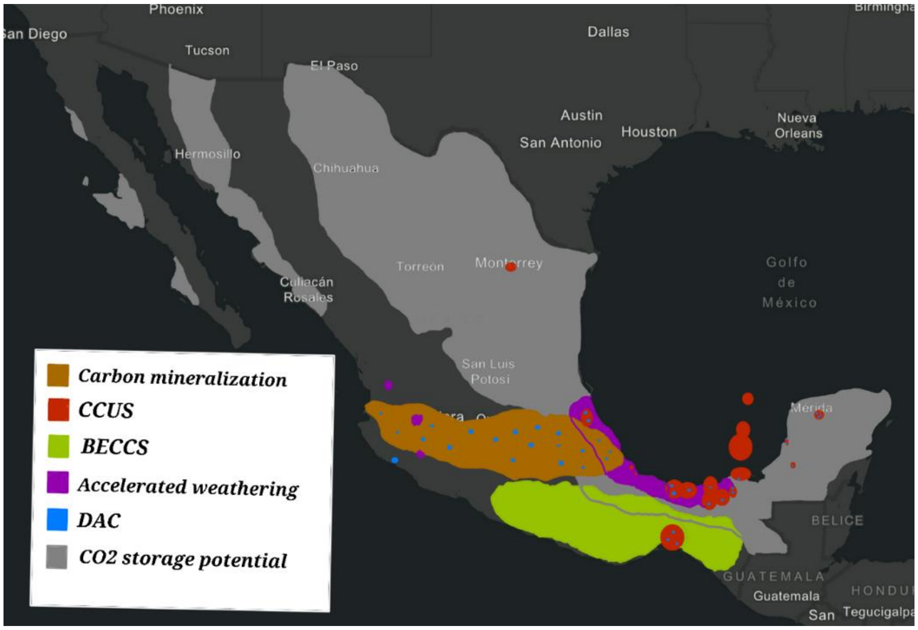

Figure 35. Potential carbon reduction technology regions. (Author's collection)

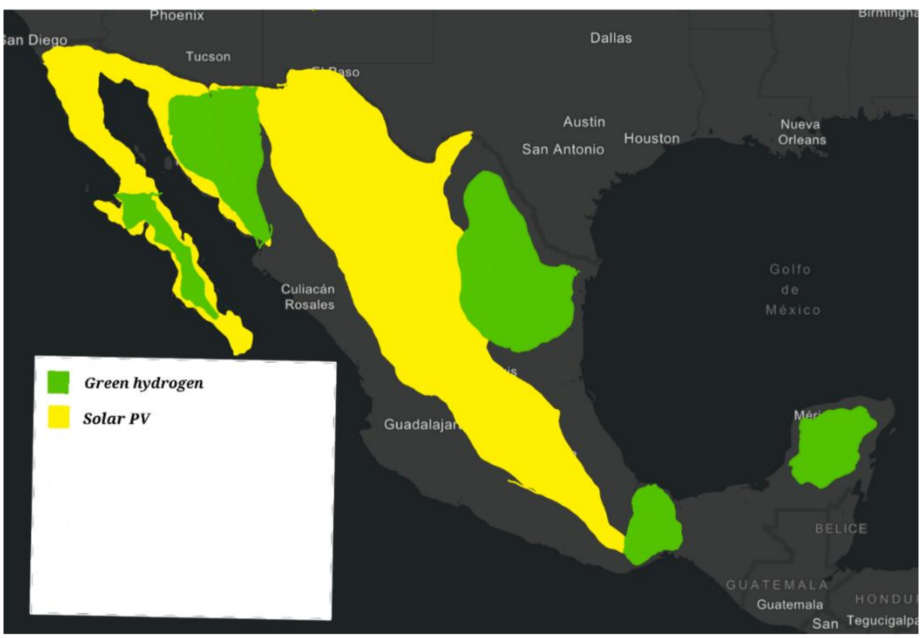

Figure 36. Potential renewable energy regions. (Author's collection)

Economic and Environmental Implications:

By integrating CCUS, NETs and CDRs with renewable energy, Mexico can potentially reduce the cost of carbon capture while fostering job creation in the renewable energy sector, contributing to the country's socio-economic development. Moreover, the combined deployment of NETs and renewables can mitigate environmental risks associated with carbon storage, such as leakage, while improving Mexico's resilience to global climate policies and carbon pricing.

Transporting CO_2

Existing pipelines can be repurposed to reduce costs associated with CO_2 transport from DAC facilities and the combustion processes of BECCS and CCUS. This approach is similar to the strategy for hydrogen pipeline transport discussed in Section 1.5. By repurposing existing infrastructure instead of constructing new pipelines, we can effectively transport CO_2, mainly when the capture facility is located a long distance from the storage site. See Table 8. [42]

Table 9. Considerations for new and repurposed CO_2 pipelines. The table outlines essential safety requirements for repurposing and constructing new pipelines. Repurposing current infrastructure for CO_2, as opposed to building nnew could reduce costs associated with building new pipelines. [42]

	Repurposed	**New**
CO_2	• The design pressure and temperature of the pipeline (avoiding the two-phase region) • Impurities in the CO_2 changing fracture propagation properties • Water dew point in the pipeline • Dense CO_2 phase acting as a solvent (elastomer effects) • Fatigue/cycling effects • Life extension of pipelines • Blowdown/venting provisions • Cleaning/purging of existing lines	• Pipeline routing and permitting. • Operating mode (gaseous, liquid or supercritical) and mass density • Public consultation • Possible cryogenic effects • Pressure maintenance (boosting for long pipelines) • Startup/shutdown impacts • Metering • Pipeline sectioning • Linepipe selection

According to the CCUS Technology Roadmap, government agencies, including Secretaría de Energía (SENER), Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT), Comisión

Federal de Electricidad (CFE) and Petróleos Mexicanos (PEMEX), would ensure the implementation of CCUS projects and guidelines are included for the regulatory bodies to establish measures to verify the safety and compliance of the projects, evaluate them, and monitor their progress.

Monitoring, measuring, and verification mechanisms will have to be designed and adopted to quantify the CO_2 captured in a permanent and effective manner through these technologies, in accordance with national and international standards. This will enable access to financing instruments and carbon markets. Collaboration will require participation of authorized bodies responsible for issuing and enforcing regulations in Mexico, ensuring their applicability while considering international standards. Academic and research institutions participation is crucial to provide technical advisory support.

Energy Transition and Policy Support:

The integration of renewable energy with NETs aligns closely with Mexico's energy transition goals, such as an increase of 10 GW of hydrogen capacity in 2024 and an additional 5 GW increase in 2030, as well as the generation of 45% of Mexico's electricity consumption from renewable sources and away from fossil fuels by 2030, with a broader goal of 50% of clean energy generation by 2050 [142], which supports a transition away from fossil fuel dependency while meeting carbon reduction targets. Policy incentives for renewable energy adoption, such as subsidies or tax breaks for solar and wind, would be essential to make, NETs and CDRs economically viable. In particular, green hydrogen production and biofuel development need support to ensure a reliable renewable energy supply that can consistently power NETs.

Infrastructure Requirements:

Developing CO_2 transport, storage, and renewable energy generation infraestructure is essential to support NETs. Specifically, DAC and CO_2 mineralization require dedicated pipelines and storage facilities, while solar and wind installations need connectivity to NET facilities. A strategic focus on infrastructure investments, potentially collaborating with private and public entities, could enable scalable and cost-effective NET deployment.

Scalability and Environmental Impact:

Scaling up NETs poses challenges, especially regarding land use and potential environmental impacts, such as water use in DAC and BECCS. Renewable energy integration, such as solar for DAC, can mitigate these environmental concerns, but continued research and careful planning are necessary to minimize adverse impacts. Land-use planning should prioritize areas where biomass is abundant for BECCS and ensure minimal disruption to local ecosystems.

Long-term Carbon Sequestration and Climate Resilience:

Coupling DAC with CO_2 mineralization provides a pathway for permanent carbon storage, ensuring that the emissions captured are permanently removed from the atmosphere. This approach is especially critical for Mexico's commitment to the Paris Agreement, as it addresses the necessity for emission reductions and permanent carbon removal.

Conclusion

This thesis highlights the vital role of integrating Carbon Capture, Utilization, and Storage (CCUS), Negative Emissions Technologies (NETs), and Carbon Dioxide Removal (CDRs) with renewable energy sources to help Mexico achieve its climate objectives. Mexico can effectively manage its energy transition by merging these technologies with renewable options like biofuels, solar, wind, and green hydrogen. The analysis of this project indicates that focusing on CCUS, particularly for fixed sources, represents the most efficient short-term approach to meeting Mexico's climate targets due to its lower costs compared to NETs and CDRs. However, if NETs and CDRs are adopted as complementary strategies, together, they can achieve net negative emissions, including the capture of CO_2 emissions that are released into the atmosphere from CCUS, as well as addressing historical emissions, thereby contributing to a reduction in overall atmospheric CO_2 levels.

Key Takeaways:

1. Impact of Renewable Energy on the viability of carbon reduction technologies: Utilizing renewable energy not only lowers the carbon footprint of NETs but also paves the way for energy independence, especially in areas rich in renewable resources.

2. Policy and Infrastructure Needs: Government support through policy incentives and infrastructure investments is crucial for creating a favorable environment for the widespread adoption of NETs.
3. Long-term Climate Goals: The integration of DAC with CO_2 mineralization guarantees carbon permanence, aligning with Mexico's commitments under the Paris Agreement and other global climate initiatives, however, if coupled with CCUS, CO_2 mineralization shows far more promising results.

Mexico's CO_2 emission trends highlight both the progress and the ongoing challenges in transitioning to a low-carbon economy. While the country has set ambitious targets under its NDCs and introduced policies to increase renewable energy adoption, it continues to rely heavily on fossil fuels. Negative emission technologies could provide a critical tool for achieving deeper reductions in emissions, especially in hard-to-abate sectors. The comparative analysis of these technologies, and the exploration of policy frameworks and financial mechanisms, could offer a clear roadmap for integrating NETs into Mexico's broader carbon reduction strategy.

In conclusion, by prioritizing CCUS, which work in harmony with renewable energy, Mexico has the opportunity to set a benchmark for carbon reduction strategies among all CO_2 emitting industries, not just the oil and gas industry. Achieving net-zero emissions and enhancing climate resilience requires a comprehensive approach that combines renewable energy, advanced NETs, and supportive policies aimed at fostering a sustainable future. This research lays the groundwork for future studies and policy decisions regarding how Mexico can effectively harness CCUS, NETs and renewable energy to fulfill its climate obligations.

It is important to note that CCUS, NETs, and CDRs are not the primary solutions for addressing climate change. As the announced pledge scenario states, Mexico must to significantly reduce emissions by drastically cutting fossil fuel use and accelerating the transition to renewable energy. These measures are essential for the country to meet its climate commitments.

Glossary

Anthropogenic emissions: Pollutants released into the atmosphere as result of huma activities, such as burning fossil fuels, deforestation, and industrial processes., 9

Biodiesel: A renewable fuel made from vegetable oils, animal fats, or recycled cooking oil, used as an alternative to conventional diesel fuel in engines., 31

Biochar: A form of charcoal produced from organic material used to improve soil quality and sequester carbon when buried or incorporated into soil., 63

Biogas: A mixture of gases, primarily methane and carbon dioxide, produced by the anaerobic decomposition of organic matter, such as agricultural waste or sewage., 32

Biomass: Organic material from plants and animals that can be used as a renewable enrgy source., 8

Calcite: A mineral form of calcium carbonate that can store carbon when formed through CO_2 mineralization., 78

Calcium: A chemical element used in CO_2 mineralization processes, often combined with CO_2 to form stable compounds like calcite., 78

CAPEX: The initial cost of purchasing and setting up equipment, infrastructure, or technology for a project or facility., 37

Carbon taxes: Financial charges imposed on the carbon content of fuels, aimed at reducing carbon dioxide emissions by making fossil fuel use more costly., 21

Carbon cycle: The natural processf carbon ng the atmosphere, oceans, soil, plants, and animals, which helps regulate Earth's climate., 7

Carbon dioxide: A colorless, odorless gas produced by burning carbon-based fuels and by respiration, and a major greenhouse gas contributing to global warming., 6

Carbon market: A market-based mechanism that allows countries or organizations to trade emissions allowances to meet greenhouse gas reduction targets., 20

Chlorofluorocarbons: Synthetic compounds madeof chlorine, fluorine, and carbon, once widely used in refrigeration and aerosols, that deplete the ozone layer and contribute to global warming., 6

Coal: A combustible black or brownish-black rock made mostly of carbon, used as fossil fuel for energy production., 10

Concentrated Solar Power (CSP): A technology that uses mirrors or lenses to focus sunlight onto a small area to produce heat, which then drives a turbine to generate electricity., 30

Conferences of the Parties (COP): Annual gatherings of countries that are parties to the UNFCCC, where global climate actions, negotiations, and policies are discussed and agreed upon., 20

Deforestation: The clearing or thinning of forests and represents one of the largest issues in global land use., 15

Economies of scale: Cost advantages gained as production increases, resulting in lower per-unit costs., 68

Electrolysis: A process that splits water into hydrogen and oxygen using electricity, often used to produce green hydrogen., 33

Energy carrier: A substance or system, such as hydrogen or electricity, that stores energy for use in various applications., 32

Enhanced Oil Recovery (EOR): A method of extracting more oil from a reservoir by injecting CO_2 or other substances to increase pressure and stimulate oil flow., 52

Exothermic: A reaction that releases heat, common in chemical reactions that store carbon through mineralization., 79

Fossil fuels: Natural energy sources such as coal, oil, and natural gas, formed from ancient organic matter, which release carbon dioxide when burned, contributing to global warming., 22

Global domestic product (GDP): The standard measure of the value added created through the production of goods and services in a country during a certain period., 18

Green hydrogen: Hydrogen produced through electrolysis powered by renewable energy, generating no greenhouse gas emissions during production., 32

Greenhouse effect: The warming of Earth’s atmosphere caused by greenhouse gases trapping heat radiated from the Earth's surface., 6

GHGs: Greenhouse gases, 6

Gigawatt: A unit of power equal to one billion watts, often used to measure the capacity of large power plants or the scale of electricity production., 29

Global warming: he phenomenon of increasing average air temperatures near Earth's surface over the past one to two centuries., 16

Greenhouse gases: Gases in the atmosphere, such as carbon dioxide and methane, that trap heat and contribute to the warming of the Earth through the greenhouse effect., 6

Hydrogen: A versatile energy carrier that can be used as fuel, especially in clean energy applications, produced through processes like electrolysis or extracted from fossil fuels., 31

International Panel on Climate Change (IPCC): A UN body that assesses scientific information related to climate change, its impacts, and potential future risks, providing guidance on mitigation and adaptation strategies., 22

Kyoto Protocol: A 1997 international treaty under the UNFCCC that commits industrialized nations to reduce greenhouse gas emissions through legally binding targets., 20

Levelized cost of energy (LCOE): A measure of the average cost per unit of electricity generated over the lifetime of an energy-producing asset, accounting for all costs, including capital, operation, and maintenance., 30

Landfill gas: A natural byproduct of the decomposition of organic material in landfills, primarily composed of methane and carbon dioxide., 31

Levelized cost of hydrogen (LCOH): The average cost per kilogram of hydrogen produced over the lifetime of the production facility, considering all associated costs., 37

Magnesium: A chemical element that reacts with CO_2 in mineralization processes to form stable compounds such as magnesite., 78

Methane: A potent greenhouse gas that is a primary component of natural gas and is also produced during the decomposition of organic matter in landfills and during digestion in animals., 31

municipal solid waste (MSW): Commonly referred to as trash or garbage, MSW includes everyday items discarded by the public, such as packaging, food scraps, and household waste., 31

Natural sinks: Ecosystems such as forests, soils, and oceans, that absorb more CO2 from the atmosphere than they release, helping to reduce greenhouse gas levels., 8

Nationally Determined Contributions: Climate action plans submitted by countries under the Paris Agreement, outlining their commitments to reduce greenhouse gas emissions., 56

Negative Emission Technologies (NETs): Techniques designed to remove carbon dioxide from the atmosphere, helping achieve net-zero emissions by offsetting residual emissions., 21

Net zero emissions: A balance between the greenhouse gases emitted into and removed from the atmosphere, achieving no net increase in overall emissions., 11

Natural gas: A naturally occurring mixture of hydrocarbon gases that is highly compressible and expansible., 15

Nuclear energy: Power derived from sunlight, which is converted into electricity or heat through technologies like solar panels and solar thermal systems., 26

Olivine: A magnesium-iron silicate mineral that can absorb CO_2 through weathering, aiding in natural carbon sequestration., 78

Oil: chemical substance that is composed primarily of hydrocarbons and is hydrophobic (does not mix with water) and lipophilic (mixes with other oils)., 15

Paris Agreement: Techniques designed to remove carbon dioxide from the atmosphere, helping achieve net-zero emissions by offsetting residual emissions., 21

Per capita emissions: The average amount of greenhouse gas emissions produced per person in a specific area or population., 13

Permanence: The ability of carbon sequestration methods to retain CO_2 for extended periods, preventing its return to the atmosphere., 77

Renewable energy: Energy sourced from natural processes that are continually replenished, such as sunlight, wind, and water, offering a sustainable alternative to fossil fuels., 26

Reservoir: A subsurface body of rock having sufficient porosity and permeability to store and transmit fluids., 15

Scalability: The capacity of a technology or system to be expanded or adapted to larger scales without losing efficiency or effectiveness., 76

Solar energy: Power derived from sunlight, which is converted into electricity or heat through technologies like solar panels and solar thermal systems., 26

Syngas: A gas mixture of primarily hydrogen and carbon monoxide, produced by gasification, and used as a fuel or as a raw material for chemical synthesis., 31

Stated Policies Scenario: A scenario that projects future energy use and emissions based on countries' public pledges, including those not yet implemented., 57

Supercritical CO_2: CO_2 held at high temperature and pressure, used in various industrial processes, including enhanced oil recovery and carbon storage, due to its liquid-like properties., 79

Sustainable aviation fuel (SAF): A cleaner alternative to conventional jet fuel, made from sustainable sources such as waste oils, biomass, and even captured carbon dioxide., 32

Sustainable Development Goals (SDGs): A set of 17 global goals established by the United Nations in 2015, aimed at addressing urgent global challenges, including poverty, inequality, climate change, and environmental degradation, by 2030., 23

Synfuel: A liquidA liquid fuel synthesized from resources like coal, natural gas, or biomass, often using the Fischer-Tropsch process., 32

Thermochemical gasification: A process that converts organic materials like biomass or waste into syngas by heating them in the presence of limited oxygen., 31

United Nations Framework Convention on Climate Change: An international environmental treaty established in 1992, aiming to stabilize greenhouse gas concentrations to prevent harmful human impact on the climate., 20

Waste to energy (WTE): A process that converts waste materials, especially municipal solid waste, into usable energy in the form of electricity, heat, or fuel., 31

Bibliography

[1] "Climate Change – Topics," IEA. Accessed: Mar. 31, 2025. [Online]. Available: https://www.iea.org/topics/climate-change

[2] G. Chichilnisky and P. Bal, *Reversing climate change: how carbon removals can resolve climate change and fix the economy*. New Jersey: World Scientific, 2016.

[3] A. Gorbold, *Climate Change*, 1. publ. California: AcademiQ Infomedia LLC, 2021.

[4] M. J. Molina and F. S. Rowland, "Stratospheric sink for chlorofluoromethanes: chlorine atom-catalysed destruction of ozone," *Nature*, vol. 249, no. 5460, pp. 810–812, Jun. 1974, doi: 10.1038/249810a0.

[5] "About Montreal Protocol." Accessed: Feb. 21, 2024. [Online]. Available: https://www.unep.org/ozonaction/who-we-are/about-montreal-protocol

[6] C. Gautier, *Oil, water, and climate: an introduction*, 1. publ. Cambridge: Cambridge Univ. Press, 2008.

[7] "Carbon cycle | National Oceanic and Atmospheric Administration." Accessed: Jul. 08, 2024. [Online]. Available: https://www.noaa.gov/education/resource-collections/climate/carbon-cycle

[8] "Deforestation, warming flip part of Amazon forest from carbon sink to source - NOAA Research." Accessed: Jul. 08, 2024. [Online]. Available: https://research.noaa.gov/2021/07/14/deforestation-warming-flip-part-of-amazon-forest-from-carbon-sink-to-source/

[9] "Carbon Fluxes in the Amazon's Indigenous Forests | World Resources Institute." Accessed: Jul. 08, 2024. [Online]. Available: https://www.wri.org/insights/amazon-carbon-sink-indigenous-forests

[10] G. of Alberta, "Alberta Carbon Trunk Line." Accessed: Jul. 08, 2024. [Online]. Available: https://majorprojects.alberta.ca/details/Alberta-Carbon-Trunk-Line/622

[11] National Academies of Sciences, Engineering, and Medicine (U.S.), Ed., *Negative emissions technologies and reliable sequestration: a research agenda*. Washington, DC: The National Academies Press, 2019.

[12] K. Kelly, "Oceanic measurements of carbon dioxide continue to decrease, as reported in this year's ocean carbon data atlas," Global Ocean Monitoring and Observing. Accessed: Jan. 07, 2025. [Online]. Available: https://globalocean.noaa.gov/oceanic-measurements-of-carbon-dioxide-continue-to-decrease-as-reported-in-this-years-ocean-carbon-data-atlas/

[13] U. of H. at Manoa, "Oceans absorb 6% more carbon thanks to rain, study reveals." Accessed: Jan. 07, 2025. [Online]. Available: https://phys.org/news/2024-09-oceans-absorb-carbon-reveals.html

[14] "Carbon sinks - Iberdrola." Accessed: Mar. 06, 2024. [Online]. Available: https://www.iberdrola.com/sustainability/carbon-sinks

[15] S. A. Rackley, *Carbon capture and storage*. Burlington, MA: Butterworth-Heinemann, 2010.

[16] "Mexico - Countries & Regions," IEA. Accessed: Jul. 10, 2024. [Online]. Available: https://www.iea.org/countries/mexico

[17] "CO2Emissionsin2023.pdf." Accessed: Jul. 12, 2024. [Online]. Available: https://iea.blob.core.windows.net/assets/33e2badc-b839-4c18-84ce-f6387b3c008f/CO2Emissionsin2023.pdf

[18] K. Calvin *et al.*, "IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.," Intergovernmental Panel on Climate Change (IPCC), Jul. 2023. doi: 10.59327/IPCC/AR6-9789291691647.
[19] "https://www.oxfordenergy.org/wpcms/wp-content/uploads/2023/06/CE8-The-outlook-for-Chinas-fossil-fuel-consumption.pdf." Accessed: Feb. 21, 2024. [Online]. Available: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2023/06/CE8-The-outlook-for-Chinas-fossil-fuel-consumption.pdf
[20] "bp Energy Outlook 2024," 2024.
[21] "Carbon emissions anywhere threaten development everywhere | UNCTAD." Accessed: Jul. 12, 2024. [Online]. Available: https://unctad.org/news/carbon-emissions-anywhere-threaten-development-everywhere
[22] "Countries & Regions," IEA. Accessed: Jul. 10, 2024. [Online]. Available: https://www.iea.org/countries
[23] "Carbon Dioxide | Vital Signs – Climate Change: Vital Signs of the Planet." Accessed: Jul. 09, 2024. [Online]. Available: https://climate.nasa.gov/vital-signs/carbon-dioxide/?intent=111
[24] "Climate Change: Atmospheric Carbon Dioxide | NOAA Climate.gov." Accessed: Apr. 21, 2024. [Online]. Available: http://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide
[25] "Hurricane Beryl leaves behind power outage in Texas as dangerous heat descends on the region | CNN." Accessed: Jul. 09, 2024. [Online]. Available: https://edition.cnn.com/2024/07/09/weather/beryl-storm-texas-power-outages-heat/index.html
[26] "Lake Fire." Accessed: Jul. 09, 2024. [Online]. Available: https://www.sfchronicle.com/projects/california-fire-map/lake-fire-2024
[27] "Coloca la UNAM placa en memoria del Ayoloco," Gaceta UNAM. Accessed: Jul. 09, 2024. [Online]. Available: https://www.gaceta.unam.mx/coloca-la-unam-placa-en-memoria-del-ayoloco/
[28] "Climate Change: Atmospheric Carbon Dioxide | NOAA Climate.gov." Accessed: Mar. 06, 2024. [Online]. Available: http://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide
[29] "Se han afectado los ciclos autorregulatorios del planeta," Gaceta UNAM. Accessed: Jul. 22, 2024. [Online]. Available: https://www.gaceta.unam.mx/se-han-afectado-los-ciclos-autorregulatorios-del-planeta/
[30] "Las altas temperaturas afectan todos los ecosistemas," Gaceta UNAM. Accessed: Jul. 22, 2024. [Online]. Available: https://www.gaceta.unam.mx/las-altas-temperaturas-afectan-todos-los-ecosistemas/
[31] "Climate change." Accessed: Jul. 22, 2024. [Online]. Available: https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health
[32] "Rodríguez - 2024 - DIRECCIÓN GENERAL DE EPIDEMIOLOGÍA.pdf." Accessed: Jul. 22, 2024. [Online]. Available: https://www.gob.mx/cms/uploads/attachment/file/930010/Pano_dengue_28.pdf
[33] "International Agreements on Climate Change - Iberdrola." Accessed: Mar. 06, 2024. [Online]. Available: https://www.iberdrola.com/sustainability/international-agreements-on-climate-change
[34] "Climate Crisis Past Point of No Return, Secretary-General Says, Listing Global Threats at General Assembly Consultation on 'Our Common Agenda' Report | Meetings Coverage and Press Releases." Accessed: Jul. 24, 2024. [Online]. Available: https://press.un.org/en/2022/sgsm21173.doc.htm

[35] “Sustainable Development Goals | United Nations Development Programme,” UNDP. Accessed: May 06, 2024. [Online]. Available: https://www.undp.org/sustainable-development-goals
[36] U. Nations, “Sustainable Development | Naciones Unidas,” United Nations. Accessed: May 06, 2024. [Online]. Available: https://www.un.org/es/teach/SDGs
[37] opinion contributors Sir David King and Sware Semesi, “We’re past the point of no return on climate emissions — it’s time we turn to carbon removal,” The Hill. Accessed: Jul. 24, 2024. [Online]. Available: https://thehill.com/opinion/energy-environment/4213981-were-past-the-point-of-no-return-on-climate-emissions-its-time-we-turn-to-carbon-removal/
[38] “Study Says 2035 Is Climate Change Point of No Return,” HowStuffWorks. Accessed: Jul. 24, 2024. [Online]. Available: https://science.howstuffworks.com/environmental/conservation/issues/point-no-return-for-climate-action-is-2035.htm
[39] L. S. Paraschiv and S. Paraschiv, “Contribution of renewable energy (hydro, wind, solar and biomass) to decarbonization and transformation of the electricity generation sector for sustainable development,” *Energy Reports*, vol. 9, pp. 535–544, Sep. 2023, doi: 10.1016/j.egyr.2023.07.024.
[40] E. Institute, “Home,” Statistical review of world energy. Accessed: Jan. 29, 2025. [Online]. Available: https://www.energyinst.org/statistical-review/home
[41] “Statistics and Insights from DNV.” Accessed: Jul. 24, 2024. [Online]. Available: https://www.dnv.com/about/statistics-and-insights/energy-transition/
[42] “Technology Progress Report, Energy Transition Outlook,” DNV, 2021.
[43] R. Eriksen, “Energy Transition Outlook: New Power Systems,” DNV, Høvik, Norway, 2023. Accessed: Jul. 28, 2024. [Online]. Available: https://www.dnv.com/publications/new-power-systems-report/
[44] “Hywind Tampen.” Accessed: May 07, 2024. [Online]. Available: https://www.equinor.com/energy/hywind-tampen
[45] “https://www.renewableuk.com/media/scccdrxe/floating-offshore-wind-2050-vision-final.pdf#:~:text=UK%20companies%20in%20our%20existing%20offshore%20wind%2C,needed%20to%20construct%20floating%20offshore%20wind%20farms.&text=The%20capability%20and%20skills%20overlap%20between%20the,as%20North%20Sea%20fossil%20fuel%20production%20declines21.” Accessed: Mar. 22, 2025. [Online]. Available: https://www.renewableuk.com/media/scccdrxe/floating-offshore-wind-2050-vision-final.pdf#:~:text=UK%20companies%20in%20our%20existing%20offshore%20wind%2C,needed%20to%20construct%20floating%20offshore%20wind%20farms.&text=The%20capability%20and%20skills%20overlap%20between%20the,as%20North%20Sea%20fossil%20fuel%20production%20declines21.
[46] “How Much Power is 1 Gigawatt?,” Energy.gov. Accessed: Jul. 28, 2024. [Online]. Available: https://www.energy.gov/eere/articles/how-much-power-1-gigawatt
[47] “Levelized Cost of Energy (LCOE)”.
[48] “Gas to liquids (GTL),” PetroWiki. Accessed: Jul. 28, 2024. [Online]. Available: https://petrowiki.spe.org/Gas_to_liquids_(GTL)
[49] P. Buchenberg *et al.*, “Global Potentials and Costs of Synfuels via Fischer–Tropsch Process,” *Energies*, vol. 16, no. 4, Art. no. 4, Jan. 2023, doi: 10.3390/en16041976.
[50] “Progress in Commercialization of Biojet/Sustainable Aviation Fuels (SAF): Technologies and policies – Bioenergy.” Accessed: Jul. 30, 2024. [Online]. Available: https://www.ieabioenergy.com/blog/publications/progress-in-commercialization-of-biojet-sustainable-aviation-fuels-saf-technologies-and-policies/

[51] "Production of biofuel by gasification of biomass validated." Accessed: Jul. 30, 2024. [Online]. Available: https://www.vttresearch.com/en/news-and-ideas/complete-production-chain-biomass-residues-fischer-tropsch-products-successfully
[52] "H2 MOBILITY," H2Mobility. Accessed: Aug. 01, 2024. [Online]. Available: https://h2-mobility.de/en/h2mobility/
[53] "Hydrogen is vital to tackling climate change," HyDeploy. Accessed: Aug. 01, 2024. [Online]. Available: https://hydeploy.co.uk/
[54] "REFHYNE," REFHYNE. Accessed: Aug. 01, 2024. [Online]. Available: https://www.refhyne.eu/
[55] "H21-Executive-Summary-Interactive-PDF-July-2016-V2.pdf." Accessed: Aug. 01, 2024. [Online]. Available: https://www.northerngasnetworks.co.uk/wp-content/uploads/2017/04/H21-Executive-Summary-Interactive-PDF-July-2016-V2.pdf
[56] "Bus Transit - Fuel Cell Electric Buses | Ballard Power." Accessed: Aug. 01, 2024. [Online]. Available: https://www.ballard.com/markets/transit-bus
[57] "Toyota Delivers Fuel Cell Bus to Tokyo Metropolitan Government | Toyota Motor Corporation Official Global Website." Accessed: Aug. 01, 2024. [Online]. Available: https://global.toyota/en/detail/15160167
[58] "HyBalance_Brochure_Sep2020_Final.pdf." Accessed: Aug. 01, 2024. [Online]. Available: https://hybalance.eu/wp-content/uploads/2020/10/HyBalance_Brochure_Sep2020_Final.pdf
[59] "A fossil-free development," Hybrit. Accessed: Aug. 01, 2024. [Online]. Available: https://www.hybritdevelopment.se/en/a-fossil-free-development/
[60] "Alstom Coradia iLint – the world's 1st hydrogen powered passenger train," Alstom. Accessed: Aug. 01, 2024. [Online]. Available: https://www.alstom.com/solutions/rolling-stock/alstom-coradia-ilint-worlds-1st-hydrogen-powered-passenger-train
[61] "The Future of Hydrogen – Analysis," IEA. Accessed: Aug. 08, 2024. [Online]. Available: https://www.iea.org/reports/the-future-of-hydrogen
[62] "2022 - Levelized Costs of New Generation Resources in the.pdf." Accessed: Aug. 08, 2024. [Online]. Available: https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf
[63] "Levelized Production Cost of Green & Blue Hydrogen: Market Trends & Outlook | GEP Blog." Accessed: Aug. 08, 2024. [Online]. Available: https://www.gep.com/blog/strategy/Green-and-blue-hydrogen-current-levelized-cost-of-production-and-outlook
[64] "ETP Clean Energy Technology Guide – Data Tools," IEA. Accessed: Oct. 25, 2024. [Online]. Available: https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide
[65] "Negative emissions technologies and practices: the way forward," CORDIS | European Commission. Accessed: Aug. 08, 2024. [Online]. Available: https://cordis.europa.eu/article/id/448423-negative-emissions-technologies-and-practices-the-way-forward
[66] International Energy Agency, *Direct Air Capture: A key technology for net zero*. OECD, 2022. doi: 10.1787/bbd20707-en.
[67] "Carbon Dioxide Removal (CDR): Its Potential Role in Climate Change Mitigation." Accessed: Mar. 22, 2025. [Online]. Available: https://www.congress.gov/crs-product/R48258
[68] O. Underwood *et al.*, "2023 Circular Carbon Market Report," 2023.
[69] "Captura y uso de carbono | Contaminación a energía," Carbon Power Mexico. Accessed: Mar. 31, 2025. [Online]. Available: https://www.carbonpowermx.com
[70] "Is carbon capture too expensive? – Analysis," IEA. Accessed: Aug. 08, 2024. [Online]. Available: https://www.iea.org/commentaries/is-carbon-capture-too-expensive

[71] B. Metz and Intergovernmental Panel on Climate Change, Eds., *IPCC special report on carbon dioxide capture and storage*, 1. publ. Cambridge: Cambridge Univ. Press, 2005.
[72] A. L. Kohl and R. Nielsen, *Gas purification*, 5th ed. Houston, Tex: Gulf Pub, 1997.
[73] I. Jones, *Engineering strategies for greenhouse gas mitigation*, 1. publ. Cambridge: Cambridge University Press, 2011.
[74] "CCUS in clean energy transitions," *Energy Technology Perspectives*, 2020.
[75] "CCS: Carbon capture and storage — making net zero possible." Accessed: Aug. 08, 2024. [Online]. Available: https://www.equinor.com/energy/carbon-capture-utilisation-and-storage
[76] "Carbon Capture, Utilisation and Storage - Energy System," IEA. Accessed: Aug. 08, 2024. [Online]. Available: https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage
[77] "Global CCS facilities status 2024 by region," Statista. Accessed: Aug. 08, 2024. [Online]. Available: https://www.statista.com/statistics/1308723/worldwide-ccs-facilities-by-region/
[78] "enhanced oil recovery | Energy Glossary." Accessed: May 20, 2024. [Online]. Available: https://glossary.slb.com/en/terms/e/enhanced_oil_recovery
[79] "miscible displacement | Energy Glossary." Accessed: May 20, 2024. [Online]. Available: https://glossary.slb.com/en/terms/m/miscible_displacement
[80] "https://www.netl.doe.gov/sites/default/files/netl-file/co2_eor_primer.pdf#:~:text=A%20successful%20CO2%20EOR%20project%20could%20add,CO2%20miscibility%20with%20the%20crude%20oil%20lower." Accessed: Mar. 22, 2025. [Online]. Available: https://www.netl.doe.gov/sites/default/files/netl-file/co2_eor_primer.pdf#:~:text=A%20successful%20CO2%20EOR%20project%20could%20add,CO2%20miscibility%20with%20the%20crude%20oil%20lower.
[81] "Mexico energy profile".
[82] M. A. L. Ramírez and J. J. L. Ng, "México | Emisiones y fuentes de los Gases de Efecto Invernadero," 2024.
[83] "Ramírez y Ng - 2024 - México Emisiones y fuentes de los Gases de Efect.pdf." Accessed: Oct. 24, 2024. [Online]. Available: https://www.bbvaresearch.com/wp-content/uploads/2024/01/2024-Emisiones-y-fuentes-GEI-Mexico.pdf
[84] "Mexico - Countries & Regions," IEA. Accessed: Oct. 24, 2024. [Online]. Available: https://www.iea.org/countries/mexico/emissions
[85] "SR15_SPM_version_stand_alone_LR.pdf." Accessed: Aug. 08, 2024. [Online]. Available: https://www.ipcc.ch/site/assets/uploads/sites/2/2018/07/SR15_SPM_version_stand_alone_LR.pdf
[86] USGCRP, "Fourth National Climate Assessment," U.S. Global Change Research Program, Washington, DC, 2018. Accessed: Aug. 08, 2024. [Online]. Available: https://nca2018.globalchange.gov
[87] M. Bui, M. Fajardy, and N. Mac Dowell, "Bio-energy with carbon capture and storage (BECCS): Opportunities for performance improvement," *Fuel*, vol. 213, pp. 164–175, Feb. 2018, doi: 10.1016/j.fuel.2017.10.100.
[88] Intergovernmental Panel on Climate Change and O. Edenhofer, Eds., *Climate change 2014: mitigation of climate change: Working Group III contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. New York, NY: Cambridge University Press, 2014.
[89] "The Power of Renewable Energy Solutions | Meg Galy News." Accessed: Sep. 02, 2024. [Online]. Available: https://meggalynews.com/29714-the-power-of-renewable-energy-solutions-07/
[90] A. Al-Rumaihi, M. Shahbaz, G. Mckay, H. Mackey, and T. Al-Ansari, "A review of pyrolysis technologies and feedstock: A blending approach for plastic and biomass towards optimum biochar

yield," *Renewable and Sustainable Energy Reviews*, vol. 167, p. 112715, Oct. 2022, doi: 10.1016/j.rser.2022.112715.

[91] X. Zhu and Q. Yao, "Logistics system design for biomass-to-bioenergy industry with multiple types of feedstocks," *Bioresource Technology*, vol. 102, no. 23, pp. 10936–10945, Dec. 2011, doi: 10.1016/j.biortech.2011.08.121.

[92] T. B. Johansson, A. Patwardhan, N. Nakićenović, L. F. Gómez Echeverri, and International Institute for Applied Systems Analysis, Eds., *Global energy assessment (GEA)*. Laxenburg, Austria: International Institute for Applied Systems Analysis, 2012.

[93] J. E. A. Seabra and I. C. Macedo, "Comparative analysis for power generation and ethanol production from sugarcane residual biomass in Brazil," *Energy Policy*, vol. 39, no. 1, pp. 421–428, Jan. 2011, doi: 10.1016/j.enpol.2010.10.019.

[94] D. L. Sanchez and D. S. Callaway, "Optimal scale of carbon-negative energy facilities," *Applied Energy*, vol. 170, pp. 437–444, May 2016, doi: 10.1016/j.apenergy.2016.02.134.

[95] "AR5 Climate Change 2014: Mitigation of Climate Change — IPCC." Accessed: Apr. 08, 2024. [Online]. Available: https://www.ipcc.ch/report/ar5/wg3/

[96] "Bioenergy with Carbon Capture and Storage - Energy System," IEA. Accessed: Oct. 25, 2024. [Online]. Available: https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/bioenergy-with-carbon-capture-and-storage

[97] "Carbon Capture and Sequestration Technologies @ MIT." Accessed: Sep. 02, 2024. [Online]. Available: http://sequestration.mit.edu/tools/projects/illinois_industrial_ccs.html

[98] "DOE Explains...Direct Air Capture," Energy.gov. Accessed: Oct. 08, 2024. [Online]. Available: https://www.energy.gov/science/doe-explainsdirect-air-capture

[99] "Direct Air Capture and Storage of CO2," Carbon Engineering. Accessed: Oct. 08, 2024. [Online]. Available: https://carbonengineering.com/direct-air-capture/

[100] "Global DAC Deployments Map," Direct Air Capture Coalition. Accessed: Jan. 15, 2025. [Online]. Available: https://daccoalition.org/global-dac-deployments/

[101] "Direct Air Capture - Energy System," IEA. Accessed: Oct. 07, 2024. [Online]. Available: https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/direct-air-capture

[102] "Calciner | VTT." Accessed: Jan. 29, 2025. [Online]. Available: https://www.vttresearch.com/en/about-us/invest-innovation/vtt-launchpad/calciner

[103] Cool Worlds, *How Thermodynamics Holds Back Negative Carbon Tech*, (Sep. 19, 2023). Accessed: Oct. 27, 2024. [Online Video]. Available: https://www.youtube.com/watch?v=EBN9JeX3iDs

[104] J. Kemper, "New IEAGHG report: Global Assessment of DACCS Costs, Scale and Potential," IEAGHG. Accessed: Oct. 08, 2024. [Online]. Available: https://ieaghg.org/news/new-ieaghg-report-global-assessment-of-daccs-costs-scale-and-potential/

[105] "¿Cuánta energía produce un panel solar?," Solar Reviews. Accessed: Mar. 01, 2025. [Online]. Available: https://www.solarreviews.com/content/blog/cuanta-electricidad-produce-un-panel-solar

[106] D. Riedl, Z. Byrum, S. Li, H. Pilorgé, P. Psarras, and K. Lebling, "5 Things to Know About Carbon Mineralization," Jun. 2023, Accessed: Oct. 10, 2024. [Online]. Available: https://www.wri.org/insights/carbon-mineralization-carbon-removal

[107] V. Romanov, Y. Soong, C. Carney, G. Rush, B. Nielsen, and W. O'Connor, "Mineralization of Carbon Dioxide: Literature Review".

[108] B. P. McGrail, F. A. Spane, J. E. Amonette, C. R. Thompson, and C. F. Brown, "Injection and Monitoring at the Wallula Basalt Pilot Project," *Energy Procedia*, vol. 63, pp. 2939–2948, Jan. 2014, doi: 10.1016/j.egypro.2014.11.316.

[109] Climate Now, *Carbon Dioxide Removal: Mineralization | Climate Now Ep. 2.7*, (Dec. 21, 2021). Accessed: Oct. 21, 2024. [Online Video]. Available: https://www.youtube.com/watch?v=LK_bCFftGaw
[110] "Making Minerals-How Growing Rocks Can Help Reduce Carbon Emissions | U.S. Geological Survey." Accessed: Oct. 10, 2024. [Online]. Available: https://www.usgs.gov/news/featured-story/making-minerals-how-growing-rocks-can-help-reduce-carbon-emissions
[111] D. Riedl, Z. Byrum, S. Li, H. Pilorgé, P. Psarras, and K. Lebling, "5 Things to Know About Carbon Mineralization," Jun. 2023, Accessed: Oct. 21, 2024. [Online]. Available: https://www.wri.org/insights/carbon-mineralization-carbon-removal
[112] "Carbon Dioxide Removal: Mineralization," Climate Now. Accessed: Oct. 21, 2024. [Online]. Available: https://climatenow.com/video/carbon-dioxide-removal-mineralization/
[113] Z.-Y. Khoo *et al.*, "Life cycle assessment of a CO2 mineralisation technology for carbon capture and utilisation in Singapore," *Journal of CO2 Utilization*, vol. 44, p. 101378, Feb. 2021, doi: 10.1016/j.jcou.2020.101378.
[114] Carbfix, *Carbfix - How it works*, (Feb. 14, 2022). Accessed: Jan. 27, 2025. [Online Video]. Available: https://www.youtube.com/watch?v=60mxSf3OPbw
[115] "Carbfix." Accessed: Jan. 27, 2025. [Online]. Available: https://carbfix.vercel.app
[116] Anonymous, "Enhanced Rock Weathering," UNDO Carbon. Accessed: Oct. 23, 2024. [Online]. Available: https://un-do.com/enhanced-weathering/
[117] "Climate interventions - Enhanced weathering (on land)." Accessed: Oct. 23, 2024. [Online]. Available: https://climateinterventions.org/interventions/enhanced-weathering-on-land/#
[118] P. Renforth, "The potential of enhanced weathering in the UK," *International Journal of Greenhouse Gas Control*, vol. 10, pp. 229–243, Sep. 2012, doi: 10.1016/j.ijggc.2012.06.011.
[119] "Enhanced Rock Weathering | MIT Climate Portal." Accessed: Oct. 23, 2024. [Online]. Available: https://climate.mit.edu/explainers/enhanced-rock-weathering
[120] K. Skov *et al.*, "Initial agronomic benefits of enhanced weathering using basalt: A study of spring oat in a temperate climate," 2024.
[121] "Exploring Direct Air Capture's Role in Enhanced Oil Recovery," Kleinman Center for Energy Policy. Accessed: Oct. 27, 2024. [Online]. Available: https://kleinmanenergy.upenn.edu/commentary/blog/exploring-direct-air-captures-role-in-enhanced-oil-recovery/
[122] "https://www.gob.mx/cms/uploads/attachment/file/315721/CCUS_ESPA_OL.pdf." Accessed: Feb. 09, 2025. [Online]. Available: https://www.gob.mx/cms/uploads/attachment/file/315721/CCUS_ESPA_OL.pdf
[123] "https://www.gob.mx/cms/uploads/attachment/file/421223/ESIA_Poza_Rica_Versi_n_Final_151018_pubRev.pdf." Accessed: Feb. 09, 2025. [Online]. Available: https://www.gob.mx/cms/uploads/attachment/file/421223/ESIA_Poza_Rica_Versi_n_Final_151018_pubRev.pdf
[124] "Plataforma Nacional de Energía, Ambiente y Sociedad," Plataforma Nacional de Energía, Ambiente y Sociedad. Accessed: Oct. 26, 2024. [Online]. Available: http://energia.conahcyt.mx/planeas
[125] S. de A. y D. Rural, "Biomasa, creación ecológica de energía," gob.mx. Accessed: Oct. 26, 2024. [Online]. Available: http://www.gob.mx/agricultura/es/articulos/biomasa-creacion-ecologica-de-energia

[126] D. M. Saharudin, H. K. Jeswani, and A. Azapagic, “Bioenergy with carbon capture and storage (BECSS): Life cycle environmental and economic assessment of electricity generated from palm oil wastes,” *Applied Energy*, vol. 349, p. 121506, Nov. 2023, doi: 10.1016/j.apenergy.2023.121506.
[127] C. S. Goh and K. T. Lee, “Palm-based biofuel refinery (PBR) to substitute petroleum refinery: An energy and emergy assessment,” *Renewable and Sustainable Energy Reviews*, vol. 14, no. 9, pp. 2986–2995, Dec. 2010, doi: 10.1016/j.rser.2010.07.048.
[128] International Energy Agency, *The Oil and Gas Industry in Net Zero Transitions*. OECD, 2023. doi: 10.1787/fd522f59-en.
[129] M. E. P. LLC, “La estructura energética de Baja California,” Mexico Energy Partners LLC. Accessed: Oct. 26, 2024. [Online]. Available: https://mexicoenergyllc.com.mx/es/blogs/mexico-energy-insights/energy-outlook-for-baja-california
[130] “Nuevo material captura CO2 directamente del aire sin degradación,” La Crónica de Hoy México. Accessed: Oct. 27, 2024. [Online]. Available: https://www.cronica.com.mx/academia/2024/10/24/nuevo-material-captura-co2-directamente-del-aire-sin-degradacion/
[131] “Direct Air Capture 101: Your Essential Carbon Capture Guide.” Accessed: Oct. 27, 2024. [Online]. Available: https://www.flowcarbon.com/knowcarbon/direct-air-capture-101
[132] J. H. Almazán-Mendoza, A. P. Gómora-Figueroa, and L. Mori, “RETENCIÓN DE CO2 POR MINERALIZACIÓN EN ROCAS. UNA PROPUESTA DE PREPARACIÓN Y ANÁLISIS DE MUESTRAS EN EL LABORATORIO,” vol. 2.
[133] A. Gómez-Tuena, Ma. T. Orozco-Esquivel, and L. Ferrari, “Petrogénesis ígnea de la Faja Volcánica Transmexicana,” *BSGM*, vol. 57, no. 3, pp. 227–283, 2005, doi: 10.18268/BSGM2005v57n3a2.
[134] E. Cantú Apodaca, “Análisis de la Factibilidad para la Eliminación de Dióxido de Carbono Mediante la Formación de Carbonatos a través de Basaltos,” UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO, Ciudad Universitaria, CDMX, 2018. Accessed: Jan. 31, 2025. [Online]. Available: http://132.248.9.195/ptd2018/febrero/0770595/0770595.pdf
[135] P. Ortiz Lucas, “ESTUDIO SOBRE LA MINERALIZACIÓN DE BASALTOS MEXICANOS EN PRESENCIA DE CO2,” UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO, Ciudad Universitaria, CDMX, 2020. Accessed: Jan. 31, 2025. [Online]. Available: https://ru.dgb.unam.mx/bitstream/20.500.14330/TES01000800736/3/0800736.pdf
[136] “X-Ray Fluorescence (XRF),” Techniques. Accessed: Feb. 04, 2025. [Online]. Available: https://serc.carleton.edu/research_education/geochemsheets/techniques/XRF.html
[137] “Glossary: WORT.” Accessed: Feb. 04, 2025. [Online]. Available: https://ec.europa.eu/health/scientific_committees/opinions_layman/nanomaterials/en/glossary/pqrs/specific-surface-area.htm
[138] ehernandez@rumbo.ventures, “Silica,” Rumbo Ventures. Accessed: Feb. 04, 2025. [Online]. Available: https://rumbo.ventures/food-agriculture-and-land-use/silica-2/
[139] “https://www.gob.mx/cms/uploads/attachment/file/421220/MRT2finalacc_2.pdf.” Accessed: Feb. 07, 2025. [Online]. Available: https://www.gob.mx/cms/uploads/attachment/file/421220/MRT2finalacc_2.pdf
[140] “Solar resource maps & GIS data for 200+ countries | Solargis.” Accessed: Feb. 04, 2025. [Online]. Available: https://solargis.com/resources/free-maps-and-gis-data
[141] “Global Solar Atlas.” Accessed: Feb. 28, 2025. [Online]. Available: https://globalsolaratlas.info/global-pv-potential-study

[142] M. E. P. LLC, “Mexico’s Renewable Energy Goals For 2030,” Mexico Energy Partners LLC. Accessed: Feb. 04, 2025. [Online]. Available: https://mexicoenergyllc.com.mx/blogs/mexico-energy-insights/mexico-s-renewable-energy-goals-for-2030