CSTEP

CARBON CAPTURE, UTILISATION, AND STORAGE

(CCUS)

A White Paper

Carbon Capture, Utilisation, and Storage (CCUS)

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Executive Summary

In 2023, India's total emissions grew to 4.2 gigatonne of carbon dioxide (CO_2) equivalent (Gt CO_2e), with the industrial and power sectors alone accounting for nearly 60% of the total emissions. Moreover, the country's total emissions are projected to reach 12–15 Gt CO_2e by 2070 (CSTEP, 2024b; Statista, 2025). Coal-based power generation and steel and cement plants are the primary sources of emissions in the country. To curb these emissions and achieve the net-zero emission target by 2070, we must consider interventions with a multifaceted approach. These interventions include the adoption of higher renewable energy and energy efficiency measures, as well as the deployment of decarbonisation technologies such as carbon capture, utilisation, and storage (CCUS). Adopting renewable energy and incorporating energy efficiency measures into processes can reduce energy and process emissions, respectively, to a certain extent. Integrating CCUS into an industry, however, can theoretically abate 100% of total emissions.

This white paper focuses on CCUS, an emerging technology that can play a crucial role in achieving net-zero goals. CCUS enables the capture of CO_2 from point sources, which can then either be utilised for different applications (enhanced oil recovery, enhanced coal bed methane recovery, and production of chemicals, carbonates, etc.) or stored (in geological sites having basalts and saline aquifers). Further, India has a theoretical CO_2 storage potential of 395–614 Gt (NITI Aayog, 2022). In 2022, India's CO_2 demand was 2 million tonne (Mt), which is expected to reach 3.5 Mt by 2035 (ChemAnalyst, 2023).

The white paper provides an overview of the following:

1. **Potential of decarbonising different industries through CCUS.**
2. **Technology options for carbon capture, transportation, utilisation, and storage.**
3. **Suitable capture technologies for different industries.**
4. **India's CO_2 utilisation market.**
5. **Challenges (technical-, economic-, and policy-related) associated with CCUS.**

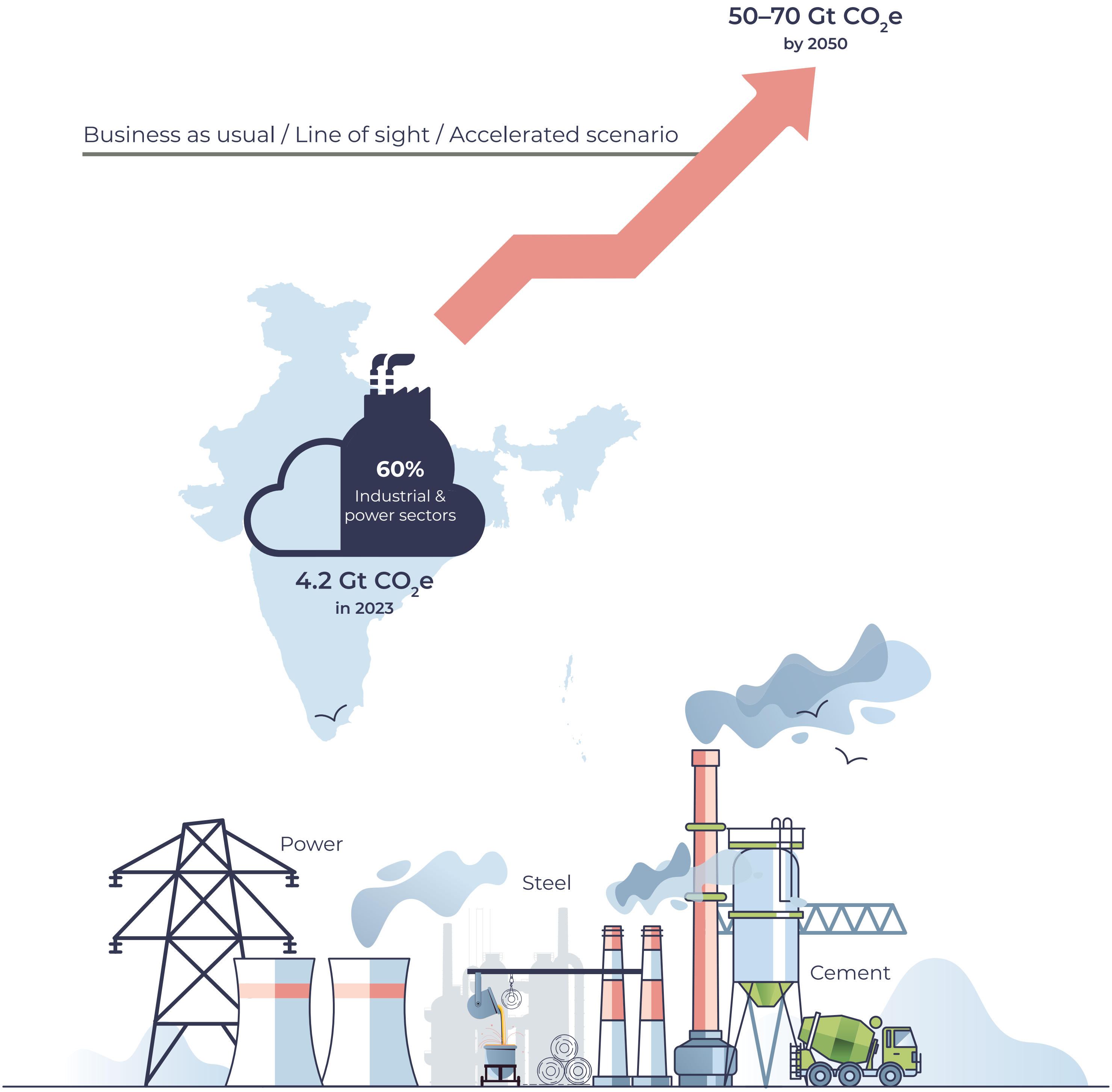
To understand the potential of CCUS in India's decarbonisation journey, the study considered three major sectors—power, steel, and cement—under various emission reduction scenarios. The analysis indicated that these sectors will release a cumulative CO_2 of 50–70 Gt by 2050. This underscores the crucial role of CCUS in tackling this volume of expected emissions.

Further, the maturity of various carbon capture technologies was reviewed using the technology-readiness-level (TRL) framework to assess the deployment potential of CCUS. The literature-review-based evaluation indicated that conventional capture methods, such as absorption and adsorption, are already at advanced stages of technology readiness (TRL 8–9), while technologies such as microalgae-based, hydrate-based, and hybrid systems remain in early development stages (TRL 3–5). This highlights the importance of supporting both the immediate deployment of mature solutions and the continued investments in emerging technologies to ensure long-term CCUS scalability.

The study also mapped key industries to appropriate CO_2 capture routes and technologies to determine which routes and technologies are most suitable for different emission-intensive industries. This suitability depends on factors such as the placement of the capture facility, the CO_2 concentration in the flue gas, the economic feasibility of the technology, and the CO_2 purity required for its intended end use. By conducting this mapping exercise, we could align specific capture technologies with industry characteristics to ensure practical and cost-effective implementation. A literature review revealed that post-combustion capture offers broader applicability across sectors, due to its compatibility with existing infrastructure. In contrast, pre-combustion is suitable for fewer industries, as it involves significant plant modifications, and oxy-combustion is constrained by its high cost and complexity. This mapping helped identify priority sectors for CCUS deployment, allowing for tailored interventions.

To build a CCUS ecosystem in India, several critical gaps need to be addressed. For instance, a comprehensive CCUS roadmap or policy framework is needed to guide large-scale deployment of CCUS. Further, this would require providing financial support or incentives such as carbon pricing, tax credits, or grants. The Union Budget 2026–27 has allocated INR 20,000 crore for CCUS, with a focus on the power, cement, steel, chemicals, and refinery sectors, addressing the economic challenges associated with this technology. Creating a robust CCUS ecosystem will also require addressing public acceptance challenges and strengthening coordination among central and state authorities, industry, and research bodies to enable the active deployment of CCUS.

Apart from these, CCUS deployment is hindered by the limited maturity of technologies, a lack of infrastructure for CO_2 transport and storage, less proven sustainable utilisation pathways, and the absence of supportive policies. Implementing effective subsidies and enhancing technical performance will boost CCUS implementation in India, which has a significant opportunity to address some of the discussed challenges following the launch of the Carbon Credit Trading System in 2026.


50–70 Gt CO_2e
by 2050
Business as usual / Line of sight / Accelerated scenario
60%
Industrial &
power sectors
4.2 Gt CO_2e
in 2023
Power
Steel
Cement

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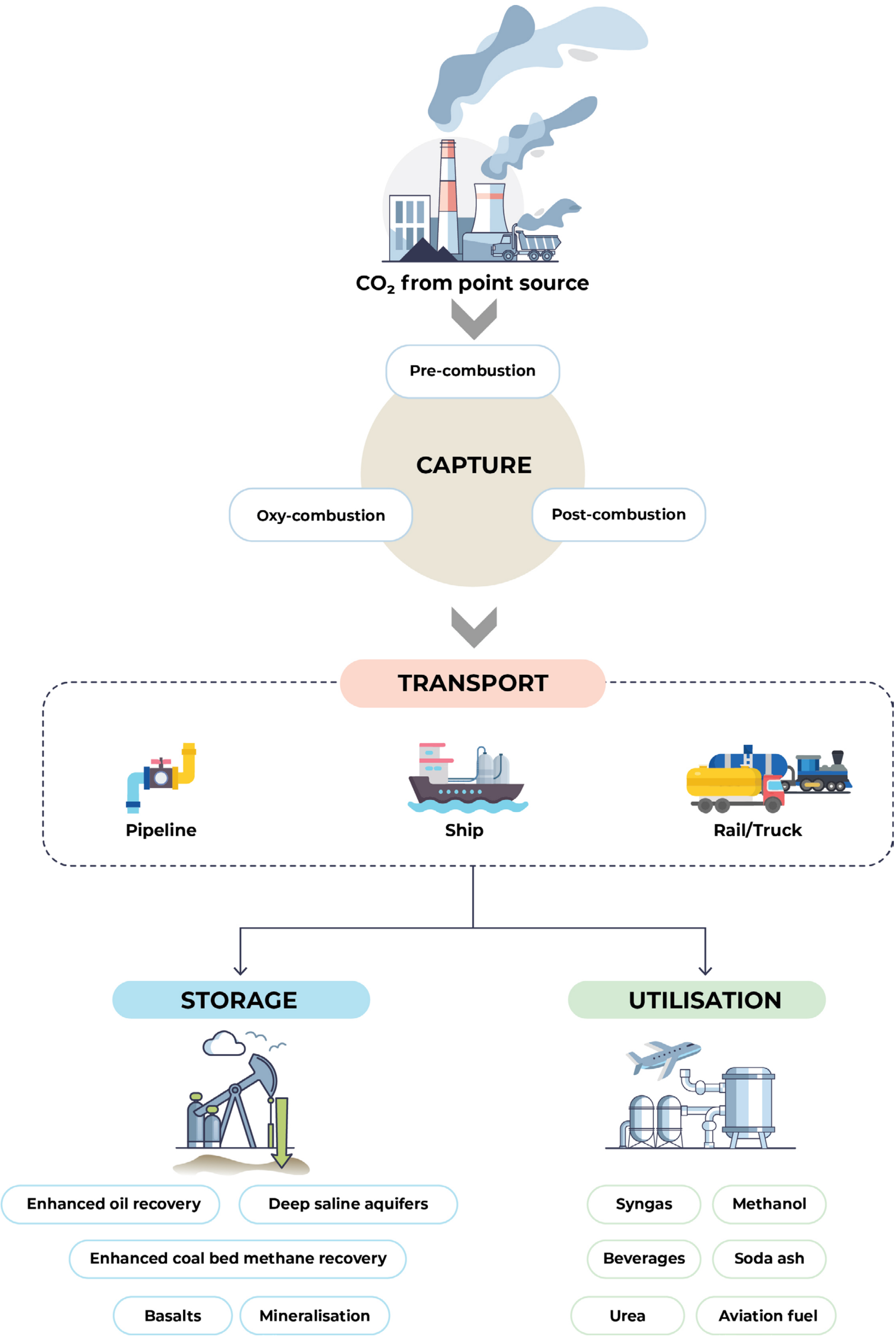
Abbreviations

BAU	Business as usual
°C	Degree celsius
CAGR	Compound annual growth rate
$Ca(OH)_2$	Calcium hydroxide
$CaCO_3$	Calcium carbonate
CaO	Calcium oxide
CCS	Carbon capture storage
CCUS	Carbon capture, utilisation, and storage
CH_4	Methane
CLC	Chemical looping cycle
CNT	Carbon nanotube
CO	Carbon monoxide
CO_2	Carbon dioxide
CRES	Constrained Renewable Energy Scenario
CuO	Copper oxide
DAC	Direct air capture
ECBMR	Enhanced coal bed methane recovery
EOR	Enhanced oil recovery
Fe_2O_3	Ferric oxide
GJ	Gigajoule
Gt	Gigatonne
H_2	Hydrogen
HBCC	Hydrate-based CO_2 capture
H_2O	Water
IEA	International Energy Agency
K_2CO_3	Potassium carbonate
LOS	Line of sight
$MgCO_3$	Magnesium carbonate
Mn_2O_3	Manganese oxide
MOF	Metal–organic framework
MPa	Mega pascal

N_2	Nitrogen
Na_2CO_3	Sodium hydroxide
NG	Natural gas
NiO	Nickel oxide
NFS	No Fossil-Fuel Scenario
ppm	Parts per million
RCA	Residual concrete aggregate
TCS	Tonne of crude steel
TERI	The Energy and Resources Institute
URES	Unconstrained Renewable Energy Scenario



CO_2 from point source
Pre-combustion
CAPTURE
Oxy-combustion
Post-combustion
TRANSPORT
Pipeline
Ship
Rail/Truck
STORAGE
UTILISATION
Enhanced oil recovery
Deep saline aquifers
Enhanced coal bed methane recovery
Basalts
Mineralisation
Syngas
Methanol
Beverages
Soda ash
Urea
Aviation fuel

1. Introduction

Rising material and energy consumption have led to an exponential increase in emissions worldwide, exacerbating the effects of climate change (United Nations, 2022). Mitigating climate change and preventing a temperature rise of 2 °C call for limiting atmospheric carbon dioxide (CO_2) levels to 445–490 parts per million (ppm) from the current levels of 422.7 ppm (Intergovernmental Panel On Climate Change [IPCC], 2023). To achieve this, managing emissions from emission-intensive sectors such as power, cement, steel, and refineries through approaches such as employing low-carbon or sustainable fuels, improving plant efficiency, transitioning to renewable energy, and implementing decarbonisation technologies is crucial. Carbon capture, utilisation, and storage (CCUS) is an emerging solution for decarbonising industries. It involves capturing CO_2 from point-source emissions (such as from industries) and transporting it to a utilisation site or geological storage site.

Need for CCUS in India

In 2023, India's total emissions were 4.2 gigatonne of CO_2 equivalent (Gt CO_2e), with the industrial and power sectors alone contributing approximately 60% of the total emissions (CSTEP, 2024b). This indicates the necessity to deploy decarbonisation technologies such as CCUS (NITI Aayog, 2022). The need for CCUS in India is summarised below.

Reducing emissions and accelerating net zero
The increasing risks of climate change necessitate a faster achievement of net zero. Under the International Energy Agency's (IEA's) Sustainable Development Scenario, CCUS contributes approximately 15% of the cumulative reduction in emissions (IEA, 2020a). Therefore, adopting CCUS, especially in emission-intensive sectors, will help mitigate emissions and accelerate India's net-zero target.

Enhancing energy security
India relies heavily on fossil fuels, particularly coal, for electricity generation, with approximately 70% of the nation's electricity still being generated from coal (Ministry of Coal, 2024). While renewable energy capacity is growing rapidly, fossil fuels are expected to remain a significant part of India's energy mix in the near future. Employing CCUS in the power sector will not only contribute to decarbonisation but also enhance India's energy security.

Promoting sustainable carbon utilisation
CO_2 abated from key industries can be utilised for enhanced oil recovery (EOR). Moreover, value-added low-carbon products such as hydrogen, methanol, urea, and acetic acid can be produced from the captured CO_2. Overall, promoting the CO_2 utilisation will reduce import requirements and provide economic benefits (Kamkeng et al., 2021).

Objectives

The objective of this white paper is to assess the potential and readiness of CCUS technologies in India as a viable pathway for industrial decarbonisation. It provides comprehensive insights into the technology landscape and sectoral applicability to accelerate CCUS deployment in the country.

Specifically, the white paper seeks to:

- Evaluate the potential of CCUS in decarbonising major emission-intensive sectors such as power, steel, and cement,
- Examine various technology options for carbon capture, transportation, utilisation, and storage,
- Identify suitable capture technologies for different industrial sectors based on technical and economic feasibility,
- Analyse India's current and projected CO_2 utilisation market and the opportunities for scale-up, and
- Highlight the key challenges—technical, economic, and policy-related—hindering CCUS deployment and propose measures to address them.

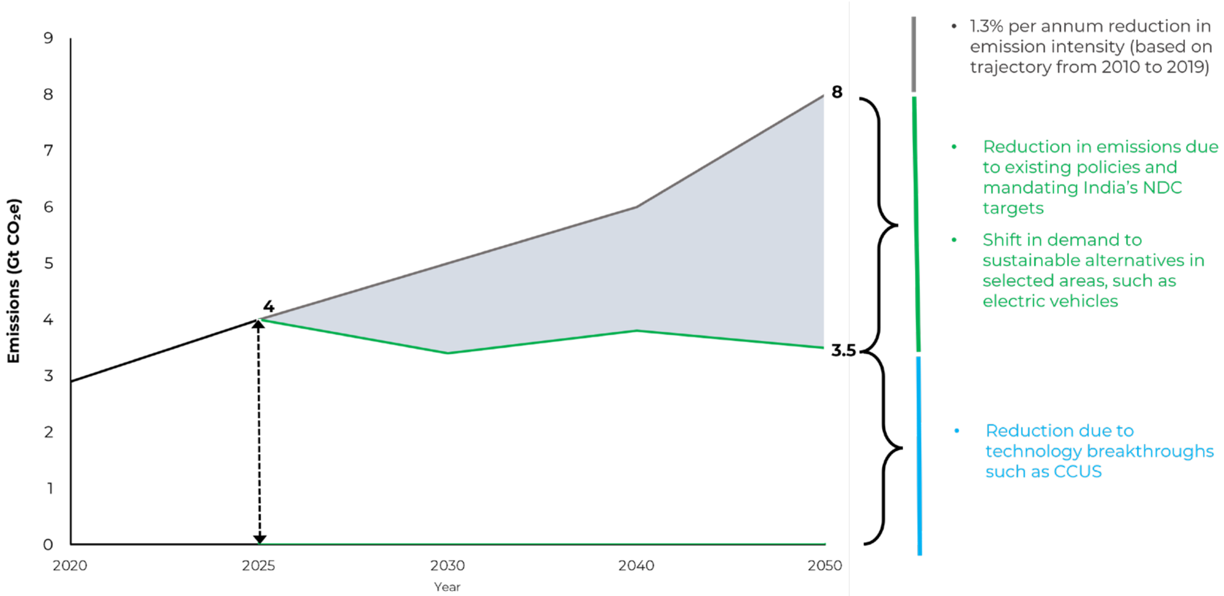
In this study, CO_2 emissions from India's emission-intensive sectors—cement, steel, and power—were evaluated, followed by an analysis of the potential CCUS requirements to abate these emissions and achieve net-zero by 2070. The technologies available for CO_2 capture, transportation, and storage are comprehensively reviewed.

This white paper is structured into eight sections. Section 1 discusses the need for CCUS, while Section 2 evaluates the potential requirement of CCUS to abate emissions from three emission-intensive sectors in India. Section 3 elaborates on different carbon capture routes and technologies; Section 4 details the compression and transportation of captured CO_2; Section 5 and 6 explain the various utilisation and storage pathways, respectively; Section 7 broadly covers the key challenges and opportunities in the CCUS system; and Section 8 discusses the conclusions and way forward.

2. Emission Projections for Emission-Intensive Sectors and the Role of CCUS

There are different approaches to reducing emissions, such as substituting fossil fuels with sustainable fuels, improving energy efficiency, and adding renewable energy. However, decarbonising emission-intensive sectors remains challenging, as switching to greener alternatives is time- and energy-consuming. CCUS is one of the prominent decarbonisation solutions that can help fill this gap. Figure 1 depicts the emission trajectory following the standard 1.3% per annum reduction in emission intensity and the implementation of India's Nationally Determined Contribution (NDC) targets and policies by 2050 (McKinsey Sustainability, 2022). The emission pathways are adapted from the 2022 McKinsey Sustainability report. The original figure extended to 2070 and included a scenario for emission reduction by adopting CCUS; however, for this analysis, the figure has been truncated to 2050.

***Figure 1**: Pathways for India to decarbonise (adapted from McKinsey Sustainability, 2022)*



The analysis reveals that, with the possible adoption of electric vehicles and other sustainable alternatives, emissions could be reduced to nearly half by 2050. Further, 60 Gt CO_2e can be reduced during 2025–2050. However, any further reduction in emissions will require a rapid scaling up of CCUS.

To determine the potential requirement of CCUS to abate emissions in India, this study first evaluated total emissions from three emission-intensive sectors—cement, steel, and power—for three emission reduction scenarios.

- **Business as usual (BAU)**: In this scenario, no new policies are undertaken to reduce emissions. The emissions are projected by following the current trend.
- **Line of sight (LOS)**: Policies and measures are implemented to reduce emissions according to current NDC goals. This pathway is more achievable as it provides ample time for a technology to mature and be implemented.
- **Accelerated scenario**: Actions to reduce emissions at a faster pace than usual are taken. These actions include implementing more stringent policies and technological advancements

The emissions from the cement, steel, and power sectors and the potential CCUS requirement to abate emissions from these sectors are discussed below.

2.1. Cement

Key features of India's cement sector

» Emissions from the cement industry are of two types: process and energy emissions. Process emissions occur during calcination. The heating of limestone (calcium carbonate) produces lime (calcium oxide) and releases CO_2.

$$CaCO_3 \longrightarrow CaO + CO_2$$

» Energy emissions are due to fossil fuel combustion.

» Around 56% of the contribution towards the cement sector's emission intensity factor is from limestone calcination, nearly 32% is due to the combustion of fuels for heating applications, and 12% is due to the generation of electricity that is used for manufacturing (Nitturu et al., 2023).

» Energy emissions can be reduced by using greener alternatives such as biomass, low-carbon fuels, or carbon-neutral fuels (Global Cement and Concrete Association, 2022). Process emissions can be reduced by reducing the amount of clinker in cement and by capturing CO_2 from the source point.

» The demand for cement is expected to increase at a compound annual growth rate (CAGR) of 6% by 2030. At a CAGR of 4.5%, the demand will reach ~1,400 Mt by 2050, with emissions reaching ~900 Mt per annum under a BAU scenario (India Brand Equity Foundation, 2024).

Figure 2 presents the emission trajectory of the cement sector, along with cement demand, from 2025 to 2050.

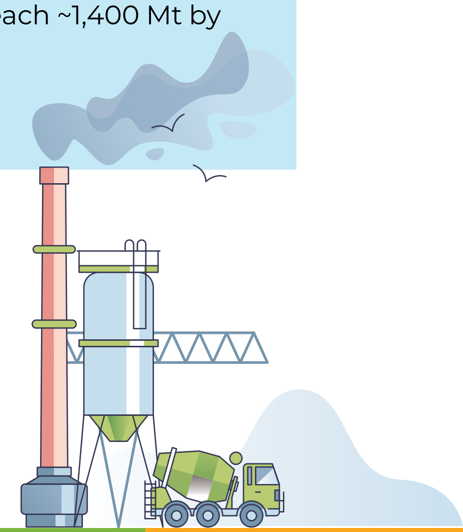
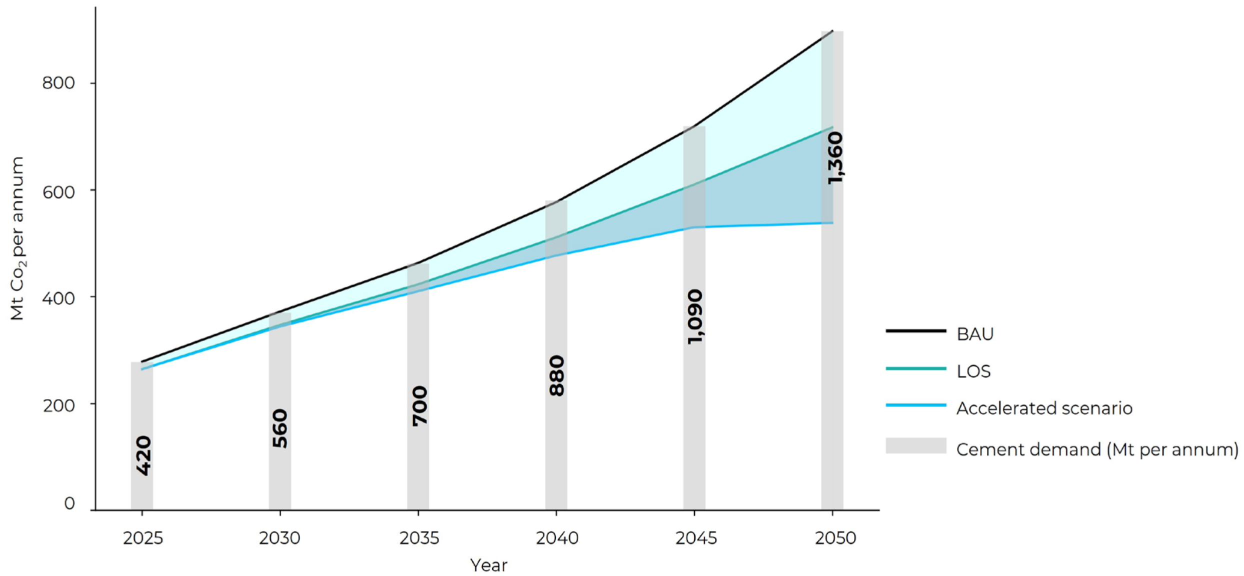


Figure 2: Emissions and demand projections for the cement sector



2.1.1. CCUS requirement under the emission reduction scenarios

The cumulative carbon storage capacity from 2025 to 2050 under the different scenarios is as follows:

BAU: In 2023, cement demand stood at 391 Mt (Ministry of Commerce & Industry, 2024). With a current emission intensity of 0.617 t CO_2/t cement, the total cement sector emissions stand at 241 Mt (CSTEP, 2024a). Assuming the emission intensity factor remains the same till 2050 (considering that further technological improvements are limited in nature and solutions such as energy efficiency measures and renewable energy integration can yield a limited reduction in emissions), the sector would emit approximately cumulative emissions of **14.3 Gt CO_2** between 2025 and 2050, with annual emissions around ~900 Mt.

LOS: In this case, decarbonisation interventions such as green fuel adoption, alternative clinker substitutes, and renewable energy can bring down emissions by 12%–20% by 2050 (Nitturu et al., 2023). These emissions are contributed by the generation of electricity required for manufacturing and heating applications. This pathway would emit approximately **12.6 Gt CO_2** between 2025 and 2050 (a reduction of 1.7 Gt CO_2 from that in the BAU scenario).

Accelerated scenario: A faster implementation of the measures mentioned in LOS and adding lean design (eliminating waste and improving efficiency) to the equipment will reduce emissions by 38%–40%. These emissions are contributed by the heat energy required for process heating (Nitturu et al., 2023). In this case, the projected emissions between 2025 and 2050 are approximately **11.5 Gt CO_2** (a reduction of 2.8 Gt CO_2 from that in the BAU scenario).

It can be seen that there is limited scope for emission reduction without the intervention of CCUS in this segment.

2.2. Steel

Key features of India's steel sector

- Steel demand is expected to rise at a CAGR of 9% by 2030, with the demand reaching 430 Mt at a CAGR of 3% by 2050 (Climate Group, 2023).
- Currently, the specific emission intensity of steel is 2.2 t CO_2/t of crude steel (TCS).
- Emissions from the steel industry can be reduced by using hydrogen (H_2). Injecting H_2 into the blast furnace–basic oxygen furnace (BF–BOF) can result in an 8%–9% reduction in emissions. In gas-based direct reduced iron (DRI) production, the injection of H_2 can potentially reduce emissions by 62% (CSTEP, 2024a).

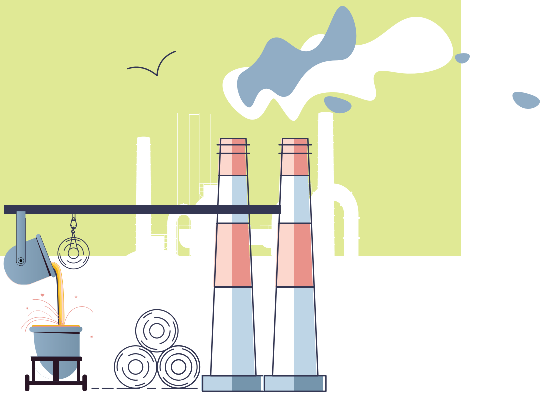
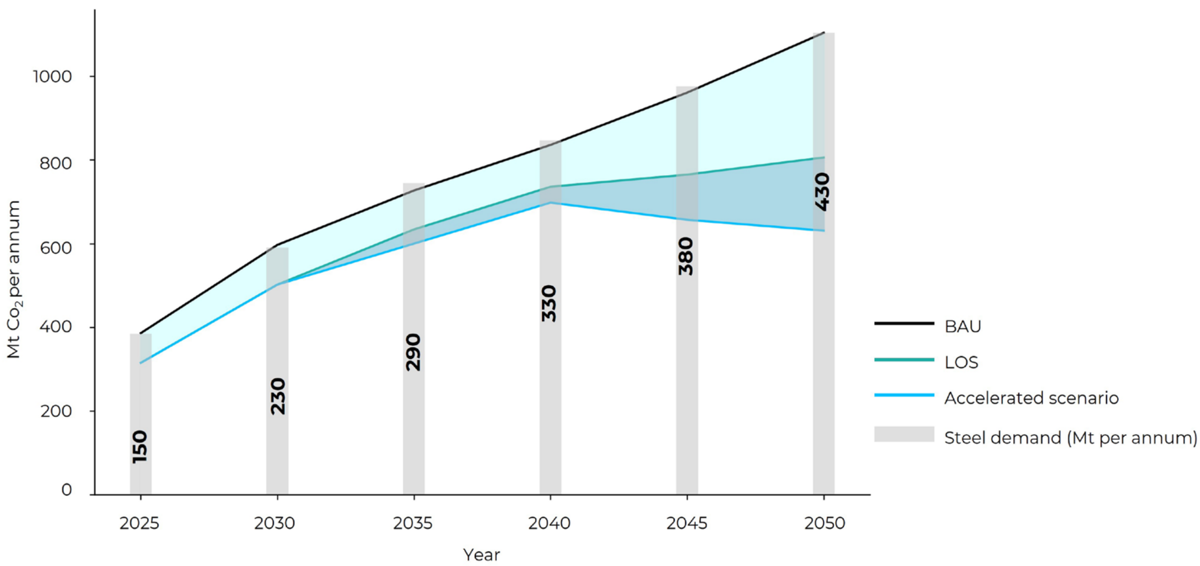


Figure 3 presents the emissions and demand projections between 2025 and 2050.

***Figure 3**: Emissions and demand projections for the steel sector*



2.2.1. CCUS requirement under the emission reduction scenarios

The cumulative carbon storage capacity from 2025 to 2050 under the different scenarios is as follows:

– **BAU:** In 2023, steel demand stood at 137 Mt (Ministry of Steel, 2024). With a current emission intensity of 2.2 t CO_2/TCS, the total emissions from the steel sector stand at 330 Mt. Assuming the emission intensity factor remains the same till 2050 (considering that further technological improvements are limited in nature and solutions such as energy efficiency measures and green H_2 adoption can yield a limited reduction in emissions), the industry will emit approximately **20 Gt CO_2** between 2025 and 2050.

– **LOS:** In this scenario, emission reduction actions such as improving energy efficiency, closing coal-based DRI, and increasing scrap-based capacity can bring down emissions by 27% by 2050. It is anticipated that steel demand may touch 230 Mt by 2030. This pathway would emit approximately **16.6 Gt CO_2** between 2025 and 2050 (a reduction of 3.4 Gt CO_2 from that in the BAU scenario).

– **Accelerated scenario:** By fastening the process of implementing the measures mentioned in LOS, along with the fast-paced adoption of green H_2 by 2040, total emissions could be reduced by 42.8% by 2050. This scenario would emit a cumulative emission of **15 Gt CO_2** between 2025 and 2050 (a reduction of 5 Gt CO_2 from that in the BAU scenario).

2.3. Power

Key features of India's power sector

» The power sector contributes about 40% of India's total emissions, making it the highest emitting sector. Power consumption is expected to rise at a CAGR of 8% by 2030, with the number reaching 5,250 billion units at a CAGR of 4% by 2050 (Central Electricity Authority, 2023).

» Emissions from the power sector are expected to decrease significantly with the use of renewable energy sources. It is expected that the average grid emission factor will reduce to 0.45 kg CO_2/kWh by 2031–32, as against 0.71 kg CO_2/kWh in 2023 (Central Electricity Authority, 2023).

Figure 4 presents the emissions and power demand between 2025 and 2050.

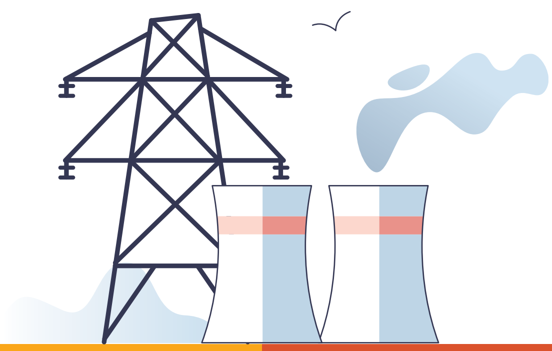
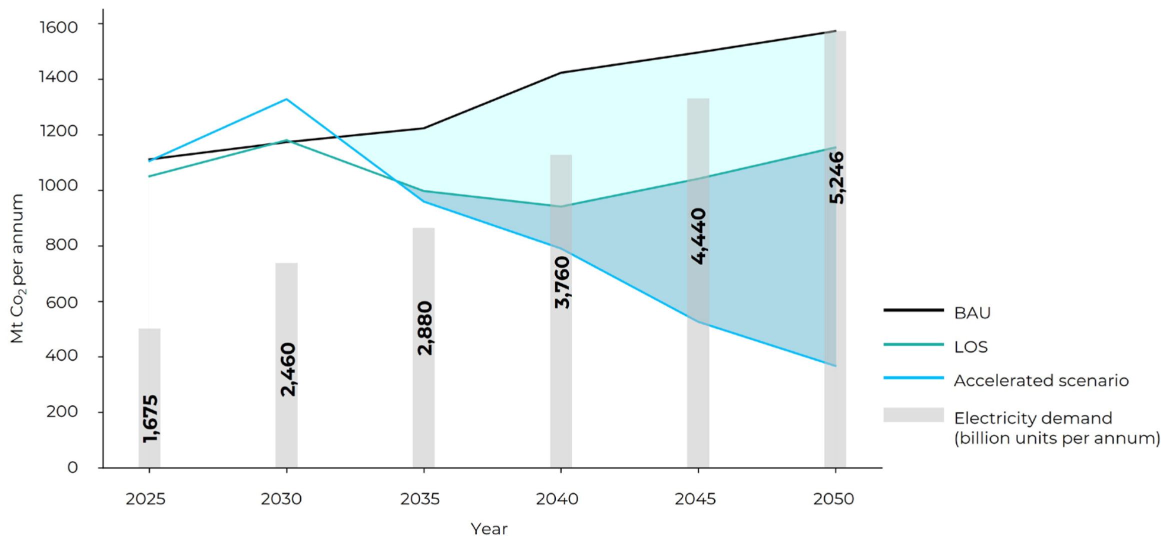


***Figure 4**: Emissions and demand projections for the power sector*



2.3.1. CCUS requirement under the emission reduction scenarios

The cumulative CCUS requirement from 2025 to 2050 under three scenarios presented in a report by The Energy and Resources Institute (TERI)—Constrained Renewable Energy Scenario (CRES), Unconstrained Renewable Energy Scenario (URES), and No Fossil-Fuel Scenario (NFS)—is discussed in this sub-section (Rodrigues et al., 2023). The three scenarios mentioned here are equivalent to the BAU, LOS, and accelerated scenario discussed in this paper.

– **BAU/CRES**: Currently, there is progress in the adoption of renewable energy in the power sector. A study shows that the share of coal- and gas-based power plants would decrease from 76% in 2020 to 24% in 2050 (Rodrigues et al., 2023). In 2022–23, total power generation stood at 1,624 billion units, with a grid emission factor of 0.71 kg CO_2/kWh (Ministry of Power, 2023). Assuming the emission intensity factor remains constant (considering renewables adoption) over the next 25 years, the power sector would emit approximately **34 Gt CO_2** between 2025 and 2050.

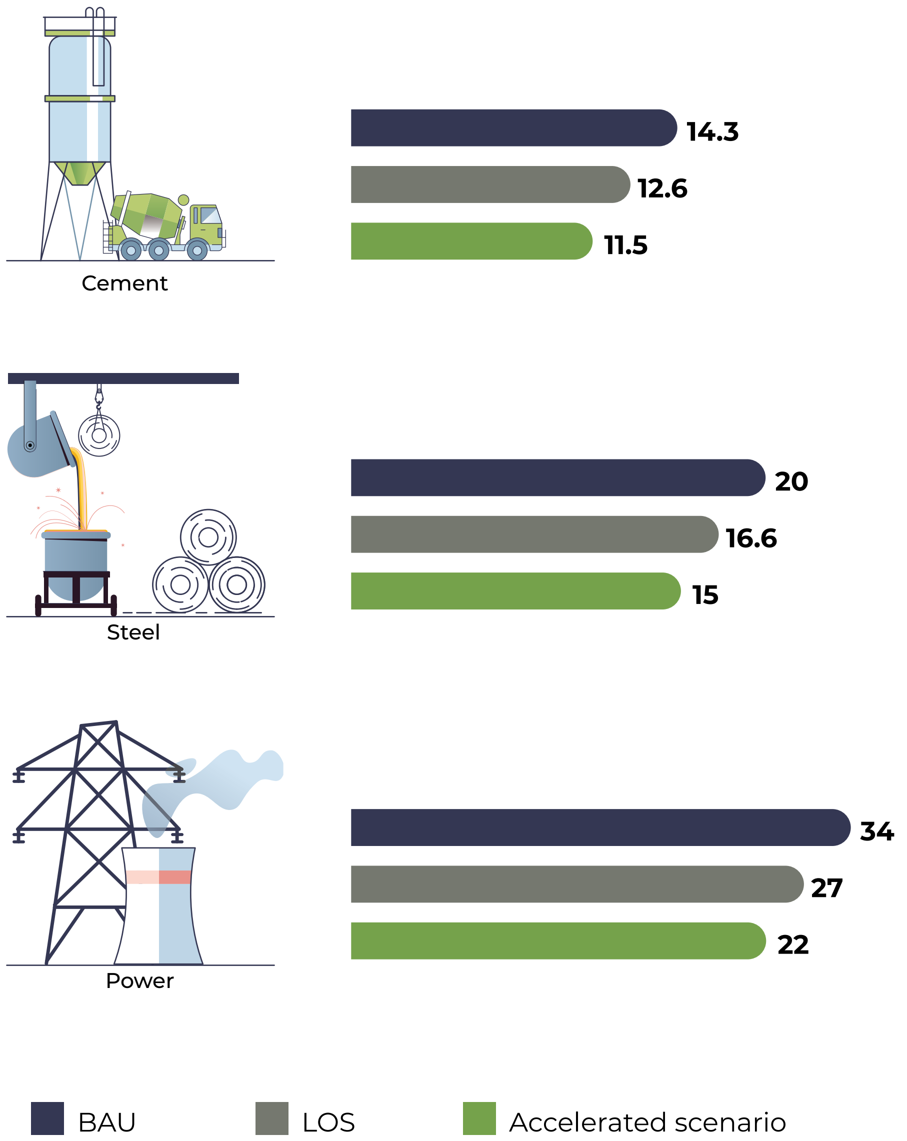
– **LOS/URES:** In this case, the share of coal- and gas-based power plants will decrease to 8% in 2050. It is anticipated that power demand will go up to 5,246 billion units by 2050 (Central Electricity Authority, 2023). This pathway will emit approximately **27 Gt CO_2** between 2025 and 2050 (a reduction of 7 Gt CO_2 from that in the BAU scenario).

– **Accelerated scenario/NFS:** In this case, coal- and gas-based power plants are completely replaced by non-conventional resources such as solar, wind, hydro, and nuclear. This pathway would emit **22 Gt CO_2** between 2025 and 2050 (a reduction of 12 Gt CO_2 from that in the BAU scenario).

2.4. Summary

As discussed in the previous sections, irrespective of the scenarios, alternative technology options, such as CCUS, are vital to decarbonise the cement, steel, and power sectors. These industries will have a CCUS requirement of 50–70 Gt by 2050. The cumulative amount of CO_2 required to be captured in the cement, steel, and power sectors is mentioned in Figure 5.

***Figure 5**: Cumulative CO_2 requirement (in Gt CO_2e) by 2050 in three emission-intensive sectors*



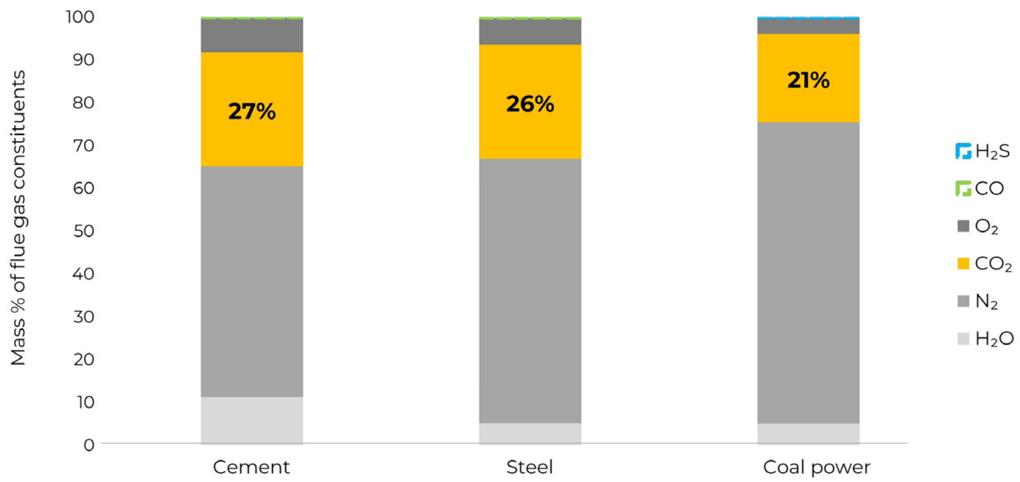
3. Capture Routes and Technologies

Carbon capture is one of the technologies to reduce greenhouse gas emissions. It involves capturing CO_2 from either atmospheric air or other point sources of emissions. Atmospheric CO_2 capture was commercialised in the 1950s (Keith et al., 2018). Currently, cement, steel, and other emission-intensive industries employ different carbon capture technologies, such as amine-based post-combustion and zeolite-based carbon capture, to tackle the emitted greenhouse gases. This section discusses various types of carbon capture routes and technologies.

3.1. Carbon capture routes

At point sources of emissions, CO_2 is emitted during the process or when fuel is burnt to produce energy. CO_2 is present in the flue gas stream, which also consists of nitrogen (N_2), oxygen (O_2), and water (H_2O; vapours) and fractions of carbon monoxide (CO) and hydrogen sulphide (H_2S). Figure 6 represents the typical flue gas concentration of cement, steel, and coal power plants in mass fractions (Arachchige et al., 2012; Schakel et al., 2018; Yun et al., 2021).

***Figure 6**: Flue gas concentration of cement, steel, and coal power plants*



As excess air is passed to ensure complete combustion, N_2 dominates the flue gas stream. Compared with cement and steel plants, coal power plants have excess N_2. This is because in the cement and steel industries, process emissions add CO_2, leading to a lower N_2 dominance.

Based on the location of the CO_2 capture unit, CO_2 removal routes are classified into pre-combustion, post-combustion, and oxy-combustion. CO_2 capture technologies are integrated into the different combustion processes to eliminate CO_2 from the flue gas stream before transporting it to utilisation or storage sites.

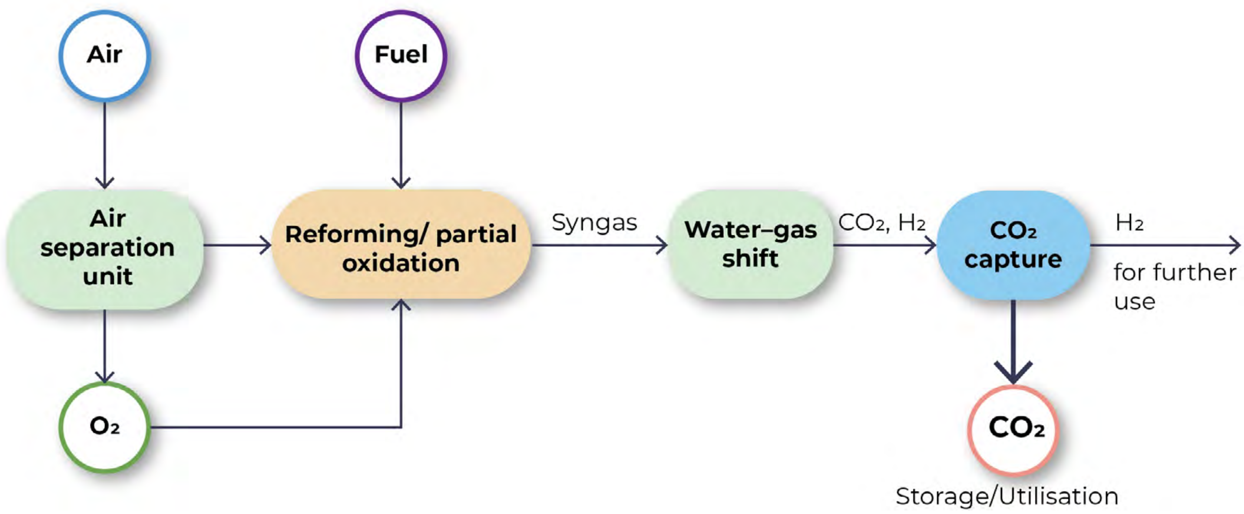
3.1.1. Pre-combustion

The pre-combustion carbon capture process is the most complex, as it occurs before the combustion stage of plant operations. The fuel is first converted into syngas—a mixture of CO and H_2—through partial oxidation or reforming. The CO then reacts with steam in the water–gas shift reaction, producing additional H_2 and converting CO into CO_2. The CO_2, now more concentrated and under high pressure, is captured at this stage. Pre-combustion capture systems are commonly applied in Integrated Gasification Combined Cycle (IGCC) power plants and natural gas reforming or refinery facilities—the former primarily for power generation and the latter for producing blue hydrogen.

Pre-combustion is a carbon capture approach where the carbon in a fuel is separated before the fuel is burned.

Figure 7 depicts a block diagram of a pre-combustion-based carbon capture unit (Kheirinik et al., 2021)

***Figure 7**: Key processes of the pre-combustion-based carbon capture system*



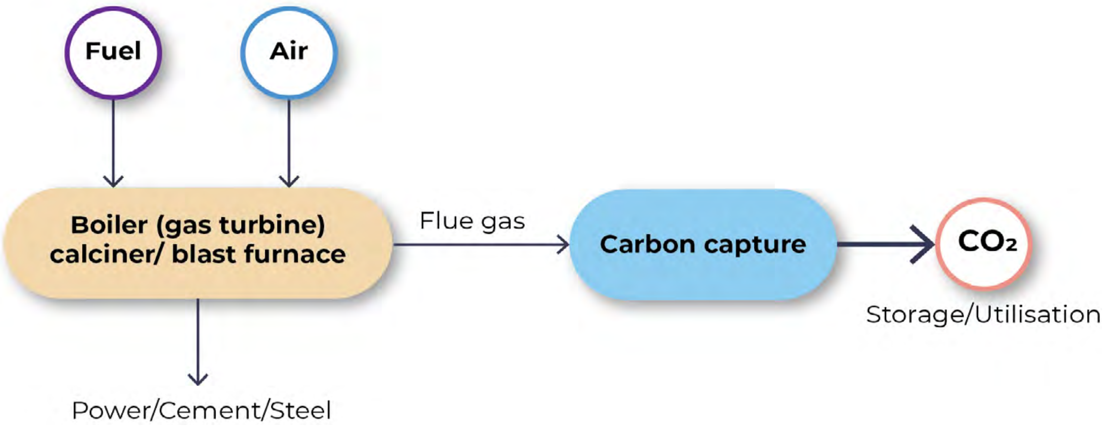
3.1.2. Post-combustion

In this process, flue gas after combustion is passed through capture technologies at ambient conditions, capturing CO_2 and releasing other gases. Most plants employ post-combustion carbon capture because it has low retrofitting costs.

In post-combustion carbon capture, CO_2 is removed after the combustion process.

Figure 8 presents the block diagram of a post-combustion-based carbon capture unit (Chao et al., 2021). Typically, post-combustion capture systems are deployed in thermal power plants where CO_2 is captured after fossil fuel combustion.

Figure 8: Key processes of the post-combustion-based carbon capture system



3.1.3. Oxy-combustion

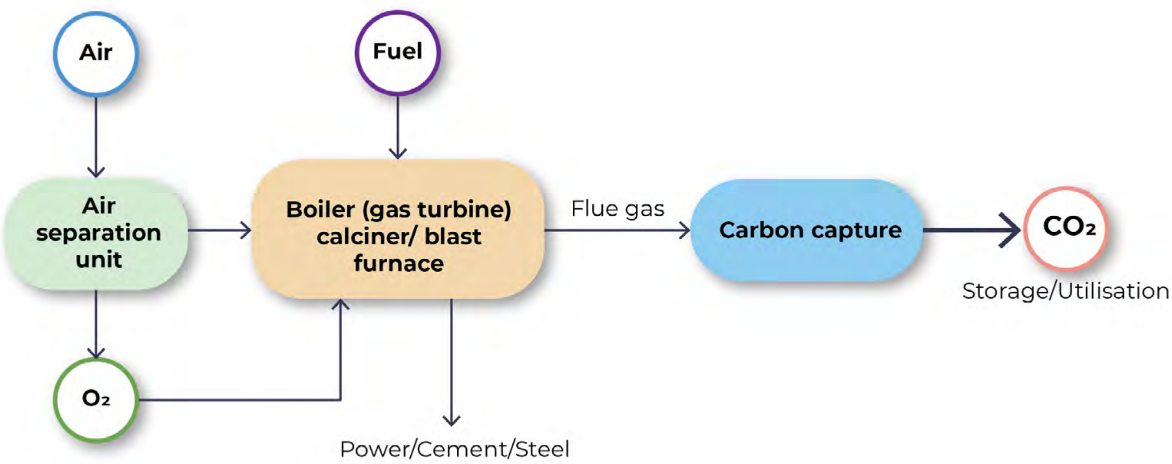
This capture route is similar to a post-combustion process except that pure O_2 is used for combustion instead of air. Due to the use of O_2, the flue gas will be devoid of N_2, unlike in the post-combustion process.

The flue gas obtained consists of CO_2 (more than 80 mol%) and H_2O. This mixture is separated by condensation. However, this process requires an expensive air separation unit to supply pure O_2 by removing N_2 from the air.

In the oxy-combustion route, fuel undergoes combustion in the presence of pure O_2 instead of air.

Figure 9 depicts the block diagram of an oxy-combustion-based carbon capture unit (Li et al., 2022).

Figure 9: Key processes of the oxy-combustion-based carbon capture system



Compared with post-combustion and pre-combustion, oxy-combustion requires less land area as the mass and volume of flue gas decrease by 60%–70%. Oxy-combustion requires slightly less energy than post-combustion, as the concentration of CO_2 is higher due to N_2 avoidance (Talei et al., 2024).

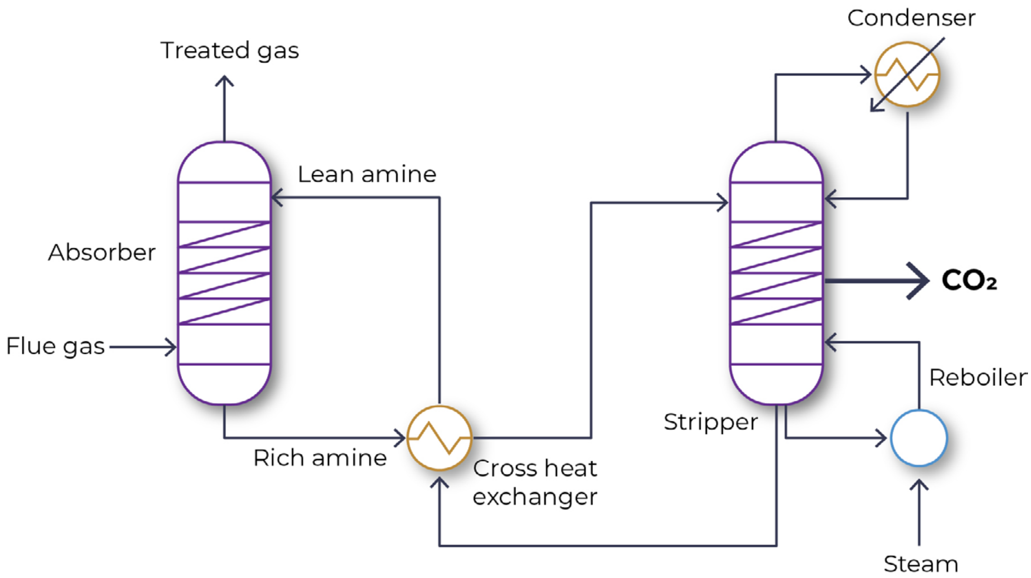
3.2. Carbon capture technologies

The prominent mature capture technologies are absorption, adsorption, cryogenic separation, membrane separation, and direct air capture (DAC). Other lab-scale technologies include chemical looping cycle (CLC), hydrate-based separation, and microalgae-based CO_2 fixation. These are discussed in detail in the following sub-sections.

3.2.1. Absorption

It involves the use of a CO_2-lean solvent, which is passed through the absorber column along with flue gas consisting of CO_2. The absorption capture system is shown in Figure 10 (Song et al., 2019). The absorber column is operated at a low temperature and under high pressure. After CO_2 is absorbed by the lean solvent, the resulting CO_2-rich solvent from the absorber is passed through a stripper column (by heating), where CO_2 is separated and the solvent is regenerated.

Figure 10: *Process flow diagram of the absorption capture technology*



Based on the nature of sorption, absorption is classified into two types.

Chemical absorption (chemisorption)

Flue gas containing CO_2 is passed through the absorber, along with the lean solvent (introduced to the system to extract more target substance—CO_2 in this case—from the feed). The flue gas is absorbed through the solvent ionisation mechanism. Solvent regeneration occurs at a temperature of 120 °C and a pressure of 2 bar (Oyenekan & Rochelle, 2007). The typical solvents used in chemical absorption include the following:

- Amines (monoethanolamine, diethanolamine, and methyldiethanolamine)
- Chilled ammonia
- Carbonate solutions

The regeneration energy required for the aforementioned solvents is 3–5 GJ/t CO_2 captured, with a capture efficiency of 90%−98% (Asif et al., 2018).

Physical absorption (physisorption)

Unlike chemical absorption, wherein chemical bonds are formed between CO_2 and the solvent, physical absorption involves the dissolution of CO_2 in a liquid solvent under high pressure through the formation of weak Van der Waals bonds. The regeneration energy required for these solvents is 0.5–0.84 GJ/t CO_2 captured, with a capture efficiency of 90%–95% (Im et al., 2015).

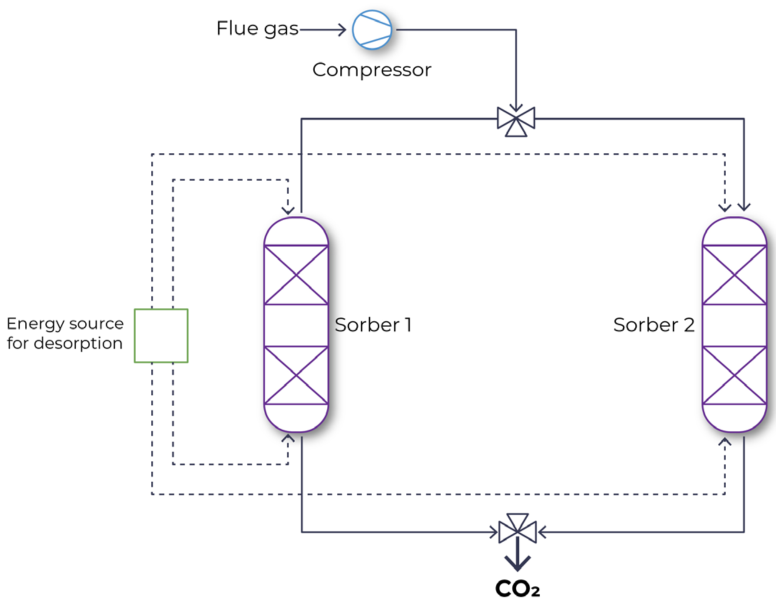
Some of the solvents used in physical absorption are the following:

- Rectisol (methanol at −4 °C)
- Selexol (dimethyl ethers and polyethylene glycol)
- Purisol (N-methyl-2-pyrrolidone)
- Fluor (propylene carbonate)

3.2.2. Adsorption

The process uses solid molecules as adsorbing agents and has a CO_2 recovery of 83.6%–90.16% (Raganati et al., 2021). At controlled pressure and increased temperature or controlled temperature and increased pressure, CO_2 molecules present in the flue gas are adsorbed onto the external surface of the adsorbent. After adsorption at decreased pressure or decreased temperature, CO_2 is released. Adsorption can be performed either physically, where the surface acts like a sponge and captures CO_2 molecules, or chemically, where CO_2 is converted into a chemical compound through a reaction. Figure 11 illustrates the adsorption process, wherein the flue gas is treated at the pre-treatment stage (Ben-Mansour et al., 2016). Pre-treatment involves at least two beds, with one bed receiving flue gas for adsorption and the second one desorbing the captured CO_2. This ensures that the system is operated continuously. While adsorption is used for ease of capture, its major limitations are low efficiency with respect to effectiveness, lower CO_2 selectivity, and lower capture efficiencies compared with other technologies such as absorption and cryogenic capture technologies.

Figure 11: *Process flow diagram of the adsorption capture technology*



Adsorption has two routes for capturing CO_2: pressure swing adsorption and temperature swing adsorption.

Pressure swing adsorption or vacuum pressure swing adsorption

CO_2 is adsorbed by the sorbent at high pressure (~30−40 bar) in the adsorption vessel. Pressure is varied depending on the selectivity of the adsorbent and partial pressure of CO_2 in the flue gas. Once the adsorbent is saturated, pressure is reduced slowly in the desorption vessel (~1 bar and 25 °C) for CO_2 separation. The power required to desorb CO_2 under vacuum is 0.6−6 GJ/t CO_2. The regeneration energy required for the adsorbent is 0.8−1 GJ/t CO_2 captured (Chaffee et al., 2007).

Temperature swing adsorption

As the name suggests, this method involves varying the temperature depending on the selectivity of the adsorbent and the partial pressure of CO_2 in the flue gas. CO_2 is adsorbed by the sorbent at a low temperature in the adsorption vessel. Once the adsorbent is saturated, the temperature is increased in the desorption vessel, and CO_2 is separated.

Although the aforementioned adsorption processes of pressure swing adsorption and temperature swing adsorption vary, the same adsorbents are used for both processes.

Some of the physical adsorbents are the following:

- Zeolite
- Activated carbon
- Metal–organic frameworks (MOFs)
- Carbon nanotubes
- Silica gel
- Hydrotalcite
- Alumina

Some of the chemical adsorbents are the following:

- Amine-based
- Functionalised MOFs

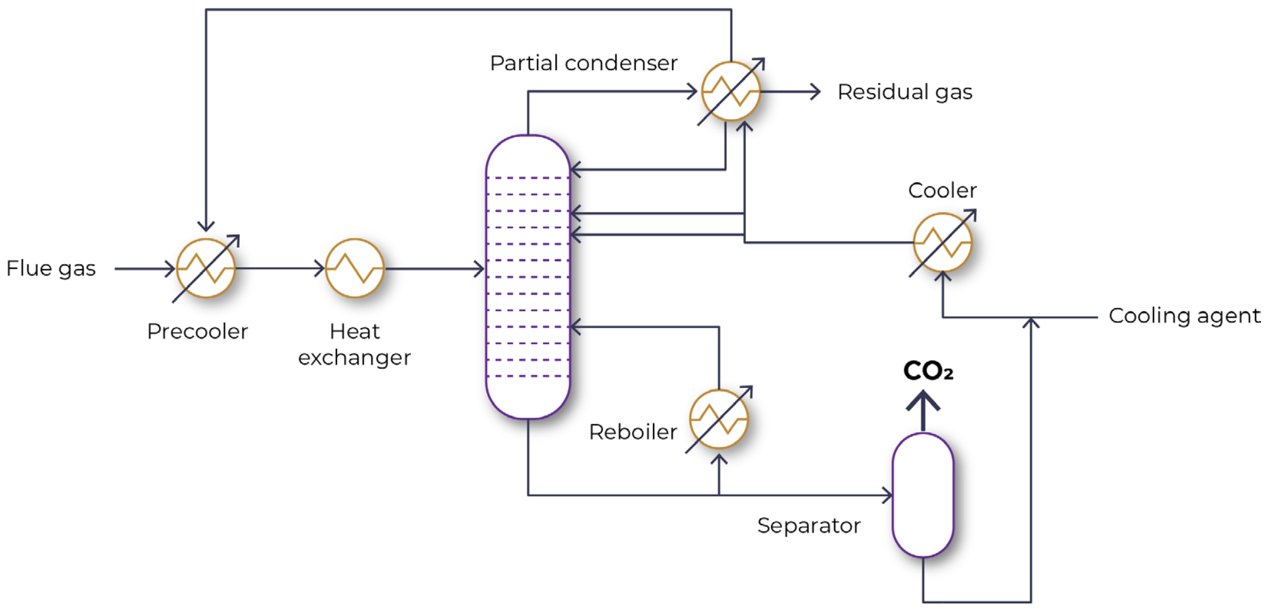
The regeneration energy required for the aforementioned adsorbents is 0.9–1.6 GJ/t CO_2 captured (Chaffee et al., 2007).

Zeolites and activated carbons are the extensively used adsorbents for the adsorption process. In recent times, there has been a gradual shift in research and exploration of MOFs. Compared with zeolites and activated carbons, MOFs have highly accessible pore volume and high regeneration capacity (An et al., 2019). Similar to zeolites, MOFs do provide accommodation sites for metal adsorbents after CO_2 desorption (Kim & Kim, 2023). However, due to some drawbacks, their practical application becomes challenging. For example, some MOFs have low thermal and chemical stability, while others have large pore spaces that do not withhold gas molecules (Ansone-Bertina et al., 2022). Studies have been undertaken to improve MOFs by combining them with materials such as ionic liquids (ILs), polyethylenimine, graphene, and carbon nanotubes (Aniruddha et al., 2020; Ghanbari et al., 2020).

3.2.3. Cryogenic separation

This technology separates CO_2 from flue gas by utilising the condensation and desublimation properties of the components. There are several types of cryogenic CO_2 capture pathways, such as cryogenic packed bed and cryogenic distillation. Cryogenic distillation, depicted in Figure 12 is one of the most commonly used cryogenic separation technologies (Baxter et al., 2009). In this process, the flue gas is cooled using a pre-cooler and passed through the heat exchanger. The chilled flue gas is then sent to the distillation column with packing materials such as zeolites, carbon molecular sieves, and activated carbon (Wang et al., 2019). Distillation separates the gas into top and bottom products. At the top, methane is separated using the partial condenser. Condensed CO_2 is collected at the bottom of the column. For vaporisation, a part of the collected CO_2 is heated and recycled back to the distillation column by using the reboiler. Subsequently, purified CO_2 is extracted from the separator. This process obtains a purity of 99% (Brunetti et al., 2010). However, the overall energy demand of the process contributes to over 50% of total operating costs (Song et al., 2019).

***Figure 12**: Process flow diagram of the cryogenic distillation capture technology*



In cryogenic distillation, carbon capture relies on cooling the gas mixture to low temperatures that cause CO_2 to condense and separate from other gases. The remaining gases (N_2, O_2, and H_2) remain in the gaseous state. The process requires a temperature of −78.5 °C for solid CO_2 formation and −57 °C for liquid CO_2 formation (Song et al., 2019). The main steps in cryogenic distillation are the following:

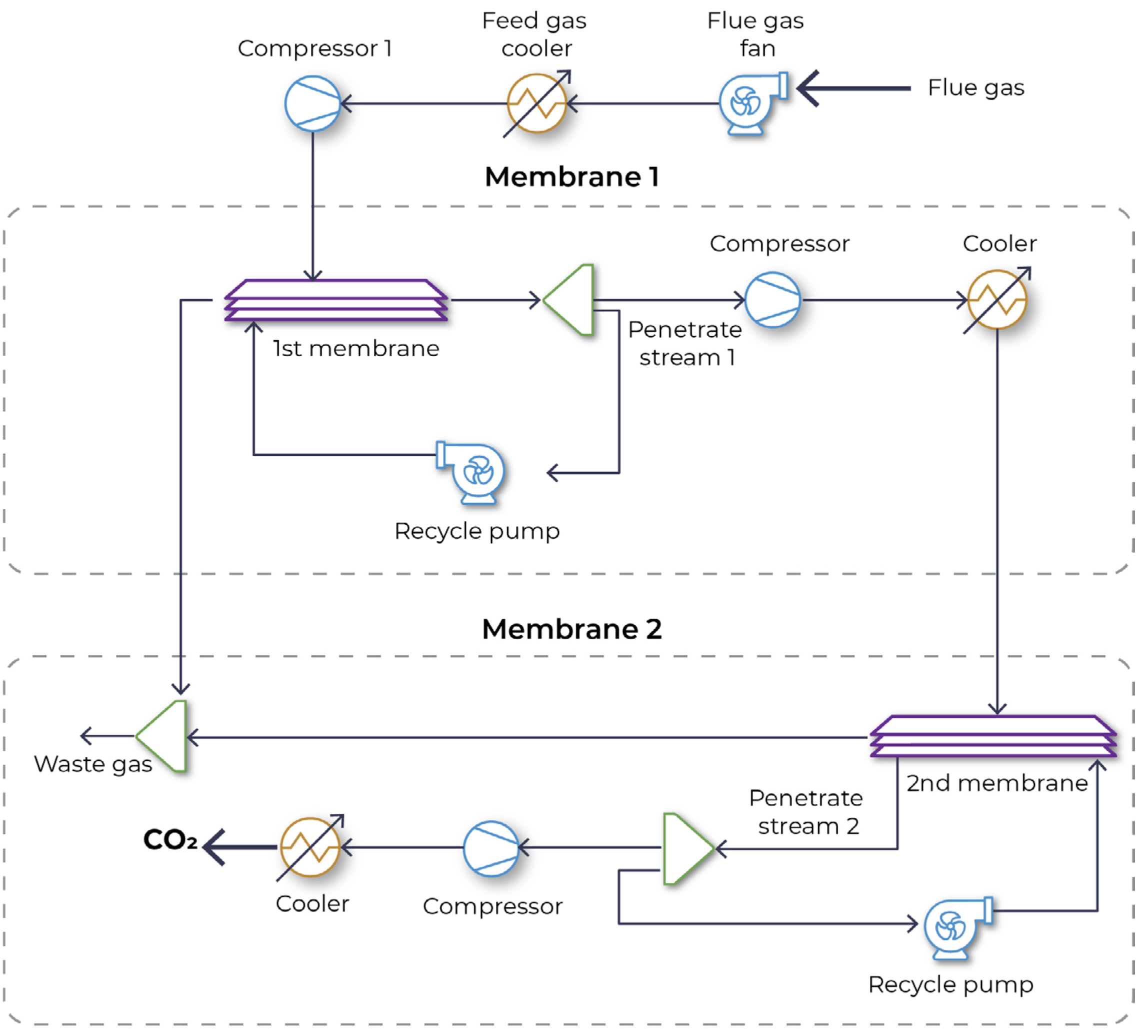
- Cooling the gas stream
- Separating CO_2
- Purifying the CO_2 stream
- Regenerating the packing materials

Cryogenic separation works well with highly concentrated CO_2 streams, which are typically observed during the natural gas sweetening process, ammonia production, and H_2 production. Cryogenic separation is an energy-intensive process, requiring 1.18–1.8 GJ/t CO_2 captured (Song et al., 2024).

3.2.4. Membrane separation

This energy-efficient and eco-friendly separation technology has been explored for a few years now (Chen et al., 2022). Figure 13 depicts the two-stage membrane separation process, wherein selectively permeable membranes are used for separating CO_2 from other gases (Hussain & Hägg, 2010). Based on the density and solubility of the gases, the membrane separation mechanism allows selective gases to pass through the membranes. In the first stage, the flue gas undergoes pre-treatment and is fed into the membrane system. In the second stage, 70% of the permeate gas (the gas that comes out of the first membrane) is passed as feed through the second membrane system. The remaining 30% of the gas is recirculated to the first membrane for efficient capture. However, 5% of the permeate gas from the second stage is also recirculated back to the second membrane. The energy consumption for CO_2 capture using membrane separation is 0.211–0.259 GJ/t CO_2 for the multistage process, with a capture efficiency of 90% (Dai & Deng, 2024). However, there are some drawbacks to using membranes for carbon capture. This system is temperature-limited, as the structure of the membranes is disrupted at high temperatures. Therefore, it is mandatory to maintain the temperature of the flue gas below 100 °C (Brunetti et al., 2010). Moreover, membranes are corrosive to SO_x, NO_x, and H_2S; therefore, a pre-treatment stage is necessary to avoid corrosion. As it is challenging to maintain membranes over a long period, this technology has limited application in industries or on a larger scale.

***Figure 13**: Process flow diagram – membrane separation capture technology*



Membranes used in membrane separation include the following:

- Polysulphone
- Polyamide
- Cellulose acetate
- Carbon molecular sieves

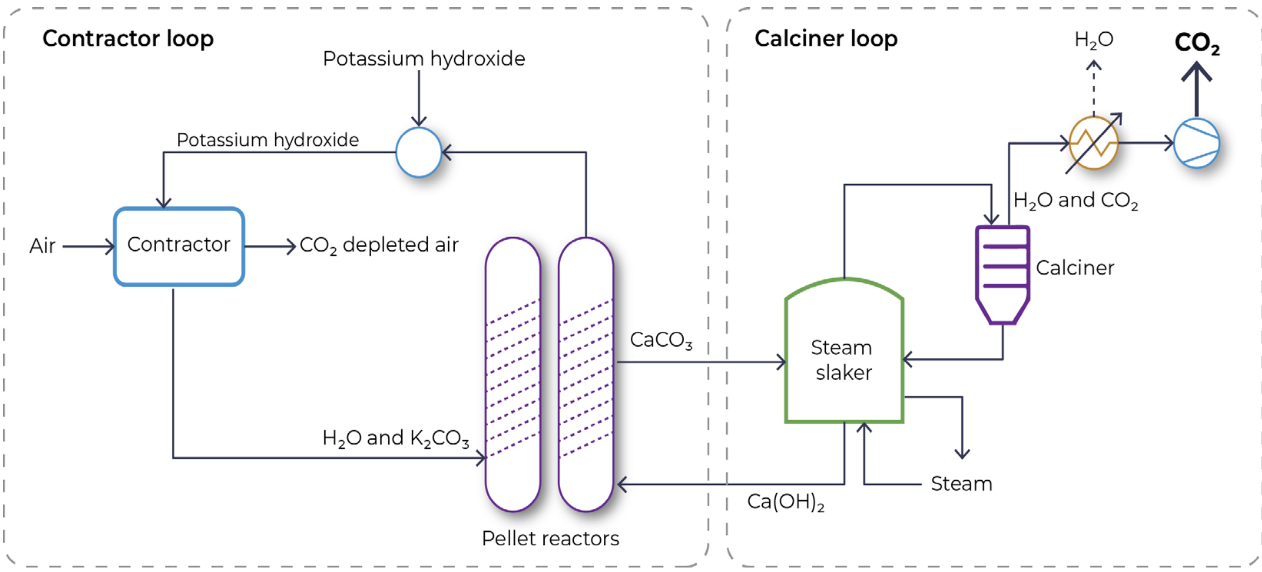
3.2.5. DAC

Although energy- and cost-intensive, DAC is one of the most popular carbon capture technology to remove atmospheric CO_2. This technology uses liquid solvent or solid adsorbent to capture CO_2. The process flow diagram for the liquid solvent DAC system is illustrated in Figure 14. The system is broadly divided into two main loops: the contactor loop and the calciner loop (McQueen et al., 2021). In the contactor loop, ambient air is pushed through the units of liquid solvents such as KOH or NaOH to packing materials (zeolites and activated carbon). The solvent captures CO_2 from the air, forming a carbonate solution, K_2CO_3 or Na_2CO_3 (Keith et al., 2018). This solution enters pellet reactors where it reacts with calcium hydroxide ($Ca[OH]_2$) via an anionic exchange to form calcium carbonate ($CaCO_3$). The regenerated solvent is pumped back to the contactor. Moreover, the reactors enable the formation of larger $CaCO_3$ crystals through controlled precipitation to produce pellets.

In the calciner, the $CaCO_3$ is heated to approximately 900 °C. The heated $CaCO_3$ decomposes to form CaO and CO_2. The CaO obtained is hydrated in the slaking unit (steam slaker) to regenerate $Ca(OH)_2$, which is recycled back to the pellet reactors.

The CO_2-rich gas from the calciner passes through the condenser for water removal, and the concentrated CO_2 is subsequently compressed. The process is both energy- and cost-intensive due to the low atmospheric concentration of CO_2. The thermal energy demand and electricity demand for this process are approximately 6 GJ/t CO_2 and 1.5 GJ/t CO_2, respectively (McQueen et al., 2021). However, the quality of thermal energy required for the DAC processes differs greatly. The solid sorbent system requires thermal energy of 80 °C to 130 °C, and this can be met using industrial waste heat (Beuttler et al., 2019). The estimated capture cost for DAC is between USD 94/t CO_2 and USD 232/t CO_2 (Keith et al., 2018).

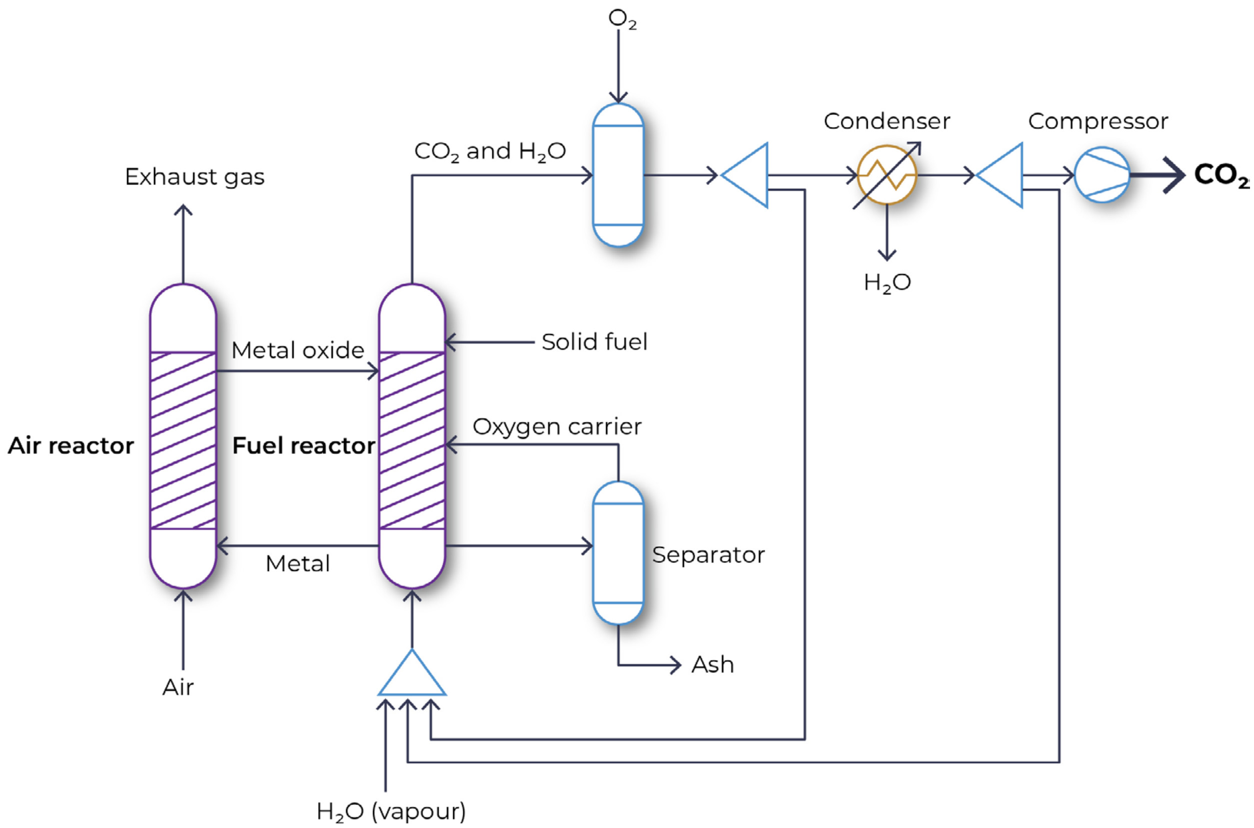
***Figure 14**: Process flow diagram of DAC*



3.2.6. CLC

To date, CLC processes have only been tested at a laboratory scale (Wang et al., 2015). Figure 15 illustrates the CLC capture process with solid fuel (coal; Song et al., 2019). The combustion process is divided into two reactions: intermediate oxidation and reduction (Erans et al., 2016). The CLC system has two reactors, an air reactor and a fuel reactor, with O_2 carriers (Fe_2O_3, NiO, CuO, or Mn_2O_3) circulating between these reactors. In the air reactor, the metal oxide is reduced to metal, which is oxidised back to metal oxide in the fuel reactor. The exhaust gas from the air reactor is predominantly N_2, which avoids the requirement of a pre-treatment stage. In the fuel reactor, the type of fuel passed through the reactor determines the type of reaction. In the case of gaseous fuels such as CH_4, the fuel reacts with metal oxide and releases the exhaust stream of CO_2, H_2O, and metal. Subsequently, the exhaust stream is passed through the O_2 carriers for further oxidation of components such as CO, resulting in the recycling of the metal in the air reactor. In the case of solid fuels such as coal, the fuel reduces metal oxide, resulting in CO_2 and partially oxidised carbon particles. In the next stage, the complete oxidation of exhaust stream components occurs, followed by the separation of the components using a condenser. The same sequence is noted for liquid fuels such as bio-oils, which are oxidised to CO_2 and H_2O (Luo et al., 2018).

***Figure 15**: Process flow diagram of CLC*



As this technology involves the use of fuel, it falls within the category of the pre-combustion capture route.

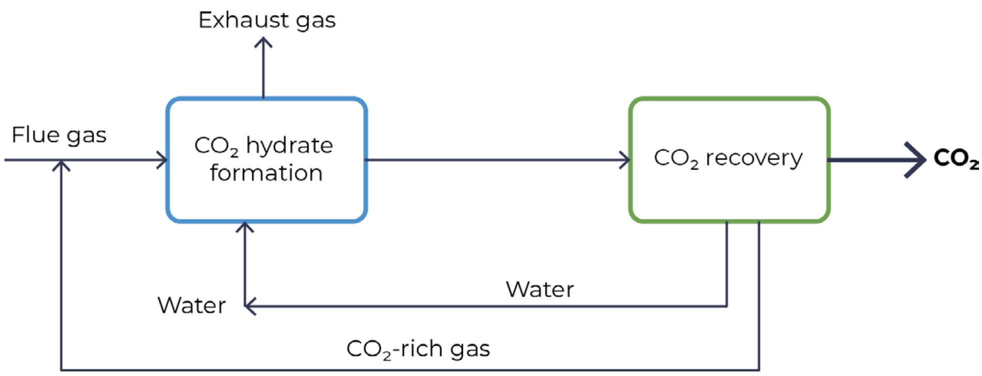
3.2.7. Microalgae-based capture

CO_2 biofixation using microalgae has gained huge momentum due to its high photosynthetic rate and a higher growth rate than that of terrestrial crops (Vale et al., 2020). Microalgae are microscopic organisms that use sunlight as the energy source and CO_2 as the carbon source. Therefore, microalgae can be used for CO_2 capture from flue gas emissions (Klinthong et al., 2015). Different types of microalgae can be used for human and animal nutrition, as well as for producing value-added ingredients for cosmetics, medical drugs, fertilisers, biomolecules, and biofuels (Zhou et al., 2017). Microalgae are sensitive towards high temperatures, imposing a requirement for the pre-treatment stage in the capture system. Higher CO_2 concentrations than tolerable levels can inhibit cell growth. Ignorance of these parameters leads to a negative impact on microalgae (Vale et al., 2020). CO_2 biofixation using microalgae is preferred in the post-combustion route over the oxy-combustion route as the latter provides concentrated CO_2 to the culture.

3.2.8. Hydrate-based separation

Hydrate-based CO_2 capture (HBCC) technology uses gas hydrates to separate CO_2 from gas mixtures. Figure 16 shows a block diagram of HBCC technology (Linga et al., 2007). Flue gas is passed through the gas hydrates, which are crystalline compounds formed by a cage-like water network that traps CO_2. These hydrates form under a low-temperature range of 0–8 °C and a high-pressure range of 0.367–10 mega pascal (MPa; He et al., 2017). These conditions depend on the chemical additives and the composition of the flue gas. Compared with other gases, CO_2 has the lowest hydrate-forming pressure, making it easier to form CO_2 hydrates. By the formation of the solid hydrate phase, CO_2 is separated from the remaining gas mixture. The CO_2 hydrate can be dissociated through depressurisation and/or heating to recover the captured CO_2. Compared with other CO_2 capture methods, HBCC offers several advantages. For example, it uses water as the raw material, making it a clean process with no pollutant release. One volume of CO_2 hydrate can hold up to 160 volumes of CO_2, making it a potential method for CO_2 storage (Sloan Jr. et al., 2007).

***Figure 16**: Process flow diagram of HBCC*



To improve the hydrate-forming conditions, different promoters and reaction enhancers are being developed. Promising approaches such as hydrate formation with membrane separations have been proposed. The scalability of membrane separation technology is challenging due to the high-pressure requirement in the first stage and the limited CO_2 withholding capacity of the membrane. The hydrate-based separation process reduces the cost of compression and the number of stages in capture. The HBCC process coupled with membrane separation is feasible and economically effective (Xiao et al., 2024).

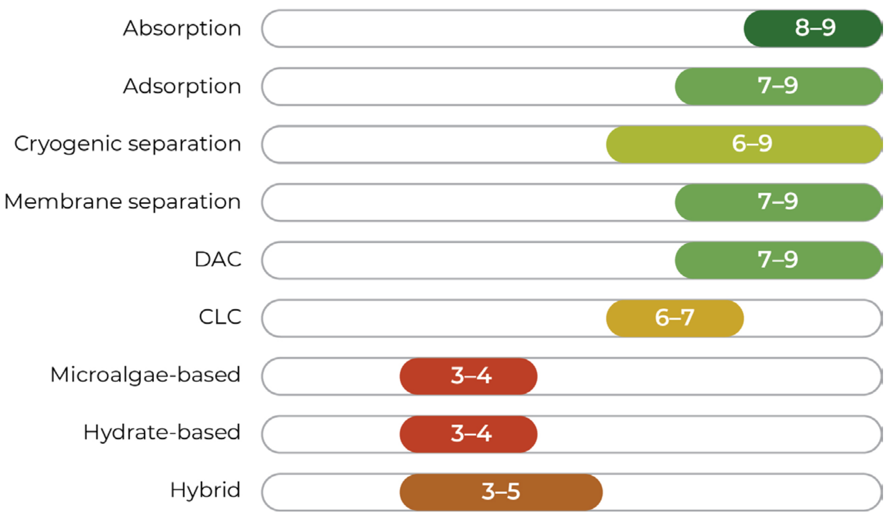
3.2.9. Hybrid capture routes

Apart from the discussed capture technologies, several hybrid capture routes such as membrane absorption, membrane adsorption, chemical absorption (electrolysis), cryogenic absorption, cryogenic adsorption, membrane-cryogenic, and cryogenic-hydrate processes are being tested at the laboratory scale (Asif et al., 2018; Song et al., 2024)

3.3. Technology readiness level (TRL) of capture technologies

The TRL of each capture technology varies according to the research, progress, development, and deployment of the technology. Therefore, in this study, a literature review of capture technologies was performed to gain an understanding of the TRL. Subsequently, the TRL of each technology was ranked on a scale of 1 to 9. Figure 17 shows the TRL of the mentioned capture technologies.

***Figure 17**: TRL of capture technologies*



The land, material, and energy requirements for capture technologies with higher TRL are listed in Table 1 (Florin & Fennell, 2010; Riboldi & Bolland, 2015; U.S. Department of Energy National Technology Laboratory, 2018; Ozkan et al., 2022).

***Table 1**: Land requirement, material inputs, and energy demand of different CO_2 capture technologies*

Capture technology	Land requirement (acre/Mt per annum)	Materials required	Energy requirement (GJ/t CO_2)
Absorption (pre)	4.4	Water and amines (solvents)	3–5
Absorption (post)	6.3		3–5
Absorption (oxy)	1.6		3–5
Adsorption	0.7	Water and zeolites	4–6
Membrane separation	4.3	Membrane	0.2–0.3
DAC	50	Liquid solvents (KOH or NaOH), air, zeolites, or activated carbon	5–10

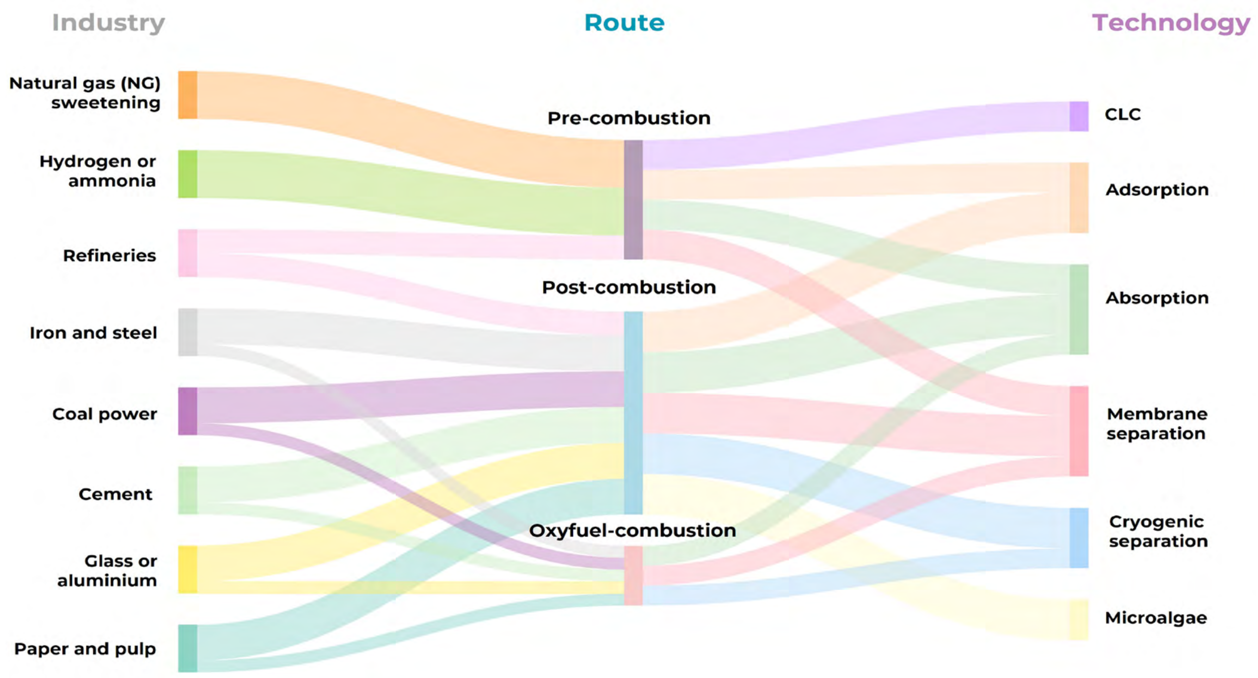
3.4. Capture technology mapping for different industries

The suitability of carbon capture routes and technologies for each industry differs on the basis of the placement of the capture facility, CO_2 concentration in the flue gas, economic feasibility of the technology, and CO_2 concentration required for the end-use purpose. To understand the suitability, a mapping exercise was performed by aligning carbon capture routes and technologies with emission-intensive industries. Based on a literature review of suitable capture routes and technologies mentioned in Section 3.1 and 3.2 for each sector, a Sankey chart was constructed (Figure 18).

The chart represents how industries capture carbon by choosing specific routes and technologies. Industries such as natural gas processing plants, hydrogen or ammonia production plants, refineries, iron and steel, thermal power, cement, glass and aluminium, and paper and pulp have been considered. Moreover, the chart depicts high-level mature capture technologies such as CLC, adsorption, absorption, membrane separation, microalgae, and cryogenic separation.

Generally, industries select any one of the capture routes among the three main capture routes—pre-combustion, post-combustion, and oxy-combustion—depending on the retrofitting possibilities. However, not all capture routes go well with all capture technologies. This is because the choice of carbon capture technologies depends on the end-use purpose of CO_2 or the purity or grade of the gas required.

***Figure 18**: Mapping of carbon capture routes and technologies for different industries*



From the chart, it is inferred that the post-combustion route shows versatility in applicability in all industries and technologies. However, pre-combustion is applicable in fewer industries, as it requires the retrofitting of existing plant parts and the adaptation of plant processes. Oxy-combustion also has limited applications as it is an expensive route to capture CO_2. It also has the requirement of more process additions compared with post-combustion.

4. CO_2 Transportation

The safe transport of captured CO_2 is a crucial stage in the CCUS value chain. In this stage, CO_2 is transported in a supercritical state (31.1 °C and 73.8 bar), which introduces safety risks. Ensuring a safe transport system is essential to prevent leaks or failures that could possibly affect the related social parameters. To prevent the risks, captured CO_2 is transported in the form of supercritical CO_2 or subcooled liquid to storage or utilisation sites. The transportation methods depend on the end use of CO_2.

4.1. Transportation methods

Based on the utilisation or storage pathway, different transportation methods can be employed.

4.1.1. Pipeline

In this transport method, CO_2 is transported at a pressure of greater than 75 bar and a temperature of above 31.1 °C (Figure A 4 in the Appendix; Zhang et al., 2006). The pipelines are usually made with stainless steel, reinforced carbon, or fibres to avoid corrosion, hydrate formation, and acid formation. Pressure drop is the major concern in pipeline transportation, and the factors influencing pressure drop are roughness and diameter of the pipe and mass flow. A study found that impurities cause a pressure drop of approximately 0.09–0.2 bar/km (Philip Suoton Peletiri et al., 2017). To maintain pressure in the pipeline, it is mandatory to have a recompression stage after every 100–300 km (Onyebuchi et al., 2018). Currently, there are over 8,000 km of CO_2 pipelines worldwide (Peletiri et al., 2018).

4.1.2. Ship

CO_2 carrier tanks are similar to liquefied natural gas tankers, where the gas is transported as a semi-refrigerated liquid. For effective transportation, CO_2 is liquefied at −50 °C and 6–7 bar (Seo et al., 2016). This mode of transportation is preferred for ocean storage (Al Baroudi et al., 2021). From the tanker, CO_2 is safely offloaded into the ocean by using a riser pipe and stored permanently.

4.1.3. Railways/Road

This mode of transportation is suitable for short distances where pipelines are not feasible. CO_2 is transported as a semi-refrigerated liquid at a temperature of −30 °C and a pressure of 20 bar (Roussanaly et al., 2017).

4.2. CO_2 levels in flue gases

This section presents the CO_2 concentration in flue gases in different industries, the levelised cost of capture, as well as capital and operational costs. Table 2 shows concentration of CO_2, levelised cost of capturing CO_2, capital expense, and operational expense.

__Table 2__: CO_2 concentration and capture costs in different industries

CO_2 emitting source	CO_2 content in flue gas (volume %)	Levelised capture cost (INR/t CO_2)	Capital expense[c] (INR crore/t CO_2/ day)	Operational expense[c] (INR/t CO_2)
Thermal power	12–15	4,300[a]–8,600	0.25	2,100–2,500
Natural gas to power	3–10	6,300–8,600	-	-
Cement	14–33	6,800[a]–10,320	0.28	1,050–1,600
Iron and steel	15	4,000[a]–8,600	0.3	1,900–2,300
Ethylene	12	2,150–3,010	0.4	-
Ammonia	99	2,150–3,300[a]	-	-
Bioenergy	3–8	2,600[a]–3,010	-	-
NG sweetening	5–70	1,290[a]–2,150	-	2,100–2,500

[a]*Data from IEA, 2020b*

[b]*Data from Naims, 2016, if not indicated*

[c]*NITI Aayog, 2022*

5. CO_2 Utilisation Pathways

CCU is an effective approach for reducing emissions and producing value-added commodities (Pérez-Fortes et al., 2014). Moreover, with the potential for commercialisation, CCU ensures a guaranteed return on investment by generating significant revenue (Singh & Colosi, 2021).

Captured CO_2 can be directly converted into fuels such as methanol, ethanol, urea, and syngas, which could be further processed to olefins, aromatics, solvents, and pharmaceutical intermediates. These fuels can also be used in plastic and polymer manufacturing. Moreover, as mentioned earlier, captured CO_2 can be used for EOR.

Utilisation projects are executed depending on the timeline for the project commencement. Table 3 presents a phased outlook on the adoption of carbon utilisation pathways, reflecting both technical maturity and market readiness. In the near term, applications such as EOR and soda ash production are expected to take precedence, owing to their established processes and existing commercial infrastructure. As the carbon utilisation market increases, the medium-term outlook will include broader uptake of pathways such as mineralisation, urea synthesis, and carbonated beverage production—areas that are gaining technical traction and economic feasibility. In the long term, more complex and infrastructure-dependent solutions, including concrete curing, aggregate manufacturing, and algae-based carbon fixation, are anticipated to be scaled up due to accelerated innovation and enabling policies. This progression underscores the need for tailored support mechanisms across time horizons to realise the full potential of CCU (Leung et al., 2014).

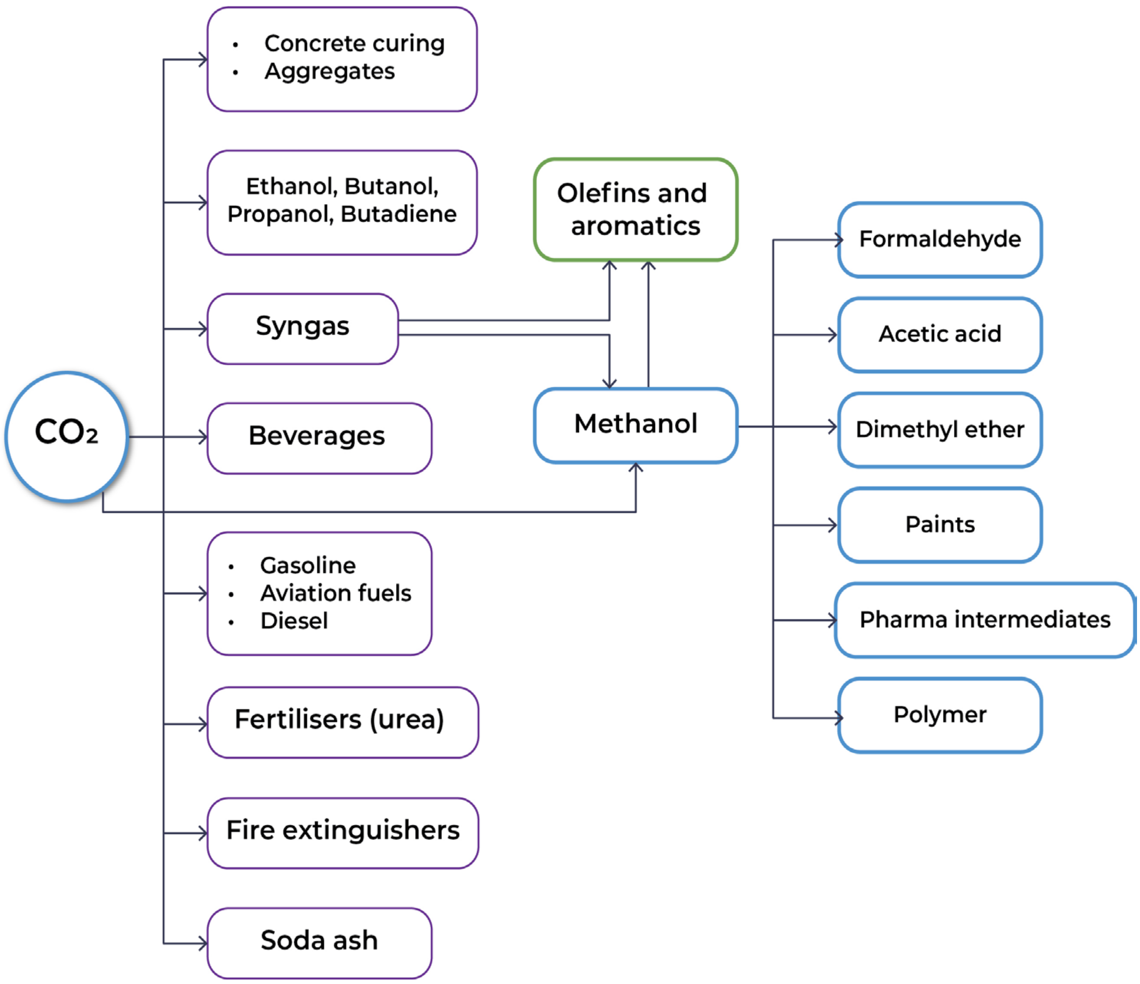
Table 3 lists potential CO_2 utilisation pathways applicable over short-, medium-, and long-term periods.

***Table 3**: Potential CO_2 utilisation pathways*

Term	Year	Utilisation pathway
Short term	3–5	EOR, soda ash, methanol, carbonates
Medium term	8–10	Mineralisation, beverages, urea
Long term	10–15	Concrete curing, aggregates, algae

Figure 19 provides CO_2 utilisation pathways (Aresta et al., 2016; Kamkeng et al., 2021). The flow diagram categorises the produced chemicals into primary, secondary, and tertiary categories.

***Figure 19**: Value-added products from CO_2*



a. Primary chemicals

These are produced through the direct conversion of CO_2.

- CO_2 to concrete curing: Concrete curing is the process of maintaining adequate moisture content and temperature in concrete to gain strength. Conventionally, moisture content is maintained by spraying water. CO_2 can be utilised instead of water. The injection of CO_2 into fresh concrete during mixing results in the binding of CO_2 to calcium silicate clinker, forming $CaCO_3$ particles. However, studies are ongoing to ensure that the concrete produced using CO_2 injection has the same strength as that obtained by using water (Ravikumar et al., 2021)

- CO_2 to aggregates: Aggregates are one of the key materials in concrete. Aggregates in concrete consist of natural stone aggregates and particles separated after recycling concrete aggregates (residual mortar). CO_2 can be used to treat recycled concrete aggregates (RCAs) and improve their mechanical properties. CO_2 is passed through RCAs to form carbonate, which provides strength to the material and makes it sustainable for construction use (Hosseini Zadeh et al., 2021).

- CO_2 to basic chemicals: Chemicals such as methanol, ethanol, propanol, butadiene, syngas, urea, and soda ash are synthesised using CO_2 as the feedstock (CSTEP, 2024b; NITI Aayog, 2022).

- CO_2 to fuels: Gasoline fuels such as synthetic natural gas (CH4), liquid fuels, and sustainable aviation fuels can be synthesised from CO_2. However, the TRL of fuel production via this route is still under laboratory scale (Hasan et al., 2021).

b. Secondary chemicals

Syngas obtained through CO_2 conversion is crucial for producing various petroleum products, including olefins and aromatics.

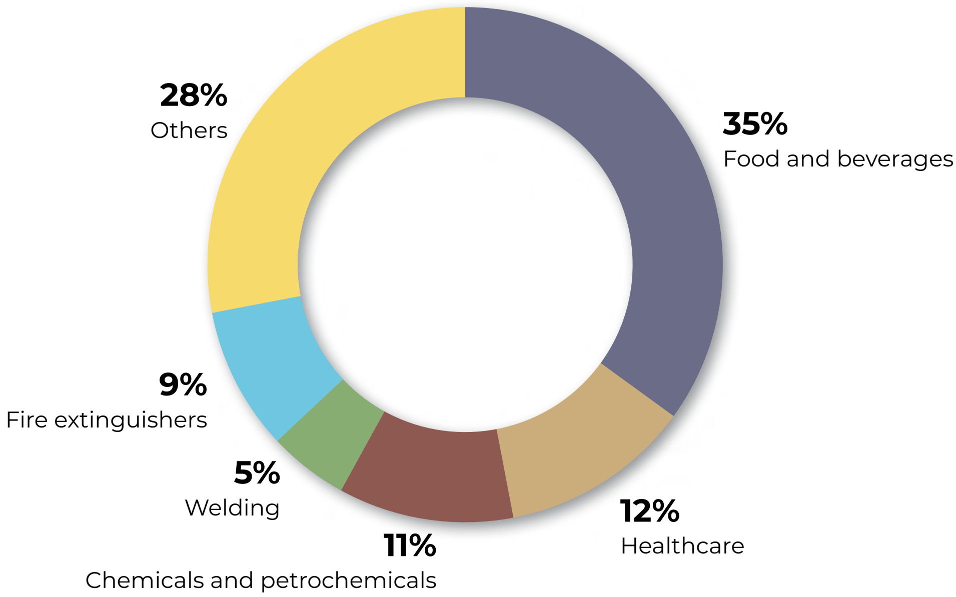
c. Tertiary chemicals

These are synthesised from secondary chemicals such as methanol. For example, methanol serves as the crucial raw material for the paint, polymer, and pharmaceutical industries.

5.1. CO_2 utilisation market in India

In India, the size of the CO_2 utilisation market is smaller than the amount of CO_2 emitted. In 2022, the size of the CO_2 utilisation market was approximately 2 Mt of CO_2, with the market expected to grow at a CAGR of 4.51% by 2035 (Chem Analyst, 2023). Based on the end use of the product, the CO_2 utilisation market can be divided into food and beverages, healthcare, chemicals and petrochemicals, fire extinguishers, and others. The food and beverage industry shares 35% of the CO_2 utilisation market, followed by healthcare at 12%, chemicals and petrochemicals at 11%, fire extinguishers at 9%, and welding at 5%. CO_2 is a crucial gas in the food and beverage industry as dry ice—a solid form of CO_2—keeps food products cool during transportation. Figure 20 shows the CO_2 demand in major industries.

***Figure 20**: Current CO_2 demand in major Indian industries*



High production cost is the main barrier to implementing CO_2 utilisation projects. The production cost of commodities produced from captured CO_2 is higher compared with that of conventional ones. However, the suitable implementation of a business model for scaling up or blending would help in price reduction.

Also, CO_2 utilisation does not permanently reduce emissions, as the carbon in most of the CO_2-based products is released back to the atmosphere during use or at the end of life.

6. CO_2 Storage

Since the 1990s, research on carbon storage has been active (Myer, 2011). Storing CO_2 in a well-maintained site or reservoir can retain CO_2 with minimal to zero risk of leakage for 1,000 to 10,000 years (Miller, 2017).

According to the database from IEA, 51 CCUS plants were in operation in 2024 across the world (IEA, 2024). Although India has a substantial storage potential of 395–614 Gt CO_2, the feasibility of CCS is still under the relatively early stage of laboratory and pilot studies (NITI Aayog, 2022).

The different pathways for carbon storage are discussed below.

a. EOR

Injection of CO_2 into underground geological reservoirs such as depleted oil and gas reservoirs helps in the recovery of oil from the wells. CO_2 swaps position with the oil in the wells and gets stored permanently. Apparently, to produce one barrel of oil, 0.25–0.5 t CO_2 is injected into the reservoir, resulting in the production of 1.8–4.2 barrel oil/t CO_2 (Farajzadeh et al., 2020). The first-order cost of CCS estimated for EOR is USD 15–31/t CO_2 (Verma & Vishal, 2023).

b. Enhanced coal bed methane recovery (ECBMR)

CO_2 is injected into unmineable coal seams. Over time, it gets accumulated in coal peats and is adsorbed and absorbed by coal, resulting in the mining of coal with a higher carbon content (Vishal, V., et al., 2021). The first-order cost estimated for ECBMR is USD 60/t CO_2 (Verma & Vishal, 2023)

c. Deep saline aquifers

CO_2 is injected into deep saline aquifers (brine water) under high pressure, where CO_2 spreads through rocks and is stored through a trapping mechanism (Al-qaness et al., 2022). A caprock layer above the aquifer acts as a seal to prevent CO_2 leakage. The following are the trapping mechanisms:

- Structural trapping: CO_2 is trapped under the caprock.
- Mineral trapping: CO_2 is trapped in the rock pores and forms solid carbonate minerals (mineralisation).
- Residual trapping: CO_2 occupies pore spaces by displacing the previous fluid.

The first-order cost estimated for storing CO_2 in saline aquifers is USD 87–107/t CO_2 (Verma & Vishal, 2023).

d. Basalts

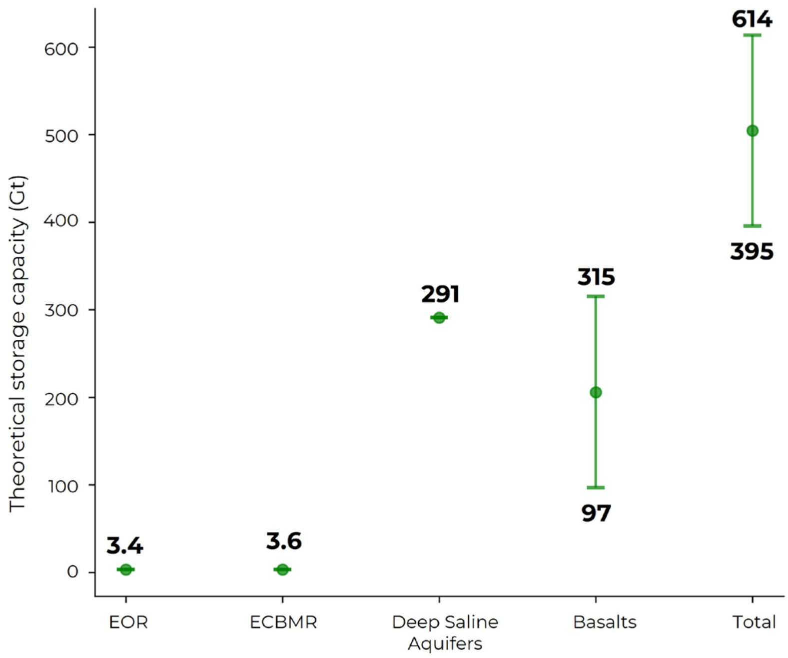
Basalts are rocks found in volcanic regions and are rich in Ca, Mg, and Fe. Moreover, mineralisation in basalts is faster than that in saline aquifers due to the abundance of Fe_2O_3, CaO, and MgO. When CO_2 is injected into basalts, these minerals react with CO_2 to form stable carbonates. However, the TRL of the basalt storage system is still at a nascent stage (Singh et al., 2024).

e. CO_2 mineralisation

This is a broad aspect where CO_2 reacts with naturally occurring minerals or industrial wastes to form stable carbonates, particularly $CaCO_3$ or $MgCO_3$. When CO_2 is injected into geological formations such as basalts and saline aquifers under pressure, mineralisation occurs. In industry, CO_2 is passed through steel slag or fly ash with oxides of calcium, silica, aluminium, iron, magnesium, manganese, sodium, potassium, and phosphorus. This results in the formation of carbonates, which are utilised for building materials, additives for cement, and road aggregates (Zajac et al., 2022).

Figure 21 presents the CO_2 storage potential in India (NITI Aayog, 2022).

***Figure 21**: CO_2 storage potential in India*



7. Challenges Associated With CCUS

The challenges hindering the application of CCUS in India pertain to technical, economic, and policy areas (Vishal, V. et al., 2021; Onyebuchi et al., 2018; Storrs et al., 2023; Bajpai et al., 2022).

a. Technical challenges

- Retrofitting the capture set-up in the existing industries is complex.
- Many technologies are still in a nascent stage, and the TRL remains low.
- Implementing CCUS in industries reduces production efficiency. In the case of thermal plants, simulation results have revealed that post-combustion amine-based capture and oxy-combustion can reduce the efficiency of net output power by 7.8 % and 10.4%, respectively (Ayyad et al., 2021; Yuan et al., 2024)
- Stringent purity and pressure requirements of CO_2 for utilisation can constrain the stream requirements of CO_2 from the capture set-up.
- Mapping suitable utilisation centres and storage fields with CO_2 source points is crucial. Developing demand centres by considering regulations and economic factors has its own complexities.
- Developing large-scale infrastructure to transport and store captured CO_2 needs to be ensured for long-term security and reliability.

b. Economic challenges

- Adding capture systems to industries increases the investment. For instance, thermal plants with capture set-up result in an increase in the capital cost by 20%–47% (Energy Justice Network, 2006).
- CCUS is an energy-intensive process; therefore, electricity requirements could go beyond the expected amount.
- Considering the low efficiency of the capture process, scaling up becomes risky. This creates an investment barrier.

c. Policy challenges

- No robust policy is available in the country for the effective operation of CCUS. While forming policies, equal interest and weight should be given to climate, industries, and government bodies.
- Policies involve multiple sectors, including coal, petroleum, natural gas, power, steel, cement, and fertiliser, thereby requiring time for effective implementation. This may create an imbalance in crediting new technologies for consideration in the system.
- Creating compliance markets in this space is essential to reducing emissions and pitching investments for green projects.

8. Conclusion

Effective management of CO_2 emissions through decarbonisation technologies is essential for India to achieve its net-zero targets. This white paper reviews one such decarbonisation solution—CCUS. The findings underscore the crucial role of CCUS in abating emissions and draw attention towards the scale of carbon capture needed.

The analysis of cumulative carbon emissions across three emission-intensive sectors—cement, steel, and power—under different emission reduction scenarios between 2025 and 2050 revealed the potential requirement of carbon capture. Under the BAU scenario, or the scenario wherein the current policies will continue, the total CO_2 emissions from these sectors are projected to be 68.3 Gt. Of this, the contribution of the cement, steel, and power sectors stands at 14.3 Gt, 20 Gt, and 34 Gt, respectively. However, by implementing moderate decarbonisation strategies under the LOS scenario, emissions can be reduced by approximately 17% to 56.2 Gt CO_2. Further, under the accelerated scenario, which incorporates advanced technologies and rapid deployment of clean solutions, emissions can be brought down to 48.5 Gt CO_2, representing a nearly 29% reduction from the BAU scenario. These findings highlight the importance of timely policy support, technology deployment, and financial investments in CCUS.

However, to realise the full potential of CCUS, some challenges need to be overcome. One of the main gaps in CCUS deployment is the lack of source–sink mapping activities. Moreover, to facilitate the operation of the CCUS system, point-to-point measures and lifecycle analysis should be performed to determine the emissions to be abated for a greener economy.

While progress is being made in reducing emissions—for instance, the power sector's transition to renewables—accelerated efforts across all sectors, such as steel and cement, are crucial to achieving meaningful climate targets. For example, the existing voluntary carbon market in India is not effective in reducing emissions due to the absence of policies to monitor and verify emission reduction certificates. As a result, low-quality carbon credits are being traded in the market. A strict compliance market by including all emission-intensive sectors can potentially displace the poor carbon credits being traded and attract finances to decarbonisation solutions such as CCUS. Further, initiatives and subsidies by the government are necessary to attract emission-intensive industries. Thus, coordinated policymaking across sectors will not only abate emissions but also bring in economic benefits.

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10. Appendix

Figure A 1, Figure A 2, and Figure A 3 illustrate the operational, planned, and under-construction CCUS facilities worldwide (IEA, 2024).

Figure A 1: *Operational capacity of CCUS worldwide*

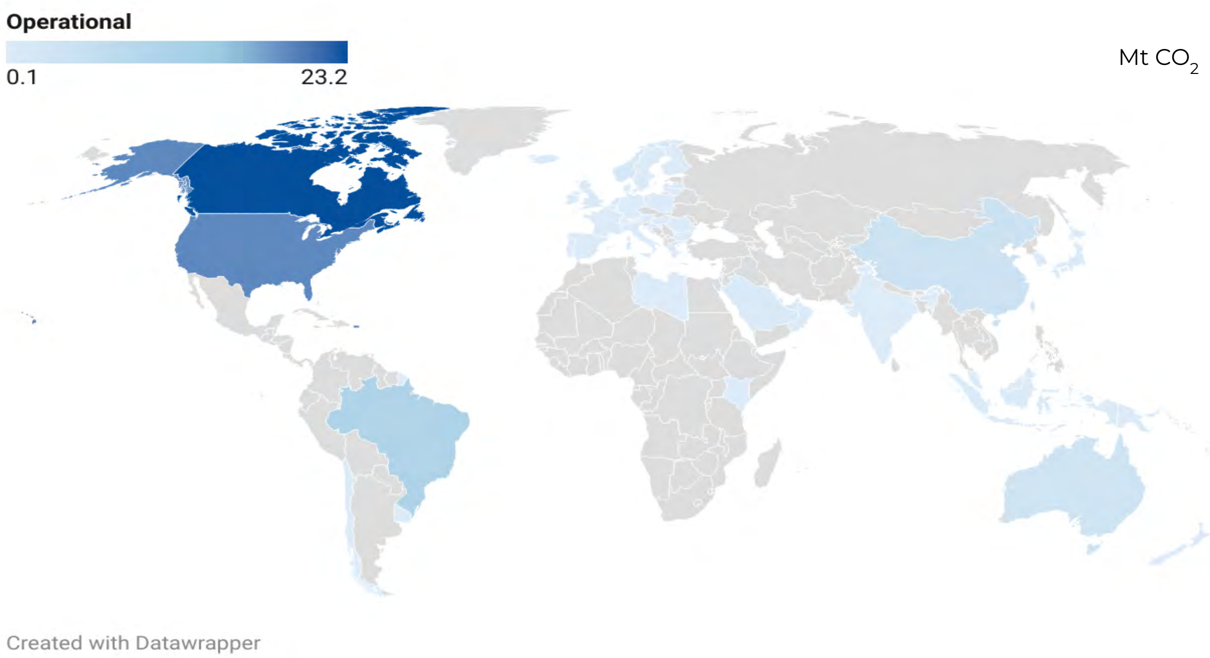


Figure A 2: *Planned capacity of CCUS worldwide*

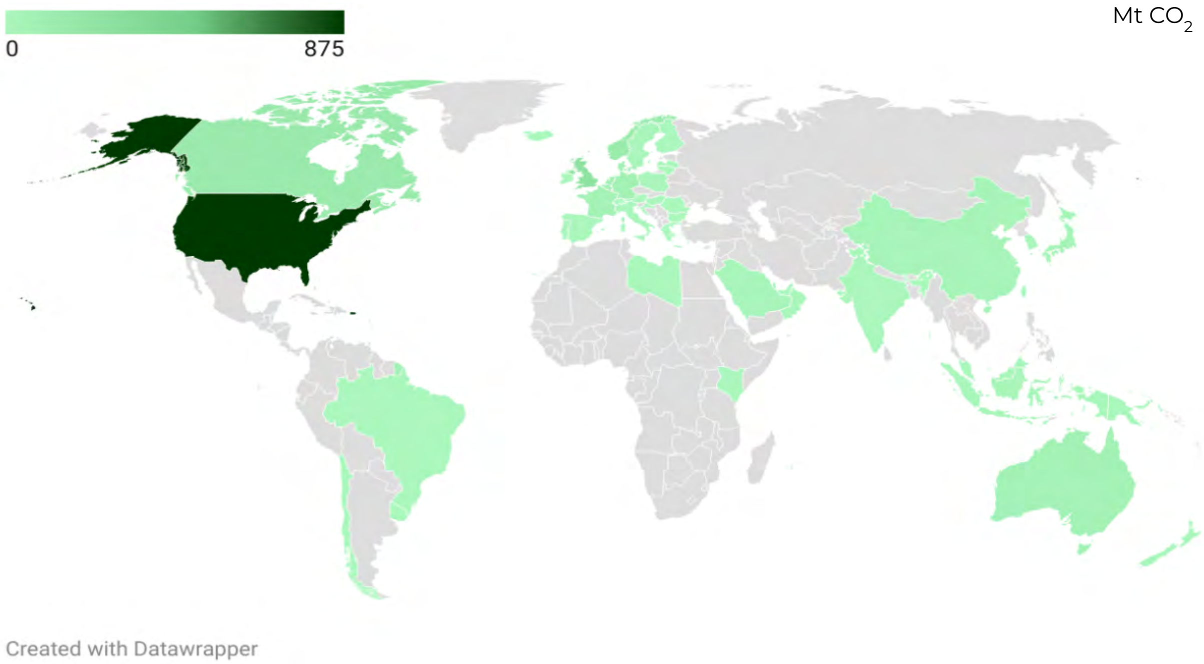


***Figure A 3**: Under-construction capacity of CCUS worldwide*

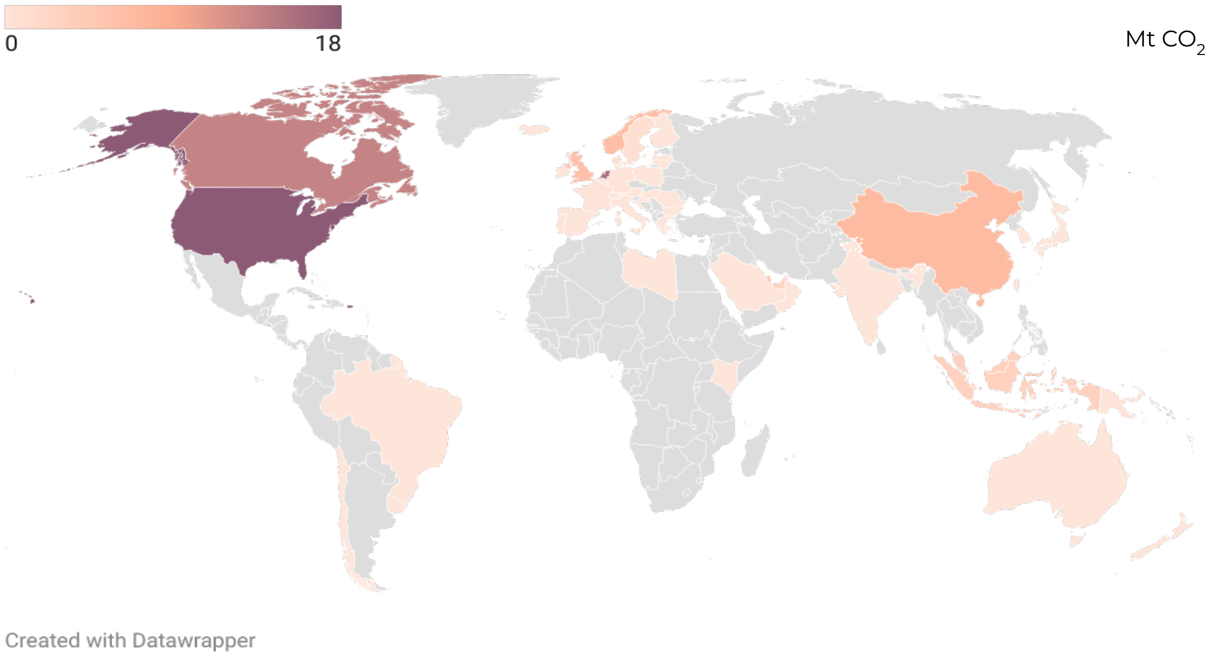
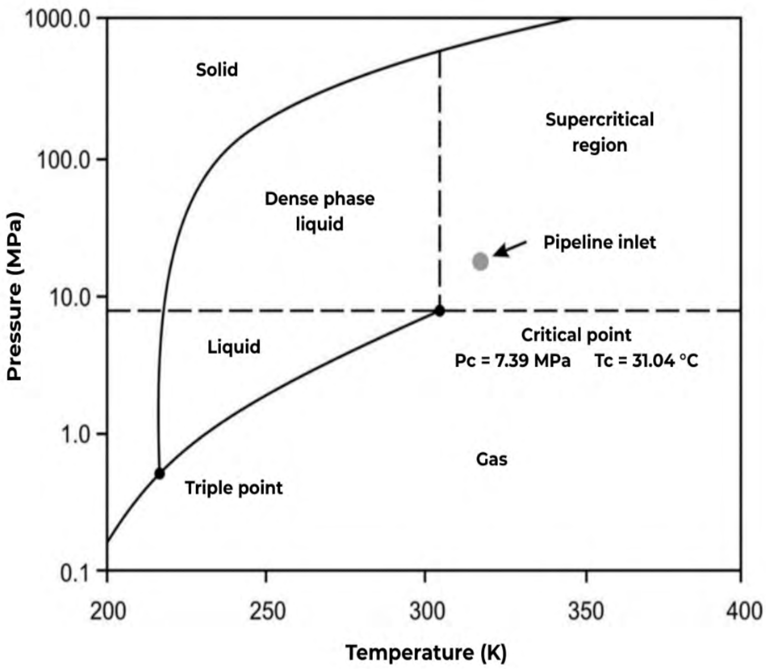


Figure A 4 represents the phase diagram of CO_2, which showcases the properties of different stages of CO_2 (Witkowski et al., 2014).

***Figure A 4**: Phase diagram of CO_2*



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