



TECHNOLOGY DEVELOPMENT FOUNDATION OF TÜRKİYE



PIONEER PROJECT PROGRAM

CARBON CAPTURE, UTILIZATION AND STORAGE (CCUS) AND CARBON DIOXIDE REMOVAL (CDR) SOLUTIONS WITH THE POTENTIAL TO CREATE ECONOMIC VALUE

DEEP DIVE STUDY - **SUMMARY**

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TTGV
**PIONEER PROJECT
PROGRAM**
#ClimatePioneer





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1. Introduction

Since 2023, the Technology Development Foundation of Türkiye (TTGV) has shifted its focus to climate technologies to meet international requirements for combating climate change and enhancing the global competitiveness of the Turkish industry. In this context, the “**Pioneer Project Program**” was launched to invest in scalable and innovative climate technology projects. The program has a comprehensive structure consisting of multiple phases. In the first phase, a deep analysis is carried out for the identified priority climate technology. During this process, in addition to conducting a comprehensive literature review, the current state of the technology is evaluated, and sectoral needs are discussed in detail by coming together with stakeholders both in Türkiye and abroad. As a result, a deep-dive report is prepared, encompassing basic information about the technology, stakeholder perspectives, and investment feasibility assessments. Additionally, the deep analysis report identifies researchers working on early-stage technologies and initiatives capable of developing product or service demos. These researchers and initiatives are supported under the “**Pioneer Seed and Demo**” phases of the Pioneer Project Program. The “**Pioneer Investment**” phase of the program aims to enhance the capacity, contribute to the development of the sector, and trigger localization and industrialization opportunities by implementing the relevant climate technology, for which a deep analysis has been carried out, on a commercial scale or pre-commercial scale as the first of its kind in the field.

Within the scope of the TTGV Pioneer Projects Investment Program, **“Carbon Capture, Utilization and Storage (CCUS) and Carbon Dioxide Removal (CDR) Solutions with the Potential to Create Economic Value”** was identified as the subject of the Vth Deep Analysis. In this context, the international and national development, as well as the current status of CCUS and CDR technologies—expected to play a critical role alongside energy efficiency and renewable energy in the decarbonization process—were thoroughly analyzed. In this comprehensive study conducted between April – November 2024, 75 sector experts and organizations were contacted, and different dimensions such as technology applications, policies, and carbon markets were addressed in detail. The resulting deep-dive report, prepared from a technology – economic perspective, aimed to assess the potential, applicability, and integration processes of CCUS technologies and CDR solutions into business models within decarbonization plans. This study contributed to a deeper understanding of the opportunities these technologies offer and provided actionable recommendations for Türkiye. This summary report, derived from the full version, is intended to serve as a guide and a catalyst for the future implementation of CCUS technologies and CDR solutions in our country.

The summarised findings and evaluations derived from the results of this study are presented below:

1. According to the Net Zero Emission (NZE) Scenario of the International Energy Agency (IEA), approximately **1 Gigatonne (Gt) of CO₂ needs to be captured and stored through CCUS technologies by the year 2030** to achieve the 1.5°C target (only 49 Mt CO₂/year are being captured and stored as of 2023). Even though the global CCUS market has been growing rapidly, with a compound annual growth rate (CAGR) of 12.2%, driven by leading countries in the CCUS field such as the United States of America (USA), Canada, Germany, the Netherlands, Denmark and Japan, **a well-functioning and mature market** has yet to emerge. This lag is attributed to **technological risks, financial risks, and a lack of comprehensive legislation**.
2. While some carbon capture and storage methods **have been commercialized**, this has typically occurred in areas where the technology **provides direct economic value** (e.g., carbon dioxide is readily captured in natural gas processing plants and used in enhanced oil recovery (EOR) processes; carbon dioxide is captured during hydrogen production and used in urea production). However, these applications do

not necessarily prioritize maximizing climate benefits. Conversely, in sectors where the development of CCUS technologies is critical for climate mitigation—**such as cement, steel, petrochemicals, energy, and direct air capture—large-scale testing remains limited**. Significant investments and large-scale projects are required in these sectors to achieve commercial viability for CCUS technologies. Furthermore, policies and regulations have to be established for large-scale applications to be financially sustainable, and, for the time being, **government support is essential** to foster the development and deployment of CCUS technologies.

3. When **CO₂ capture technologies** are analyzed, **no single technology—pre-combustion, post-combustion, or oxy-fuel combustion—emerges as a clear winner**. Various applications (coal/natural gas power plants, different industrial plants) require a portfolio of different capture technologies: **Whereas** the application areas of **pre-combustion technologies** are generally limited to the power sector and hydrogen production, post-combustion technologies have a wider range of applications, including the power sector and most industrial sectors. **Oxy-fuel combustion** technologies, due to their ability to produce high purity CO₂ and very high capture efficiency, are particularly interesting to sectors, especially **the cement industry**. Despite their high cost and energy requirements, the use of oxy-fuel combustion is expected to expand in industrial applications. In **power plants**, the selection of carbon capture technologies to be used varies greatly based on cost, fuel type, and operating conditions. **While pre-combustion capture technologies are more cost-effective in coal-fired gasification combined cycle plants, post-combustion capture technologies offer an economic advantage in natural gas plants. In the industrial sector, post-combustion technologies** are currently the most preferred systems owing to their easy integration into the existing plant.
4. When **CO₂ separation processes** are analyzed, **amine-based solvent systems**, which have undergone gradual improvements, **are currently regarded as the most promising carbon dioxide separation technology** and are applicable across various sectors. While the most advanced and widely adopted capture technologies rely on chemical and physical absorption, **the second and third-generation technologies (membranes, adsorption technologies, solid cycles, etc.)** are under development **and have the potential to surpass the existing technologies. In the cement sector, advanced amine absorption and oxy-fuel combustion** methods are emerging as

the most appropriate technological solutions, while **in the steel sector, advances in carbon capture are limited** due to the challenge of emissions from multiple point sources with varying gas flows. For capturing CO₂ during hydrogen production from fossil fuels (commonly referred to as blue hydrogen), chemical/physical absorption technologies, as well as **PSA/VSA (Pressure/Vacuum Swing Adsorption) systems utilizing solid adsorbents**, are the preferred options. Meanwhile, in the aluminium sector, no commercial carbon capture projects have yet been implemented.

5. **Direct Air Capture (DAC)** technologies for capturing CO₂ from the outdoor ambient air or diluted resources such as those in the ceramic sector, are currently being developed with a focus on energy efficiency, scalability, and cost reduction. It is aimed to increase the technology readiness level (TRL) of these technologies to 6–7.
6. The utilization and storage of captured CO₂ constitute critical solution areas for carbon management. Currently, approximately **5%** of the captured CO₂ is projected to be **utilized**, while the remaining **95% will need to be permanently stored**. Whereas commercially oriented applications such as **enhanced oil recovery (EOR)** and urea production stand out amongst the current uses, converting CO₂ into synthetic fuels and valuable chemicals is regarded as a promising way to offset the costs of carbon capture technologies. In particular, the production of synthetic fuels, such as **sustainable aviation fuel (SAF)**, holds significant potential for application in the aviation and maritime sectors.
7. **CO₂ storage solutions** are recognised as **the most critical phase** of CCUS projects in line with the climate targets. Globally, 79% of the captured CO₂ is currently stored through EOR, while 21% is stored in dedicated geological storage sites. By 2030, these proportions are projected to shift to 80% dedicated geological storage, 9% EOR, and 11% undefined storage methods. **In Türkiye, no comprehensive study on the identification of storage areas has been publicly disclosed to date.**
8. **The costs** of CCUS technologies are categorized into three main components: capture, transport, and storage. **Capture costs constitute approximately 60%–80% of the total costs, while transport and storage each account for 10%–20%. The cost of carbon capture in CCUS projects** is influenced by several factors, including **the selected carbon capture technology, the properties of flue gas** (concentration of CO₂, other impurities), **CO₂ capture efficiency, the CO₂ purity desired to be achieved, the degree of operational flexibility, the size of the project** (scale of the plant) and

regional economic conditions (energy costs, etc.). Additional factors, such as **the operational life of the plant, load factor, annual carbon capture rate, integration into existing infrastructure, and market demand for captured CO₂**, also play a role in determining costs. **Geographical location** and **energy costs** have a significant impact on the overall cost of CCUS projects.

9. **The costs** of CCUS technologies are still **high** today and are expected to **be €130 - 150 per tonne by 2030** (depending on various factors mentioned above and differing significantly across sectors, stated here as an average), which remains above the current prices in the **European Union (EU) Emissions Trading System (ETS)**. To be able to compensate for these costs, **government subsidies** and **carbon credit revenues** stand out as potential sources of financing. Beyond subsidies, it is essential to incorporate **high-quality technical credits** into national targets and ETS frameworks. On the other hand, CDR markets are not yet sufficiently **liquid, particularly in the absence of prepaid agreements**. In the initial phase, **voluntary carbon markets (VCMs)** can play a facilitative role in advancing CCUS/CDR projects. However, in the long term, more efficient **carbon utilization strategies** will need to be developed to ensure sustainability and cost-effectiveness.
10. **The CO₂ captured through DAC technology** can be sequestered for extended periods (thousands of years) through methods such as storage or mineralisation. It also has significant potential for use in **private markets**, providing on-site supply for CO₂ consumers such as carbonated beverage producers and greenhouses, as well as in the **production of renewable fuels**. Additionally, DAC technology is being considered for the creation of carbon certificates **in CDR projects**.
11. **Industrial CCUS clusters** are regarded as enablers for transitioning from small-scale, point-sources projects (<1 Mt CO₂/year) to larger-scale, impactful initiatives (10–50 Mt CO₂/year). **By utilizing shared transport and storage infrastructure, these clusters can help mitigate both costs and risks**. Thanks to these clusters, carbon can be captured from smaller-scale emission sources, commercial risks for storage can be mitigated, economies of scale can be created, and opportunities for merging with clean hydrogen valleys and linking with other regional CCUS clusters can be established.
12. Although **Türkiye** has identified CCUS technologies as a strategic approach for achieving its net zero emission target, progress in this area has been limited due to the absence of legislation, high costs, and technological risks. **Uncertainties surrounding**

the economic benefits of CCUS projects further constrain their implementation. The United States supports CCUS projects through the Inflation Reduction Act (IRA) and the 45Q tax credit, while the European Union provides support through initiatives such as Fit for 55 and the Innovation Fund. However, Türkiye has not yet developed an incentive system of a similar scale. **Government subsidies, private sector investments, co-operation between the public and private sectors and carbon pricing policies are needed for the rapid development and deployment of CCUS and CDR projects.** The introduction of the **National ETS** is expected to pave the way for **the realisation of CCUS projects by creating a cost element for the enterprises engaged in carbon emission.** Transferring ETS revenues to CCUS and CDR projects may accelerate the deployment of these technologies. Furthermore, **the crediting of CO₂ removed through CDR projects** has the potential to create additional income for investors.



2. An Overview Of CCUS Technologies And CDR Solutions

How Do We Define CCUS?

Carbon Capture, Utilization and Storage (CCUS) briefly refers to a range of low-carbon technologies aimed at capturing carbon dioxide (CO₂) emissions from major point sources, such as power generation plants and industrial facilities that rely on fossil fuels or biomass. Additionally, CO₂ can be captured directly from the atmosphere. There are four distinct stages of CCUS as shown in Figure 2.1: capture, transport, utilization and/or safe storage.

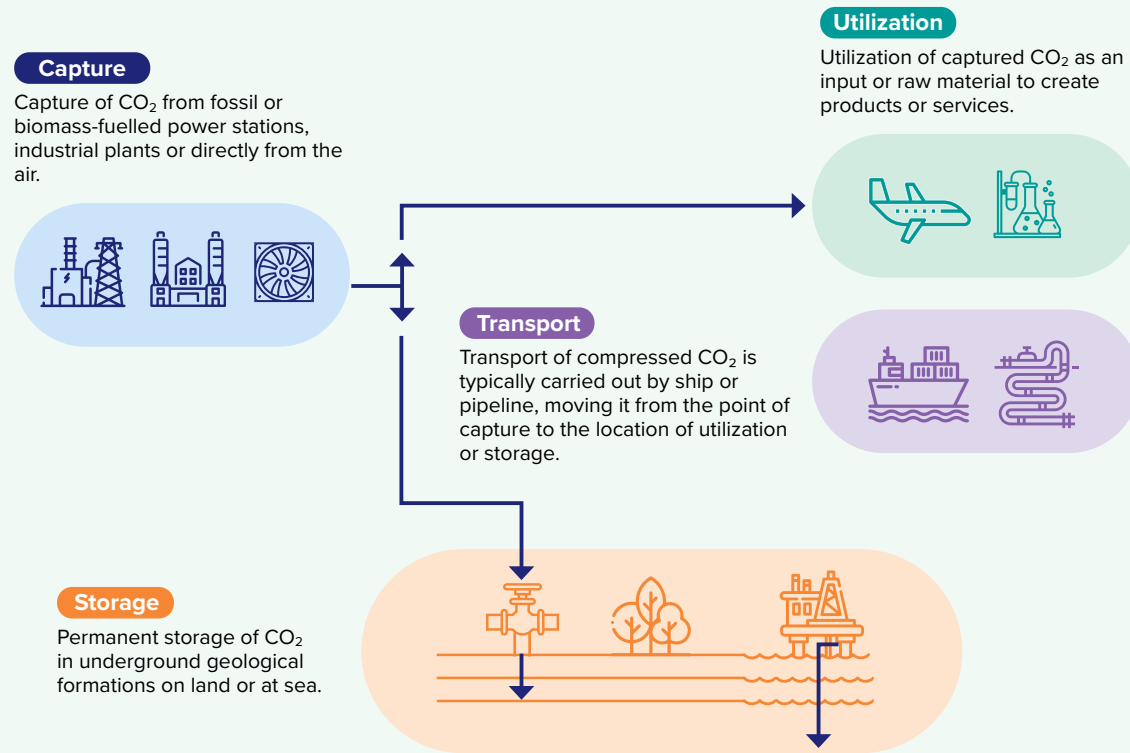


Figure 2.1 CCUS Diagram [1]

How Do We Define CDR?

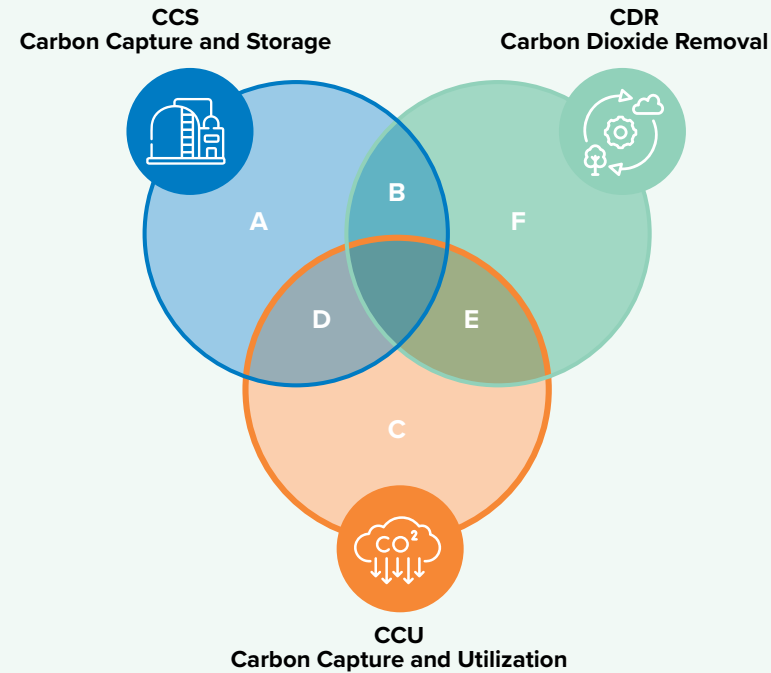
Carbon Dioxide Removal (CDR) is defined as anthropogenic activities that capture CO₂ from the atmosphere through technology or nature-based solutions and store it in various environments such as geological formations, terrestrial or oceanic reservoirs, ecosystems or valuable products for periods ranging from decades to tens of thousands of years [2, 3]. Unlike CCUS, the goal of CDR is to remove **CO₂ directly from the atmosphere** or to **enhance natural carbon sinks** [4]. CDR methods aim to reduce the excess CO₂ accumulated in the atmosphere and to achieve net-zero or negative carbon emissions. In CCUS, on the other hand, the methods of capturing and controlling emissions from industrial processes come to the forefront.

For any method or technology to be recognised as a CDR, three fundamental principles need to be fulfilled [5]:

- I. Removal of CO₂ from the atmosphere;
- II. The removed CO₂ must be stored outside the atmosphere either in the short term (decades to centuries) or the long term (tens of thousands of years or longer);
- III. A comprehensive assessment of upstream and downstream greenhouse gas emissions is essential. This includes emissions from processes such as the use of biomass in removal and storage stages, energy consumption, by-products management, and the methods of CO₂ storage. The total emissions from these processes must be lower than the amount of CO₂ removed from the atmosphere and stored, resulting in a negative final carbon balance.

In addition to these fundamental principles, it is important for CDR solutions to avoid creating negative impacts on biodiversity and ecosystems in accordance with the principles of “Precautionary” and “Do not Significant Harm”.

A combined assessment of existing CDR solutions and innovative technologies, such as CCUS, can make a substantial contribution to establishing a pathway towards achieving the set objectives. Furthermore, this approach will provide guidance for pilot Research & Development (R&D) activities by accommodating different maturity and cost levels, while facilitating the integration of various CDR approaches into broader policy instruments and supportive financing mechanisms. Figure 2.2 illustrates the relationship between CCS, CCU and CDR in different applications.



- A** CCS applications that reduce emissions and have permanent storage but do not lead to CO₂ removal
- B** CCS applications that may lead to CO₂ removal
DACCS, BECCS (if renewable biomass is used)
- C** CCU applications that reduce carbon intensity but do not lead to the permanent storage or removal of CO₂
Capturing CO₂ from any source and utilizing it in short-term use products (e.g: Synthetic fuels, plastics, carbonated drinks)
- D** CCU application, which reduces emissions and has long-term (though not geological) storage, but does not lead to CO₂ removal
Capturing CO₂ from fossil fuel and process emissions and utilizing it in products to which CO₂ is chemically and permanently bound (e.g. building materials)
- E** CCU application that may lead to CO₂ removal
Capturing CO₂ from renewable biomass and the atmosphere and utilizing it in products where CO₂ is chemically bound in a long-term manner (e.g. building materials)
- F** Non-CCS or Non-CCU CO₂ removal technologies
Forests, soil carbon, biochar, enhanced weathering/erosion, ocean fertilisation

Figure 2.2 The Relationship between CCS, CCU and CDR in Different Applications [6]

CCUS in the World: Examples of Applications

Carbon capture and storage (CCS) activities have been carried out since the 1970s. In those years, natural gas processing plants in the Val Verde region of Texas began capturing and marketing CO₂ to support oil production. The main objective during this period was to capture the high concentration of CO₂, which is relatively easy to separate from natural gas, and sell it to oil companies for utilization in enhanced oil recovery (EOR). In other words, the focus of these early applications was predominantly commercial rather than climate-orientated. Since these early projects, CCS applications have expanded to encompass more regions and sectors. The first large-scale carbon capture and storage project driven by climate regulations, incorporating a CO₂ storage and monitoring system, was implemented at the Sleipner offshore natural gas processing plant in Norway in 1996. To date, this project has stored over 20 million metric tons (Mt) of CO₂ in deep saline aquifers approximately 1 km beneath the North Sea.

The number and capacities of commercial CCS plants, at various development stages (operational, under construction, in advanced and early development), as of 2023, are demonstrated in Table 2.1, according to the Global CCS Institute. Between 2022 and 2023, the number of facilities increased from 194 to 392, with a total capacity of 361 Mt/year. Of these facilities, 41 are operational and have a capture and storage capacity of approximately 49 Mt CO₂/year. However, a considerable number of them (so-called early CCS applications) were not developed with climate objectives in mind, as already mentioned, and do not primarily aim to minimise CO₂ emissions and maximise the storage of the captured CO₂.

Table 2.1. Commercial CCUS Facilities – 2023 [7]

	Operasyonel	İnşaat Aşamasında	İleri Geliştirme Aşamasında	Erken Geliştirme Aşamasında	Toplam
Number of facilities	41	26	121	204	392
Capacity (Mt CO ₂ /year)	49	32	144	135	361

Although the applications of CCUS have lagged behind expectations in the past, they have gained significant momentum in recent years and more than 700 projects are currently being developed at various phases along the CCUS value chain. By 2030, it is projected that these projects will achieve an annual capture capacity of approximately 435 Mt CO₂ and an annual storage capacity of 615 Mt CO₂. However, these capacities correspond to only 40% and 60%, respectively, of the target to capture and store 1 Gt (1000 Mt) of CO₂ per year set for 2030, as outlined in the 2050 Net Zero Emission (NZE) Scenario [8]. This scenario is visualised by the graph in Figure 2.3, which compares the capacity of existing and planned large-scale CO₂ capture projects with the targets outlined in the NZE Scenario. As shown in the graph, a significant increase in capacity is projected for 2030 with the commissioning of projects across all development phases. Nevertheless, the orange area (the gap between the NZE target and the current capacity) is still quite large, which indicates that more projects and capacity increases are needed to achieve the NZE targets.

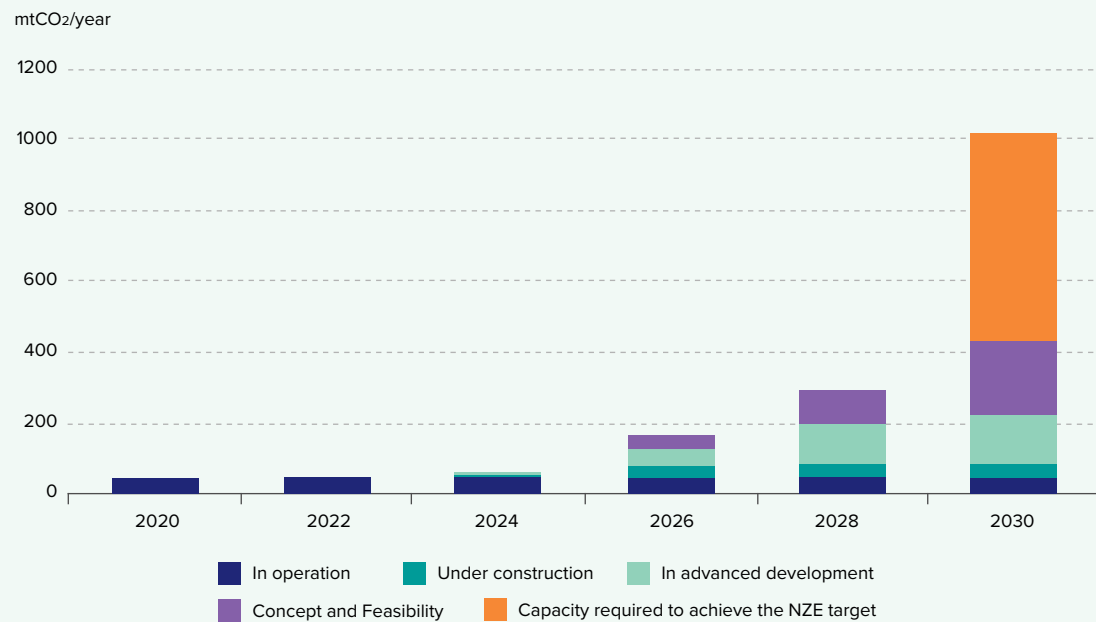
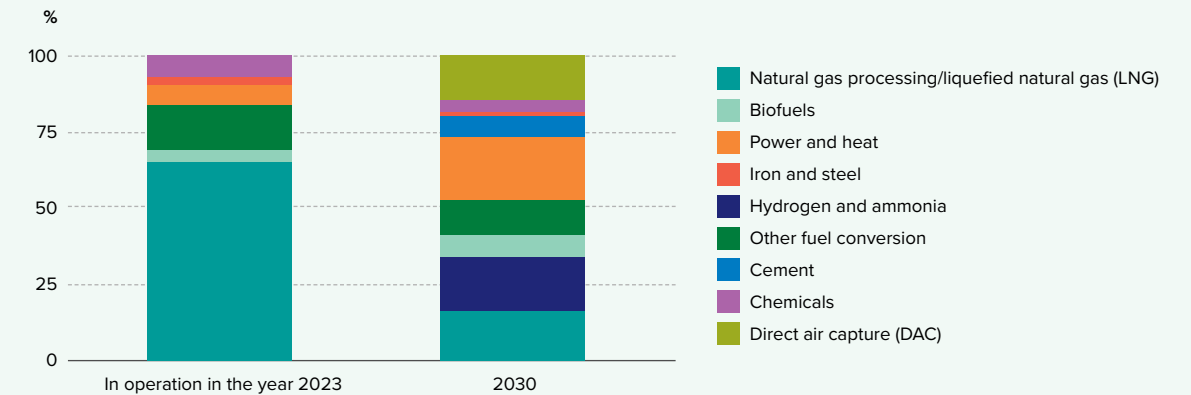


Figure 2.3 Comparison of the Capacity of Existing and Planned Large-Scale CO₂ Capture Projects and the Net Zero Emission (NZE) Scenario, 2020-2030 [9]

Figure 2.4 illustrates the percentage capacities of CCUS facilities in operation in the year 2023 and those planned to be operational in the year 2030, by sectors. From this figure, it is understood that while current projects are primarily concentrated in natural gas processing plants, future developments are expected to expand rapidly into sectors where emission reductions are more challenging, such as cement, energy, chemicals and hydrogen production. These industries are characterized by high-emission-intensity production processes that are difficult to mitigate through clean energy and process changes alone. It is also predicted that the capacity for direct air capture of carbon dioxide, which is currently near zero, will increase significantly by 2030 [10, 11].



Şekil 2.4 Percentage Capacities of Operational and Planned CCUS Facilities by Sector [11]

2.1 Carbon Capture Technologies

There are three traditional main methods of carbon dioxide capture: “pre-combustion”, “oxyfuel combustion” and “post-combustion” (see Figure 2.5).

- a. **Pre-Combustion:** Air is introduced into an air separation unit to be separated into nitrogen (N₂) and oxygen (O₂). The purpose of this process is to obtain a very high purity of O₂, which is then introduced into the gasifier. In the gasifier, solid fuel or oil residues react with oxygen to produce syngas, a mixture containing high-pressure hydrogen (H₂) and carbon monoxide (CO). In shift reactors, water vapour (H₂O) is used to convert CO into CO₂ and even further H₂. In the gas separation unit, the high-pressure CO₂ is captured, compressed and transported for the purposes of utilization or permanent geological

storage. This process produces nearly pure hydrogen, which is subsequently burned in a gas turbine to generate electricity without releasing CO₂ into the atmosphere.

- b. Oxy-Fuel Combustion:** Air is introduced into an air separation unit, where it is separated into nitrogen (N₂) and oxygen (O₂). The O₂ is then delivered to the boiler together with the fuel. When the fuel is combusted with pure oxygen, the boiler temperature increases significantly. In order to control this temperature rise, a portion of the combustion gases is recirculated back into the boiler. The remaining combustion gas, which contains of 90 - 95% CO₂, exits the boiler and is directed to the capture process. In this process, the gas is dewatered, compressed, and prepared for transport.
- c. Post Combustion:** CO₂ is separated from the flue gas produced during the combustion of fuel. After removing impurities with pre-treatments, CO₂ capture is carried out with appropriate technologies. It provides application flexibility thanks to its ability to be integrated into existing facilities.

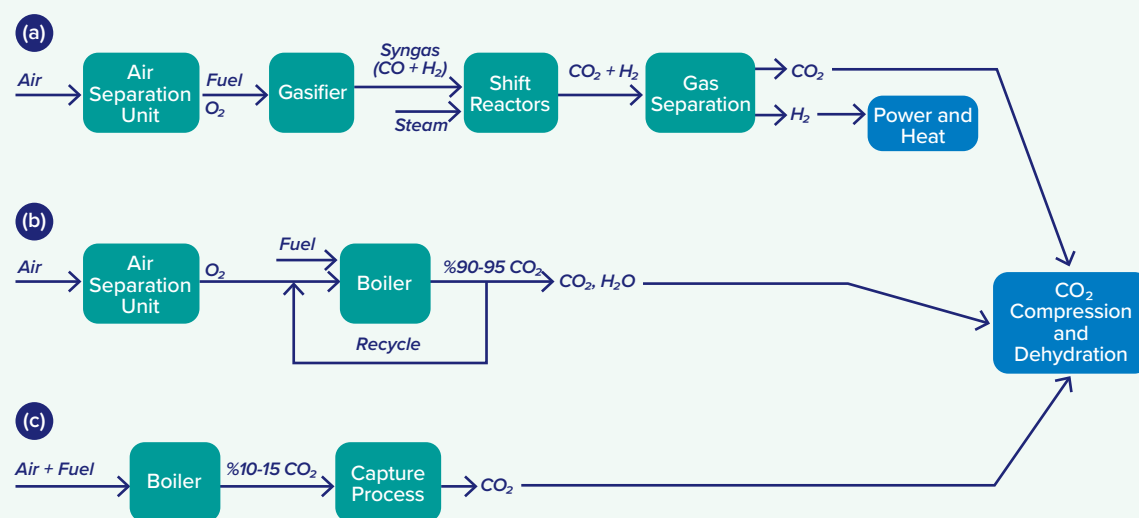


Figure 2.5 Processes of Conventional CO₂ Capture Technologies (a) Pre-Combustion,

The fields of application, advantages and limitations, and TRL of these technologies are summarised in Table 2.2.

Table 2.2 Carbon Capture Technologies [13-17]

Capture Technology	Field of Application	Advantages	Disadvantages	TRL
Pre-Combustion	Integrated Gasification Combined Cycle (IGCC) plants; Natural Gas Combined Cycle (NGCC) plants; hydrogen production; some industrial processes	- A gas flow with high CO₂ concentration and high partial pressure is generated, thus reducing the energy requirement and cost of capture. - High purity hydrogen can be produced and can be utilized as a clean fuel. - Higher separation efficiency and lower energy cost compared to the post-combustion method.	- Applicable in limited existing facilities (such as IGCC facilities) - This technology requires high investment costs and is a complex technology. - New infrastructure and plant redesign are required. - The utilization of hydrogen-rich fuel in the gas turbine creates efficiency problems.	TRL 9 (used for many years in gas-water exchange reactions, removal of acidic gases) <u>Carbon Capture applications:</u> TRL 8 – 9 (absorption processes) TRL 6 - 7 (adsorption processes) TRL 4 - 6 (membrane processes)
Oxy-Fuel Combustion	Power generation; high emission industrial processes (such as cement and steel production)	- High purity CO₂ is produced, the capture process is quite easy, and it has a very high capture efficiency. - Since the amount of flue gas is small, CO₂ separation costs are reduced.	- It requires energy-intensive air separation units for oxygen production; costly. - It is difficult to integrate into existing plants, requires changes in combustion processes. - Its large-scale applications are limited and have complex operational requirements.	TRL 7 (globally there are 2 facilities with oxy-fuels technology)
Post-Combustion	Existing fossil-fuelled power plants (coal, natural gas); large industrial processes; oil refineries	- It can be easily integrated into existing plants, providing flexibility. - It does not require major changes in the main combustion process.	- The low partial pressure of CO₂ reduces the capture efficiency. - It requires high energy costs for solvent regeneration. Furthermore, the utilization of conventional solvents poses environmental problems. - It requires high capital and operating costs (due to the large equipment size requirement for high volumes of flue gases).	TRL 8 - 9 (absorption processes) TRL 4 - 6 (adsorption processes) TRL 4 - 5 (membrane processes)

2.2 Carbon Dioxide Separation Processes/Technologies

CO₂ capture technologies rely on appropriate CO₂ separation processes. The selection of a CO₂ separation process depends on factors such as the conditions under which the process will be carried out, the type of fuel used, the partial pressure of CO₂, and the composition of the gas to be processed. CO₂ separation processes include absorption with liquid solvents, adsorption with solid materials, membrane separation, cryogenic separation and other technologies (calcium looping, chemical looping combustion) (see Figure 2.6). The advantages/disadvantages, capture efficiency and energy requirements of these technologies are summarised in the Table 2.3.

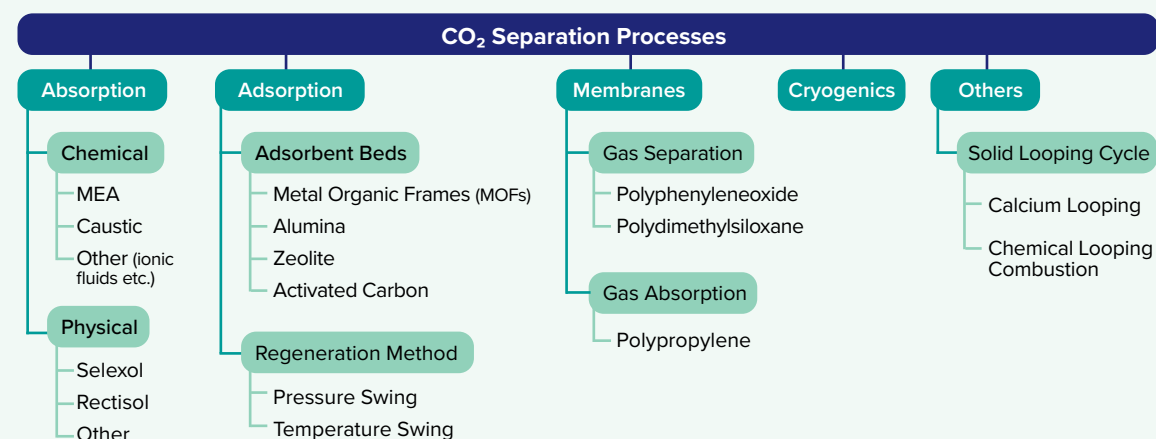


Figure 2.6 Summary of CO₂ Separation Processes [12]

Table 2.3 Comparison of Carbon Dioxide Separation Processes [12, 15, 18]

Separation Processes	Advantages	Disadvantages / Difficulties	Efficiency of Capture (%)	Energy Required (kg CO ₂)
Absorption (Physical)	Low toxicity; low energy requirement	Limited CO ₂ sequestration capacity; expensive	90–98	4.0–6.0
Absorption (Chemical)	Wide range of commercial application; applicability at low CO ₂ concentrations; easy integration; CO ₂ purity > 99%	Regeneration process is expensive (energy intensive); low recovery rate; corrosive; toxic; large equipment size requirement	90–98	2.0–4.5

Separation Processes	Advantages	Disadvantages / Difficulties	Efficiency of Capture (%)	Energy Required (kg CO ₂)
Absorption (Ionic Liquids)	Low evaporation rate; most are non-toxic; thermally stable	In viscous structure; expensive regeneration and high capital cost	95–99	1.5–2.0
Adsorption	Low energy requirement for CO ₂ recovery and regeneration; large porous structure and adjustable morphologies of adsorbents (such as SiO ₂ , MOF)	Low CO ₂ selectivity; loss of stability of sorbents chemically, thermally and mechanically over a large number of cycles	80–95	2.0–3.0
Membrane	High commercial availability of materials; high separation efficiency (> 80%); no need for regeneration process; simple modular system	Blocked mass transfer; blockage and fouling problems; it is not proven in the industrial CCS applications	80–90	0.5–6.0
Cryogenics	Mature technology; high CO ₂ recovery rate	Applicable at CO ₂ concentrations > 90%; requires very low temperature; energy intensive	>95	6.0–10.0
Solid Looping	Synthesis of sorbents with cheap raw materials; since CO ₂ is the main combustion product and does not mix with N ₂ , there is no need for energy-intensive separation.	Rapid degradation of sorbents; insufficient stability of oxygen carriers; insufficient large-scale operational experience.	85–95	3.0–5.0

2.3 Carbon Utilization Systems

Carbon Capture and Utilization (CCU) represents an important method employed in the global carbon management toolkit [19]. As seen in the Figure 2.7, CO₂, which is captured from point sources or directly from the air could be converted into synthetic fuels (methanol/ ethanol/aviation fuel), chemical intermediates, polymers (polyurethane, plastics) or construction/building materials through various conversion processes. Furthermore, CO₂ can be utilized directly, without conversion, to increase efficiency in greenhouses/fertiliser production, as a heat transfer fluid in cooling systems, in the food/beverage industry or as a solvent in enhanced oil recovery (EOR).

The commercial applications of CCU today mostly involve the areas where CO₂ is utilized directly, such as in the production of urea (~130 Mt - 57%), which is the raw material of fertiliser, in EOR (~80 Mt - 34%), in food and beverage production, and in greenhouses [21, 22]. In addition to these commercial applications, methanol, ethanol or formic acid production processes are now carried out at pilot or demonstration scale. Laboratory-scale systems are investigating the utilization of CO₂ to produce alcohols, aldehydes, dimethyl ether (DME), organic acids and carbamates [23]. Recently, the transformation and utilization of CO₂ within the context of Carbon Capture and Utilization (CCU) have gained attention due to factors such as national and international emission reduction targets, the rise of renewable energy, and the pursuit of energy security. CO₂ is converted into valuable products using three main methods: biological conversion, chemical conversion and mineralization [24]. In biological conversion, microorganisms (e.g. microalgae) rapidly absorb CO₂ and use sunlight to convert it into a final product such as chemicals or fuel [25]. In chemical conversion, the carbon-oxygen bond is broken and carbon is bonded to other elements (hydrogen) to produce the final product. In this process, CO₂ is utilized as a reactant or feedstock for the synthesis of commodity chemicals and fuels [25]. In mineralization or carbonation, CO₂ reacts naturally with minerals containing calcium or magnesium to produce valuable building/construction materials. In this method, CO₂ could be integrated into the final product (concrete/aggregate) and stored as solid carbonates [26].

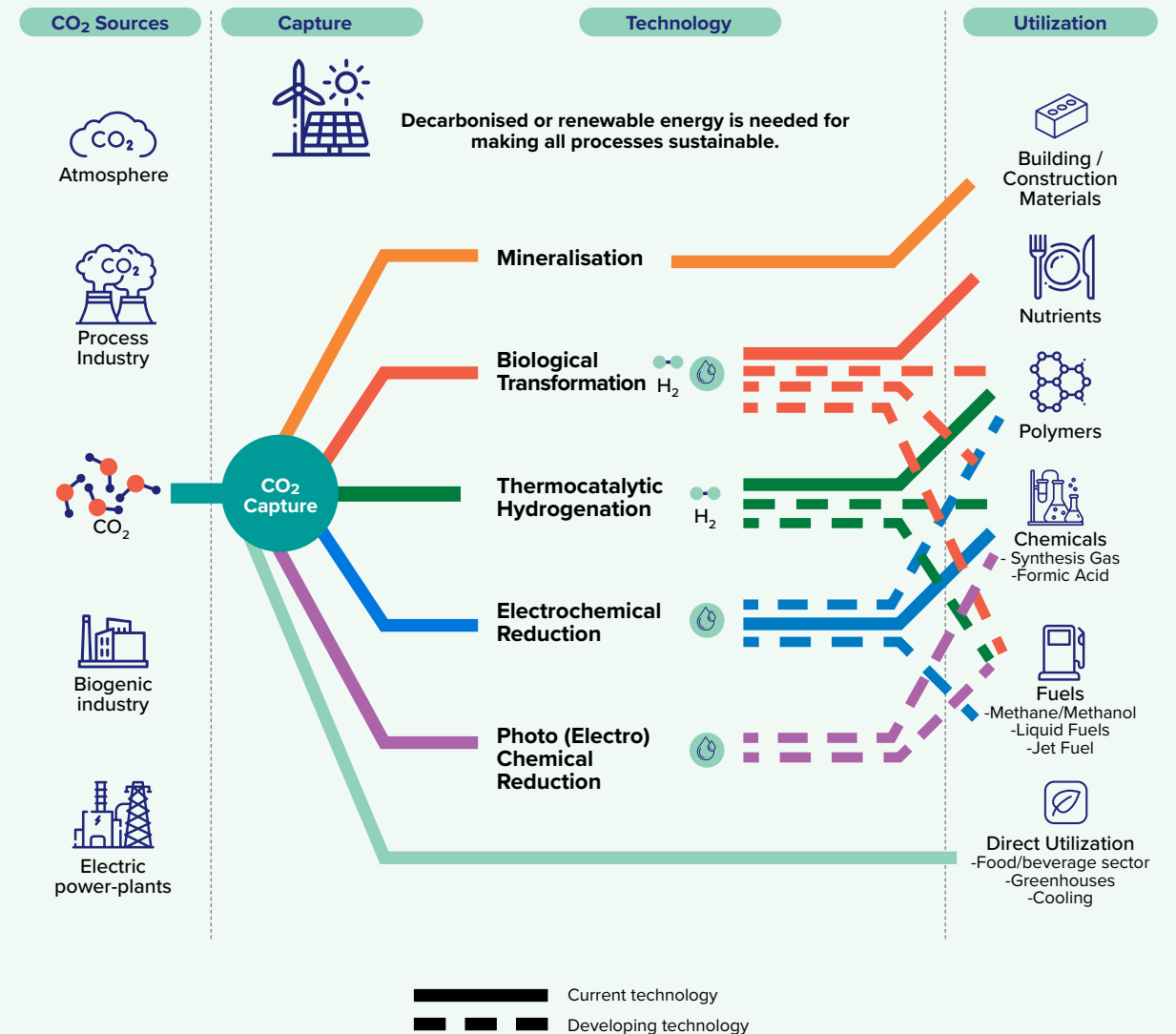


Figure 2.7 CCU Process and CO₂ Conversion Methods [20]

2.4 Carbon Storage Systems

Carbon Capture and Storage (CCS) technology is based on the principle of transporting CO₂, captured from point sources or directly from the air, to geological storage sites. Geological storage of CO₂ refers to the storage of CO₂ in liquid or supercritical form in deep geological formations deeper than 800 - 1000 m underground and at high pressure (greater than 100 bar) [27]. Through this process, CO₂ is permanently removed from the atmosphere. Despite of unsuccessful attempts, CO₂ injection and storage has been operating in a safe and effective manner for more than 50 years. In Norway alone, the Sleipner and Snøhvit plants are known to have stored around 26 million tonnes of CO₂ since 1996 [28]. In the IPCC's CCS Special Report, it was reported that properly selected and managed geological reservoirs could “very likely” hold more than 99% of the injected CO₂ for a period of more than 100 years, and even “possibly” for a period of more than 1000 years [29].

Options for safe and permanent storage include Storage in Saline Aquifers, Storage in Depleted Oil and Natural Gas Reservoirs, Storage in Deep Coal Seams (Enhanced Coal Bed Methane (ECBM) Recovery), Storage in Basalt Formations, Gas Hydrate Storage and Ocean Storage (Figure 2.8) [29]. The specifications, advantages and disadvantages of these storage options are presented in Table 2.4.

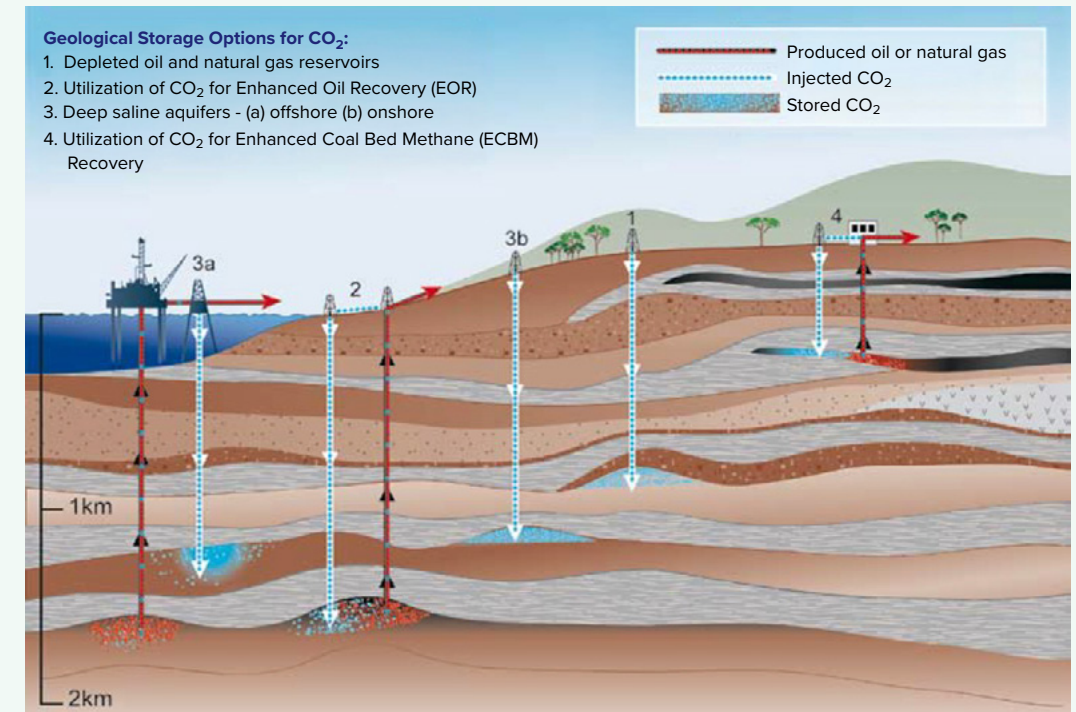


Figure 2.8 Geological Storage Options for CO₂ [29]

The amount, injection rate and duration of the CO₂ to be injected need to be accurately determined in order to safely sequester CO₂ in deep underground formations without posing any risk of leakage. Key physical properties affecting this process include the porosity of the rocks (their capacity to hold fluids), the permeability level affecting fluid/gas flow through the rock, and pressure [30]. CO₂ injected into geological formations is trapped by physical and chemical processes, and could be safely stored for thousands of years [29].

Table 2.4 CO₂ Storage Methods

Storage Options	Properties	Advantages	Disadvantages
Saline Aquifers	These are deep underground aquifers containing saline water. CO ₂ dissolves on contact with water and is stored in the rock pores.	• Wide geographical distribution • High storage capacity • Safe because of CO₂ solubility	• Saline reservoirs are limited • Leakage risks
Depleted Oil and Natural Gas Reservoirs	CO ₂ is pumped back into wells from which oil or gas was previously extracted.	• Built-in infrastructure • Pressure management is easy • Recovery with EOR (enhanced oil recovery)	• Cost-effective but limited capacity • Depleted wells may have leakage problems
Deep Coal Seams	Deep coal seams absorb CO ₂ , and the pores within the coal bind the CO ₂	• Methane recovery by replacement of CO₂ with methane • Good capacity in some reservoirs	• Risk of release of methane gas into the atmosphere • Coal seams of sufficient depth are limited
Basalt Formations	It is a storage method where CO ₂ is mineralized with basalt rocks. CO ₂ reacts with basalt, transforming into carbonate minerals.	• Permanent storage • Mineralization provides safety	• It is difficult to control the reaction rate • Applicable in limited areas
Gas Hydrate Storage	Gas hydrates are solid-structured gas-water compounds formed at high pressures and low temperatures. CO ₂ could be replaced by these structures.	• Large potential capacity • Replacement with methane	• High pressure requirement • Instability of gas hydrates and risk of dissolution
Ocean Storage	It takes place either by injecting CO ₂ into the ocean floor or by dissolving CO ₂ on the ocean surface.	• Very large volumes • Geographically wide applicability	• Risk of ocean acidification • Negative impacts on the ecosystem • Challenges in terms of international legislations

2.5 Sectoral CCUS Applications and Cost Analyses

One of the primary barriers to the widespread implementation of carbon capture and storage (CCS) technologies is the costs involved.

The total cost of carbon capture and storage activities includes the following factors: [31]:

- CO₂ capture from the emission source – installation and operation of technologies for separating CO₂ from the gas stream to a purity of over 95 percent by volume,
- CO₂ dehydration and compression/liquefaction costs depending on the transport method,
- Infrastructure investments required for CO₂ transport by pipeline or ship, mobile vehicles,
- Identification and exploration of suitable areas for CO₂ injection,
- Monitoring and verification activities of stored CO₂.

The selection of CCS technology is a critical factor in determining the cost of CCS projects, but it is not the sole factor influencing expenses. Numerous other factors affect costs across the CCS value chain. The cost of CCS projects varies depending on various factors such as flue gas characteristics (e.g. partial pressure of CO₂), the specific technology employed, the capture efficiency of CO₂ and the desired CO₂ purity, the flexibility of the operation, the size of the project and regional economic conditions. In general; the project cost is expressed as the components of investment cost (CAPEX), operating cost (OPEX) and Levelized Cost of Carbon Capture (LCCO).

For example, advanced amine-based post-combustion capture technology with an annual capture capacity of 1 - 1.5 Mt CO₂ (equivalent to the annual CO₂ emission value of an average-sized cement plant) would have the following cost structure (these values are based on estimates):

CAPEX: \$400 million

OPEX: \$75 million / year

LCCO: \$80 / tonne CO₂ (excluding transport and storage)

It is known that the costs of CCS projects are project-specific; moreover, factors such as the operational lifetime of the plant, load factor, annual carbon capture rate, integration into existing infrastructure and market demand for captured CO₂ also affect the associated costs [32].

Even though extensive studies have been carried out on the techno-economic performance of CCS applied to industrial sources, it has been observed that there are large variations in cost estimates. These variations are partly attributable to differences in the projects analyzed and the selection of capture technologies, but they are primarily due to inconsistencies in cost assessment methods and underlying assumptions. Although CCS costs are generally perceived as high, the cost profile depends on numerous parameters. Therefore, it varies from project to project and from geography to geography. For example, in industrial processes that produce “pure” or highly concentrated CO₂ streams (such as ethanol production or natural gas processing), the cost of capture (levelized capital cost) ranges from **\$15–25** per tonne, while in processes such as cement production and power generation with ‘diluted’ gas streams, the cost of capture can range from **\$40–120** per tonne. Consequently, accurate conclusions can only be drawn by conducting cost assessments tailored to each specific project or application.

Average CO₂ capture costs for 2019 by sectors are demonstrated in Figure 2.9.

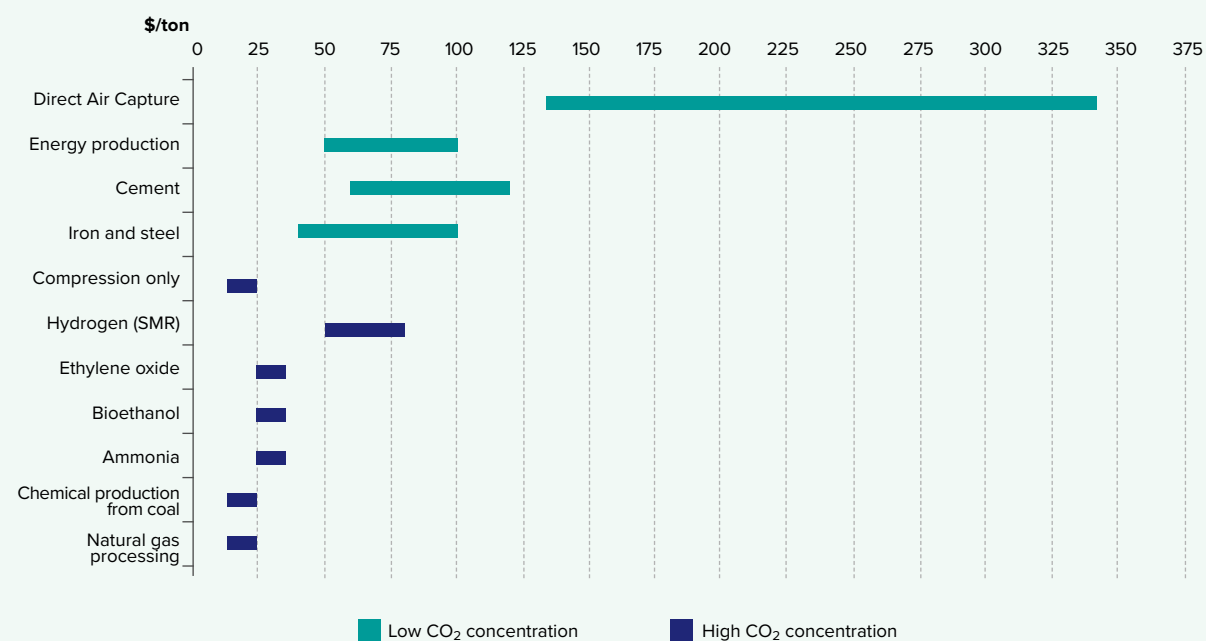


Figure 2.9 Levelised CO₂ Capture Costs by Sector, 2019 (Cost estimates are based on data available in the United States. The capture costs include compression costs) [33]

Transport and storage costs also vary greatly from project to project and primarily depend on CO₂ volumes, transport distances and storage conditions. For instance, in the United States of America, onshore pipeline transport costs range from \$2–14 per tonne, while onshore storage costs can range more widely (<\$10 to \$60). However, in some certain cases where storage provides economic benefits, for example, when CO₂ is injected into oil fields to increase oil production and stored permanently, storage costs can (theoretically) become negative [33].

In Table 2.5, examples of CAPEX of CCS facilities in operational phase on sectoral basis are presented. Furthermore, comprehensive cost analyses in the literature for the relevant sectors are also examined and the results of avoided CO₂ costs are given.

Table 2.5 Sectoral CCS Application Examples

Sector	Highlighted Technology	Application Example at Industrial Scale	Avoided CO ₂ costs
Cement	- Chemical Absorption (TRL 7-8) - The Calcium Looping Cycle (TRL 7-8)	- Not operational yet - Heidelberg Materials Brevik Cement (Norway, the end of 2024) 0.4 M tonnes CO₂/year - CAPEX: €420 million [34].	€52.4/tCO ₂ , €80.2/tCO ₂ , €102.9/tCO ₂ [35, 36].
		- Single application: Al Reyadah Emirates Steel – DRI (Abu Dhabi) 0.8 Mt CO₂/year - No available cost data	€55/tCO ₂ , €60.6/tCO ₂ [37].
Steel	Chemical Absorption (TRL 9)	- ArcelorMittal –Blast Furnace (France, 2030) 1 Mt CO₂/year - Permanent storage to be carried out, first zero emission steel with CCS	

Sector	Highlighted Technology	Application Example at Industrial Scale	Avoided CO ₂ costs
Energy	• Chemical absorption (coal + natural gas) (TRL9) • Chemical absorption (biomass) (TRL 7-8)	Boundary Dam-Coal (Canada) • 1 Mt CO₂/year • CAPEX: Ca.\$1.47 billion (50% is for the capture) [38].	\$52/tCO ₂ – \$85/tCO ₂ (NGCC) [34].
		Petra Nova – Coal (USA) • 1.4 Mt CO₂/year • CAPEX: \$1 billion (50% is for the capture) [38].	
Hydrogen	• Chemical/physical absorption (TRL 9) • Solid Adsorbent (VSA) (TRL 9)	Port Arthur – Air Products (USA) • 0.9 Mt CO₂/year • CAPEX: \$431 million [38].	€36.4/tCO ₂ , €55.5/tCO ₂ , €58.7/tCO ₂ (for SMR) [39].
		Shell Quest (Canada) • CAPEX: Ca.\$790 million [38].	
Fertiliser	The capture of fertiliser production emissions is actually related to the capture of carbon dioxide generated during the production of its raw material, hydrogen.		
Aluminium	Currently, there is no planned carbon capture project related to aluminium production.		

2.6 Carbon Dioxide Removal (CDR) Solutions

Although there is no single agreed methodology for categorizing the CDR methods identified by the IPCC (2018), in this study, CDR solutions are examined in two main categories as nature-based solutions and technology-based solutions.

Nature Based Solutions (NBS) are defined as strategies aimed at addressing societal challenges and providing benefits to both people and nature through the conservation, sustainable management and restoration of natural and human intervened ecosystems [40]. These solutions offer sustainable development approaches to address globally

significant challenges such as climate change, disaster risk, food and water security, biodiversity loss, and human health [41]. Afforestation and reforestation, wetland and peatland restoration, soil carbon sequestration, and blue carbon management stand out as CDR methods within the scope of NBS. It is believed that placing a greater emphasis on NBS methods on a global scale could promote a more resilient system against future challenges by encouraging a human- and environment-oriented development.

Technology-based CDR solutions are defined as innovative methods that seek to remove carbon from the atmosphere on a long-term basis. These solutions include Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Carbon Capture and Storage (DACCS), biochar derived from biomass, enhanced weathering, and ocean alkalinity enhancement. Each technology has the objective of removing carbon from the atmosphere and storing it for a long-term, either through biological processes or chemical and physical mechanisms.

The CDR methods listed in the IPCC and UNEP reports, as shown in the Figure 2.10, are categorized according to their carbon capture mechanisms, feasibility, scalability, ease of monitoring, reporting and verification (MRV), potential outcomes, average costs, public perception, storage methods, and duration of storage. Following the analysis of this figure, it is seen that NBS solutions, especially afforestation and reforestation, not only have high carbon capture potential but also enjoy greater public acceptance. Nevertheless, it is evident that in most of these solutions, the MRV activities have not reached the desired level yet and require further work. Additionally, for nature-based solutions to be effective and long-lasting, the duration of carbon storage through these methods is crucial. The fact that the storage durations of nature-based methods can range from decades to centuries requires careful consideration regarding their permanence. Due to their complex structures, CDR solutions require the use of methodologies such as Life Cycle Assessment (LCA) to accurately evaluate the upstream and downstream environmental impacts within the value chain [42]. Although technology-based solutions offer much longer storage durations (ranging from centuries to tens of thousands of years), research is ongoing to reduce the costs of these methods. In addition, efforts to improve public perception and develop capacity should be prioritized.

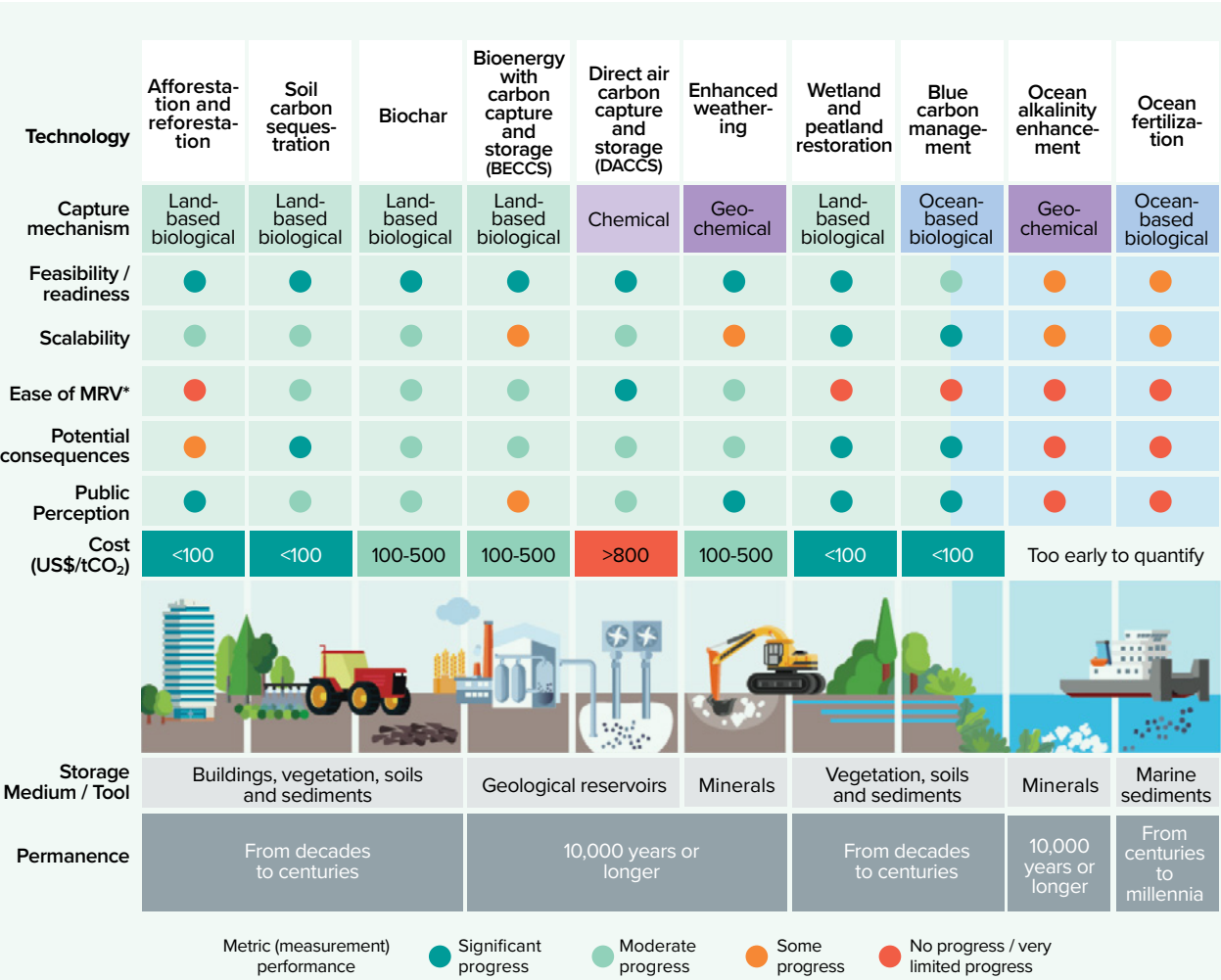


Figure 2.10 CDR Methods and Basic Features [19]

Serious steps are being taken on a global scale with the aim of both regulating and promoting CDR solutions. CDR solutions are undergoing a significant transformation and incentivization process on a global scale, offering key opportunities to contribute to sustainable development goals. Considering the results obtained from global case studies generating carbon credits [43], it can be concluded that afforestation and reforestation, wetland and peatland restoration, soil carbon sequestration, and blue carbon management solutions stand out in accordance with Türkiye’s ecosystem. Furthermore, it would be an appropriate step for Türkiye to also evaluate BECCS.

Specific criteria have been established for the certification of CO₂ removed through CDR solutions. These criteria ensure that CO₂ removals are accurately measured, that the carbon is stored for a defined period (at least 35 years for carbon stored in products), that the approach goes beyond current practices, and that it contributes to broader sustainability goals, such as having positive effects on biodiversity.

3.

The Role of Carbon Markets in Enabling CCUS And CDR Solutions

Innovative solutions in carbon management such as CCUS and CDR solutions, have not yet gained investors' confidence or received the expected attention due to their high costs and their inability to ensure a predictable and stable revenue stream. This situation constitutes a major obstacle for the development and scaling of CCUS solutions, especially those with low TRL. Evaluating CCUS and CDR solutions alongside potential business models can contribute to increasing investments in this field. Many CCUS and CDR-focused companies have built their business models on selling carbon removal credits (CRCs) from related projects to other companies or countries. In other words, the carbon removed from the atmosphere through CCUS and CDR projects can create an additional source of revenue by being traded on the carbon credit market. This approach can be implemented in three primary ways:

1. **Mandatory Carbon Markets (Compliance Markets):** Emission Trading System (ETS) established at the national, regional or local level

2. **Voluntary Carbon Markets (VCM):** For individuals or organizations seeking to reduce their carbon footprint on their own initiative
3. **Niche Voluntary Carbon Markets:** Smaller-scale markets that focus on specific projects

Mandatory Carbon Markets (Compliance Markets) within the Framework of CDR and CCUS:

These markets operate in line with mandatory emission reduction targets established by governments. For instance, a national ETS or an implemented carbon tax enables the trading of carbon credits within the scope of these systems. In mandatory markets, businesses can generate carbon credits by reducing their emissions below a specified baseline emission level or through the permanent sequestration of carbon. This process generates a verified supply of credits [44].

The ETS plays an increasingly significant role in promoting CDR and CCUS projects. The high costs and early integration challenges of innovative technologies such as BECCS and DACCS can be overcome by integrating carbon removal credits into ETS. Such an integration could increase the liquidity of carbon markets, support early learning processes for these technologies, and accelerate technological development [45].

The European Union (EU) Carbon Removals and Carbon Farming Certification (CRCF) Regulation serves as a good example for a certification system that could be developed in Türkiye [46]. Such a system has the potential to support CDR and CCUS projects by providing transparency and standardization, thereby facilitating access to funding for these initiatives. Designing an ETS to cover CDR and CCUS technologies would increase the flexibility of carbon markets, promote the adoption of innovative technologies, and become an effective tool in combating climate change. This approach would contribute to both economic growth and environmental sustainability.

Voluntary Carbon Markets within the Framework of CDR and CCUS:

Voluntary Carbon Markets (VCM) are defined as frameworks where private sector actors buy and sell carbon credits generated from projects that reduce or remove greenhouse gas emissions from the atmosphere, without being dependant on a central authority [47]. In these markets, each carbon credit represents one tonne of CO₂,eq. reduced or removed from the atmosphere. In the context of VCMs, project-based carbon credits are

certified by standard-setting bodies in line with voluntary demand, and this process is audited through independent verification [48]. Consequently, carbon credits in the market, possessing different qualities, are categorized into two main categories as “mitigation” and “removal”. These categories directly influence the market price of carbon credits, with removal projects generally being acknowledged as having higher integrity and being costlier. Among the certification standards within VCMs, the methodology published by Verra under the leadership of the CCUS+ Initiative for CDR and technology-based CCS activities stands out [49, 50]. This standard specifies the general requirements for CDR and CCS projects and provides a set of modules for the measurement of removed CO₂ in line with CO₂ capture, transport and storage activities [51]. For example, work is ongoing on the first module, which covers DACCS activities, the transport of CO₂ and the storage of CO₂ in saline aquifers and depleted oil and gas reservoirs, with its release planned in the near future [52]. This example demonstrates that certification processes will advance in parallel with the development of CDR and CCUS technologies, allowing the credits generated from these technologies to gain a stronger presence in VCMs.

Niche Voluntary Carbon Markets within the Framework of CDR and CCUS:

To support the scaling of DAC and CCUS projects, various VCM initiatives have emerged, achieving significantly higher credit prices than the rest of the market. Major technology companies such as Microsoft [53] and Stripe [54], alongside large firms such as Airbus [55] and Shopify [56], as well as financial sector players like UBS [57] and SwissRe [58], have specifically started purchasing credits generated from CDR and CCUS projects in line with their net zero goals. These firms have allocated substantial resources across a broad spectrum, ranging from commitments to purchase all removals achieved by individual projects up to a certain limit to innovative mechanisms such as advance market commitments.¹ A new ecosystem referred to as carbon removal marketplaces, is rapidly developing by combining carbon removal-specific standards and market mechanisms. Companies such as Puro.Earth, Nori and Isometric have been developing innovative methodologies in CDR areas, including biochar, carbonated building materials, and soil carbon sequestration [59-62]. However, these companies face criticism due to a lack of methodological transparency and approaches focused on increasing credit volumes. On the other hand, this new ecosystem contributes to the growth of international

1. Fixed-price forward contracts lasting up to ten years at a price several times higher than the average price in the voluntary carbon market

voluntary niche carbon markets, while enhancing access to funding for CDR and CCUS projects, and supporting the sustainability of these projects. However, for a reliable and effective market structure, transparency, accountability, and development of regulatory frameworks is critical.

4.

Findings and Recommendations for Türkiye

It is evident that CCUS technologies will play a critical role for Türkiye to achieve its 2053 net zero emission target. This requirement has been clearly emphasized for both the energy and industrial sectors in the Climate Change Mitigation Strategy and Action Plan covering the 2024 - 2030 period. Furthermore, during the recent COP29, Türkiye published its Long-Term Climate Strategy report. In this report, CCUS technologies were included as the 5th strategic priority, emphasizing the focus on increasing their applicability in the manufacturing sector, with a particular priority given to the cement and steel industries. In our country's private sector (in collaboration with universities), projects supported by the European Union and The Scientific and Technological Research Council of Türkiye (TÜBİTAK) have been developed within the scope of CCUS technologies, covering capture, utilization and storage. However, it has been observed that these projects are carried out by a limited number of industrial sectors. On the academic side, it is noted that the number of theses and dissertations in this field is notably low. Considering the fact that the development of CCUS technologies requires long-term research and development studies, it is evident that the number of high-quality academic studies in our country should be increased, and the transfer of these studies from academic level to pilot plants and the industry should be supported. When examining initiatives working in the CCUS field in

Türkiye, no end product or patentable process has yet been identified. As a result of the studies carried out within the scope of this report, our findings and recommendations for Türkiye are listed below:

1. **The Necessity of Conducting Feasibility Studies on a Country and Project Specific Basis:** Geographical location and energy costs have a significant impact on the feasibility of CCUS projects. Therefore, Türkiye needs to carry out country- and project-specific analyses for the full assessment of the potential of CCUS in Türkiye. Furthermore, the high potential of renewable energy in the energy mix of Türkiye may place Türkiye in an advantageous position in terms of energy costs. Although CCUS technologies are not considered as a priority solution for Türkiye in the short and medium term, provided that the costs decrease in the long term, they could contribute to reducing emissions, particularly in the cement and iron-steel sectors, thereby supporting Türkiye's 2053 targets.
2. **The Necessity of Creating a Storage Atlas:** Carbon storage solutions are widely recognized as the most critical phase of CCUS projects in line with climate targets. The most important aspect to be considered during the development of CCUS projects in Türkiye is the identification of CO₂ storage solutions. In this context, projects/studies are needed to demonstrate that geological storage options are both technically and economically feasible. For the feasibility and success of these projects, a legal and regulatory framework, along with incentive mechanisms, need to be established.
 - a. It is estimated that some data on potential CO₂ storage sites already exists; however, access to open data sharing by relevant institutions has not been achieved.
 - b. An extensive geological storage area is required to store large quantities of CO₂ captured from point sources. However, the capacity of depleted oil fields in Türkiye where CO₂ can be stored is highly limited (West Raman Field ~ 100 million tonnes CO₂ - EOR), therefore it is especially necessary to determine the storage capacities of saline aquifers [63].
 - c. Additionally, it is known that the Dodan Field, which stands out as Türkiye's largest CO₂ reservoir, may offer storage potential. Deep aquifers identified

in Thrace, Western Black Sea, and Southeastern Anatolia may be suitable for CO₂ storage. Soda caves may be considered among the alternative storage options, although it is predicted that their storage capacity is limited due to their small volumes and close proximity to the surface. Moreover, salt tectonics in the Sivas Basin are known to have CO₂ storage potential; however, the CO₂ storage capacities of these geological formations need to be investigated in detail.

- d. It has been observed that Türkiye's geothermal energy fields have high-purity CO₂ capture potential. Injecting the captured CO₂ back into the reservoir could not only enhance reservoir efficiency but also serve as an alternative CO₂ storage solution. To accurately determine the duration of storage; monitoring, reporting, and verification studies need to be conducted.
- e. Alternative CO₂ storage options geographically close to Türkiye (Bulgaria, Greece) should be evaluated through cross-border transportation.

3. The Necessity for Legal Legislation and Incentive / Support System: Clear policy frameworks and government support are necessary to accelerate the development of CCUS and CDR technologies. Besides government subsidies, investments from industry and the private sector are also crucial for the widespread and effective implementation of these projects. In this context, a strong collaboration between the public and private sectors should be established. While the private sector plays a pioneering role in technology development, management of operational processes and commercialization, the public sector can shape projects through regulatory and infrastructure support. Furthermore, companies operating in different fields in the private sector should work in cooperation with each other. For instance, technology companies can partner with project developers, shipping companies with ports, and industrial carbon emitters with companies specializing in transportation and storage.

4. Evaluation of a Sectoral Approach: In order to maintain its competitiveness in the global market, especially in the cement and steel sectors, Türkiye must rapidly switch to the production of low-carbon products. The supply of low carbon products offers a high benefit/cost ratio. Nevertheless, while many heavy industries are more familiar with the approach of purchasing off-the-shelf units

or system components, carbon capture projects require facility-specific designs that must undergo prolonged pre-FEED and FEED (Front End Engineering Design) development phases. Facilities in Türkiye need to take this into account.

5. Importance of Industrial Clusters and Collaborations: As seen in other successful examples worldwide, forming industrial clusters in Türkiye and sharing CO₂ infrastructures will be crucial for increasing the cost-effectiveness of CCUS applications and reducing associated risks. The utilization of carbon captured from multiple point sources or from the air, in the production of fuels, chemicals and materials can be demonstrated on a commercial scale and thus, both economic gains can be achieved and the dissemination of the technology can be accelerated. Industrial clusters will serve as catalysts for developing such collaborations and optimizing costs through shared infrastructure. Additionally, Türkiye must strengthen international cooperation in the field of CCUS and increase knowledge and experience sharing in this field by joining international cooperation platforms (e.g. Clean Energy Ministerial, Mission Innovation, Carbon Management Challenge [CMC]). The development of CCUS technologies should be accelerated by taking advantage of the funds and projects offered by the European Union and other international financing organizations.

6. Utilization of Various Industrial Waste Fractions in CO₂ Mineralization: The conversion of CO₂ into calcium/sodium carbonate by mineralization method by making use of various waste fractions (steel slag, ash, mining waste, construction-demolition waste, etc.) and its subsequent use in building materials (supplementary cementitious materials, aggregate, ceramics, etc.) is a utilization method with high market demand, and also allows long-term (centuries) storage of CO₂. This method holds significant potential for applicability in Türkiye, particularly in the cement sector. Furthermore, the use of CO₂ in concrete curing within the cement industry stands out as another useful application area.

7. Evaluation of the Conversion of Captured CO₂ into Other Economically Valuable Chemicals: Projects aimed at developing innovative catalyst and reactor technologies for processes that convert CO₂ into methanol, formic acid, polyurethane, sustainable aviation fuel (SAF) and other valuable chemical products should be supported. Pilot and demonstration plants need to be established to demonstrate the economic

and technical feasibility of processes for CO₂ conversion. Furthermore, studies on biofuel production with microalgae cultivation, which enables biological conversion of CO₂, come to the forefront as a circular model that offers economic value.

8. Implementation of CDR Solutions: Whereas CDR solutions have only recently started to gain momentum on a global scale, the potential of CDR solutions in the national context of Türkiye has not been finalized yet. Even though various projects have been implemented in Türkiye within the scope of nature-based solutions, it is possible to state that most of these projects are not CDR-oriented. Considering the results obtained from global case studies generating carbon credits [43], afforestation and reforestation, wetland and peatland restoration, soil carbon sequestration, blue carbon management, and biochar solutions stand out as promising approaches in accordance within the ecosystem of Türkiye. Moreover, it is crucial for Türkiye to also evaluate the potential of BECCS.

9. The Importance of Establishing a National ETS: Determining the sectoral scope and legislative elements of the National ETS planned to be implemented in Türkiye has a critical importance in terms of clarifying the legal obligations of the private sector within the scope of mitigation activities.

- a. Sectors to be included in the ETS, the types of greenhouse gases, and reporting obligations must be meticulously defined.
- b. Clarification of the legislative body of the ETS and establishment of an effective governance structure is essential.
- c. The structural effects of the ETS on economic growth, employment and technology preferences must be taken into consideration in long-term impact analyses. Long-term impacts of carbon pricing on human capital and technology, especially in the industrial and energy sectors, should be evaluated.
- d. A framework for measuring, monitoring and verifying decarbonisation in Türkiye should be established and a national decarbonisation certification system should be developed.
- e. The ETS design should incorporate a flexible governance framework that can quickly respond to unforeseen developments.

- f. Clarifying the policy objectives affecting price formation and developing strategies to reduce uncertainties remain important.
- g. Limited allowance of compensation mechanisms of the national ETS to be established in Türkiye under certain conditions may increase the interest in CDR and CCUS projects. Nevertheless, these mechanisms must be designed in such a manner that they do not hinder mitigation efforts.
- h. The inclusion of direct air carbon capture and biomass utilizing plants in the ETS (and providing free allowances to these plants) may enable carbon credits generated through DACCS and BECCS to be traded in the market. Furthermore, the carbon credits generated by Türkiye through DACCS and BECCS could be utilized by trading with other countries under Article 6 of the Paris Agreement. This would allow Türkiye to strengthen its climate actions by developing voluntary collaborations to support its Nationally Determined Contribution (NDC) targets.
- i. Determining the amount of CO₂ that can be stored in Türkiye's geological structures and including this amount within the ETS system should be considered.
- j. Effective utilization of revenues constitutes a critical element in the ETS design. ETS revenues could be utilized as incentives and investments in innovative technologies such as CCUS and CDR, and special funds could be created for this purpose.
- k. Establishing special funds for the development of CCUS and CDR technologies will lead to innovations in environmental and industrial processes in the long term.
- l. Integrating the national ETS of Türkiye with other international carbon markets could enhance market liquidity and create wider emission mitigation opportunities. In order to achieve this integration, harmonization and mutual recognition standards need to be improved.
- m. The establishment of an independent and competent regulatory body such as the Carbon Markets Board is of great importance for the effective management of the ETS.

10. Importance of Identifying the Risks of CCUS Projects: CCUS projects involve a high level of financial and technological risks, as well as risks stemming from the value chain and regulatory frameworks.

- a. It is significant to assess the risks across the entire CCUS value chain to understand the impact of decisions across all project phases.
- b. Currently, CO₂ emissions are less costly than CCUS projects which brings the risk of commercialization. Government support becomes crucial to mitigate these risks.
- c. Since a CCUS project to be implemented in Türkiye will be the first of its kind, it involves high technological risks. Furthermore, technical infrastructure risks during the construction phase of the project could critically affect the project's success.
- d. Since there is currently no CCUS-specific legislation in Türkiye, bilateral infrastructure agreements could be evaluated in order to avoid possible regulatory risks.

11. The Importance of Increasing the Applicability of CCUS Projects in Türkiye: It is crucial to carry out demonstration and pilot projects for the development of CCUS technologies in Türkiye. These projects play a critical role in terms of building know-how and increasing local capacity as well as revealing the technical and economic feasibility of the technologies. Moreover, these projects will encourage industry-university collaborations.

12. Requirement of Supporting Research and Development Studies / Academic Research: Türkiye's limited footprint in the field of CCUS technologies and CDR constitutes a major barrier to the widespread adoption of these solutions. Therefore, more resources should be allocated to research and development activities and academic research on CCUS and CDR projects in Türkiye. Cooperation between local universities, research centres, and the private sector can facilitate the development of these technologies and reduce their costs. Furthermore, related research and development investments will also increase the technological competence of Türkiye in this field.

5.

Conclusion

Despite continuous progress in CCUS technologies, the main issue appears to lie in the implementation of these technologies. As investments accelerate, further technological advancements and cost reductions are already expected. Nevertheless, it is clear that the biggest obstacle lies in the development of business models and securing financing. Therefore, significant steps need to be taken, especially in the development of carbon utilization areas, to demonstrate the feasibility of these technologies. It is observed that the investment capital (CAPEX) costs of large-scale (1 – 1.5 Mt CO₂/year) carbon capture projects from point sources (this value corresponds to the annual CO₂ emission value of an average-sized cement factory) start from €400 – 500 million. In the absence of government support and incentive mechanisms for investments of this magnitude, it is very difficult for the sector to bear these costs alone. Moreover, a significant portion of the carbon captured in these projects needs to be stored, yet there is no comprehensive study on suitable storage sites in Türkiye. In addition, implementing a CCUS project in Türkiye would be first of its kind, carrying high technological and financial risks. Minimizing these risks requires the development of the ecosystem, market preparation, ecosystem training, technology testing, and the creation of techno-economic parameters. Therefore, it is crucial to implement projects in this field as soon as possible, with a focus on conducting technical feasibility studies as a priority.

In addition, the adoption of carbon pricing mechanisms such as ETS or national carbon taxes and the utilization of financial structures such as tax incentives and subsidies, as well as the establishment of regulatory and administrative infrastructures, are of great importance for the success of CCUS applications. The implementation of a national ETS, along with the establishment of trade regulations and international standards in alignment with the Carbon Border Adjustment Mechanism (CBAM), could impose cost burdens on carbon-emitting businesses, thereby encouraging the realization of CCUS and carbon removal projects.

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PIONEER PROJECT PROGRAM

CARBON CAPTURE, UTILIZATION AND STORAGE (CCUS) AND CARBON DIOXIDE REMOVAL (CDR) SOLUTIONS WITH THE POTENTIAL TO CREATE ECONOMIC VALUE

DEEP DIVE STUDY - **SUMMARY**



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