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Review Article

Carbon capture in the iron and steel industry

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ABSTRACT

About 7–9% of all CO_2 emissions come from the iron and steel sector, making it one of the most carbon-intensive industries in the world. Carbon Capture, Utilization, and Storage (CCUS) is a viable and promising decarbonization strategy that is especially suitable for existing infrastructure. The most developed and extensively used technique at the moment is post-combustion capture with amine-based solvents. The practicality of CCUS applications in steel production is shown by successful commercial projects like Steelanol in Belgium and Al Reyadah in the United Arab Emirates. High capital and operating costs, energy-intensive procedures, solvent degradation, and the requirement for extensive CO_2 transport and storage infrastructure are some of the major obstacles to wider adoption. Despite these obstacles, in countries with production in emission-intensive sectors, have a lot of potential for CCUS deployment—as long as funding sources, supportive laws, and technical assistance are put in place.

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SUMMARY

The iron and steel sector is an energy-intensive sector, accounting for around 7-9% of global carbon emissions. Blast furnace (BF) and basic oxygen furnace (BOF) methods in particular are the highest emission sources, emitting 2.33 tons of CO_2 per ton. Alternative methods such as Electric Arc Furnaces (EAF) offer lower emissions (0.65-1.37% CO_2/ton of steel). With 70% of emissions coming from the blast furnace, iron production should be in focus. CCUS technologies aim to capture, transport, and store/utilize CO_2 before it is released into the atmosphere. Capture methods include chemical absorption (most common), adsorption (PSA/TSA), membrane separation, and cryogenic separation [1]. Progress of CCUS technology in the iron and steel industry and the suggestion of the integrated application schemes for China. Captured CO_2 is transported by pipeline, tanker, or ship. Storage is provided by geological formations or mineral carbonates, while utilization (CCU) involves the conversion of CO_2 into fuels, chemicals, and building materials [2]. Countries such as the EU (2050), China (2060), and India (2070) have also set low-carbon roadmaps. Organizations such as the IEA and Worldsteel emphasize CCUS as a strategic tool. The feasibility of CCUS presents challenges such as high costs, energy needs, and process integration. A plant with a capacity of 1 million tons of CO_2 costs $300-500 million. Existing examples include pilot projects such as Emirates Steel (UAE), Arcelor-

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Mittal (EU), COURSE50 (Japan) and POSCO (Korea). Despite the 2.6 Gt CO_2 emission potential of the steel sector on a global scale, only a few million tons can be captured today [3]. Although CCUS technologies have a high potential for developing and underdeveloped countries where iron and steel industry production is carried out, which is one of the priority sectors with high emissions and high energy consumption, implementation requires legislation, financing, and technical infrastructure. CCUS is of strategic importance in the future, especially for irreducible emissions [4].

Highlights

- With around 7–9% of world emissions, the iron and steel sector is a significant CO_2 emitters.
- Particularly by post-combustion capture with amine-based solvents, CCUS technologies provide a reasonable decarbonizing path.
- Commercial models showing its viability are Al Reyadah and Steelanol. When support mechanisms are planned for nations or companies that cause high carbon emissions, satisfactory results can be obtained despite the high costs and sophisticated infrastructure requirements of carbon capture technologies.

INTRODUCTION

The contemporary global employment scenario of the iron and steel sector reveals a substantial workforce, with approximately 6 million individuals directly employed in this sector worldwide. This sector's economic impact is equally significant, generating an annual income of approximately 2.5 trillion US dollars [5]. Steel is considered a strategic product, providing input to numerous fundamental sectors, including the automotive, construction, transport, energy and machinery industries. It is therefore considered an indispensable part of the global economic structure [6].

The advent of technological developments has led to a substantial enhancement in energy efficiency during the steel production process. Over the past five decades, there has been a significant decrease in the energy consumed per tonne, with a reduction of approximately 60% being observed. Nevertheless, despite these advancements, the sector continues to exhibit considerable untapped potential for further energy savings [7]. However, despite advances in energy efficiency, the iron and steel sector remains a significant source of global greenhouse gas emissions, hence the need for advanced technologies to reduce these emissions remains urgent. In this context, Carbon Capture, Utilization, and Storage (CCUS) technologies, which play a critical role in the sustainable transformation of carbon-intensive industries, stand out.

CCUS Technologies

Carbon Capture, Utilization and Storage (CCUS) refers to a range of technologies designed to capture carbon dioxide (CO_2) emissions from large industrial sources or directly from the atmosphere, then use the captured CO_2 or store it safely underground to prevent its release into the atmosphere and mitigate climate [8].

CCUS (Carbon Capture, Utilization, and Storage) technology, which consists of CO_2 capture, transportation, and end-use or storage processes, starts with the separation of CO_2 from the air, primarily from high-emission sources such as steel, cement, refineries, and power plants or by direct air capture (DAC) methods. The captured CO_2 is condensed under pressure and transported to the use or storage sites by transportation methods such as pipelines, ships, rail, or trucks. It can be used as feedstock in industrial raw materials (fertilizers, chemicals, synthetic fuels, building materials) or enhanced oil recovery (EOR) applications, or it can be injected into deep geological formations such as depleted oil-gas reservoirs or brine aquifers, providing long-term safe storage. CCUS technology is considered imperative by the IPCC and IEA to achieve global net zero targets by 2050. It is critical in decarbonizing carbon-intensive "hard-to-reduce" sectors such as steel, cement, and chemicals. In addition, by integrating BECCS (CCUS with biomass energy) or direct air capture, "negative emissions" can be achieved by the net removal of CO_2 present in the atmosphere. Today, around 29 operations worldwide have reached a total capacity of 40 million tons of CO_2 sequestration per year, and more than 100 projects are at different scales and stages of development [9,10].

LITERATURE

Overview

The iron and steel sector has been observed to demonstrate a high energy intensity structure, and it has been determined that it ranks second after electricity generation in terms of coal consumption [11]. In the context of steel production, coke is utilised as the primary energy and chemical input in blast furnaces, accounting for approximately 75% of the total energy consumption in these furnaces [11]. Carbon dioxide (CO_2) is responsible for 90% of global industrial greenhouse gas emissions, with 11% of these emissions being directly attributable to the iron and steel sector [12]. As of 2022, the average emission of carbon dioxide (CO_2) amounted to 1.41 tonnes for each tonne of steel produced. In addition, indirect emissions resulting from the utilisation of electricity, imported heat and by-gases reached approximately 1.1 gigatonnes of CO_2 per year [10]. Consequently, the sector is responsible for approximately 25% of industrial emissions and 7% of energy system-related emissions, with a total annual emissions output of approximately 2.6 gigatonnes of CO_2 [3].

Current CCUS Technologies

Increasing CO_2 emissions as a result of human and industrial activities seriously threaten both human health and the balance of the ecosystem. Especially in energy-intensive sectors such as steel, aluminum and cement, high amounts of emissions are released and they have become responsible for climate change. Therefore, it is critical to reduce these emissions and ensure good carbon management.

Carbon capture, utilisation and storage (CCUS) is an innovative technology that involves capturing and storing or utilising carbon by various methods before it is released into the atmosphere. Carbon can be captured in various ways, including pre-combustion, post-combustion and oxygenated combustion [1]. It can then be stored long-term in salt or oil fields. Carbon capture technologies, the graph of which is given in Figure 1 and some characteristics in Table 1, are as follows:

Pre-combustion carbon capture: In this technique, CO_2 is removed from fossil fuel or fuel to be used before combustion takes place. The fuel is converted into CO, H_2 and syngas, usually through a gasification process. Syngas plays a role in synthesizing green fuels and generating electricity. The separation of CO_2 from syngas is achieved by i) selexol process, ii) purisol process, iii) rectisol process and iv) morphysorb process. The advantage of these processes is the low energy requirement, while the disadvantage is the decrease in thermal efficiency and increase in operating costs due to the first cooling and then heating of the synthesis gas. New studies are aimed at reducing these disadvantages [13,14].

Post-combustion carbon capture: In this technique, normal combustion takes place and gases of carbon and other components are released. In this flue gas, CO_2 is separated by separation processes. Once captured, the CO_2 is compressed into liquid form and transported to storage sites, where it is usually stored for long periods in old oil fields or salt reserves. For carbon capture from flue gas, i) solvent-based absorption, ii) adsorption-physical separation, iii) membrane separation, iv) chemical and calcium cycle washing and v) cryogenic methods are used. Since this system is designed in addition to the existing process, its applicability is higher and its cost is relatively lower, so it is a more preferred mature method [13,14].

Oxy-fuel combustion capture: In this technique, combustion takes place with pure oxygen and not with air. For this, nitrogen is removed from the air. The flue gas produced as a result of pure oxygen combustion contains a high percentage of CO_2. From the flue gas released, CO_2 gas is obtained as a result of a number of condensations, separation and compression processes. Since this technology requires large amounts of pure oxygen, energy consumption and operating costs are quite high [13,14].

Absorption Technology

Given that Figure 2, the absorption method is based on the physical or chemical capture of CO_2 in flue gas by contacting it with a liquid solvent. Liquid phase chemical absorption, especially the so-called reactive absorption, is the most common and effective technique for CO_2 removal. In this process, CO_2 is captured by chemical reactions in the liquid by gas-liquid contact in an absorption tower operating at 40-60 °C; the enriched solution is then heated to 120-140 °C with a heat exchanger and transferred to the desorption tower and CO_2 is liberated under hot steam. The purified liq-

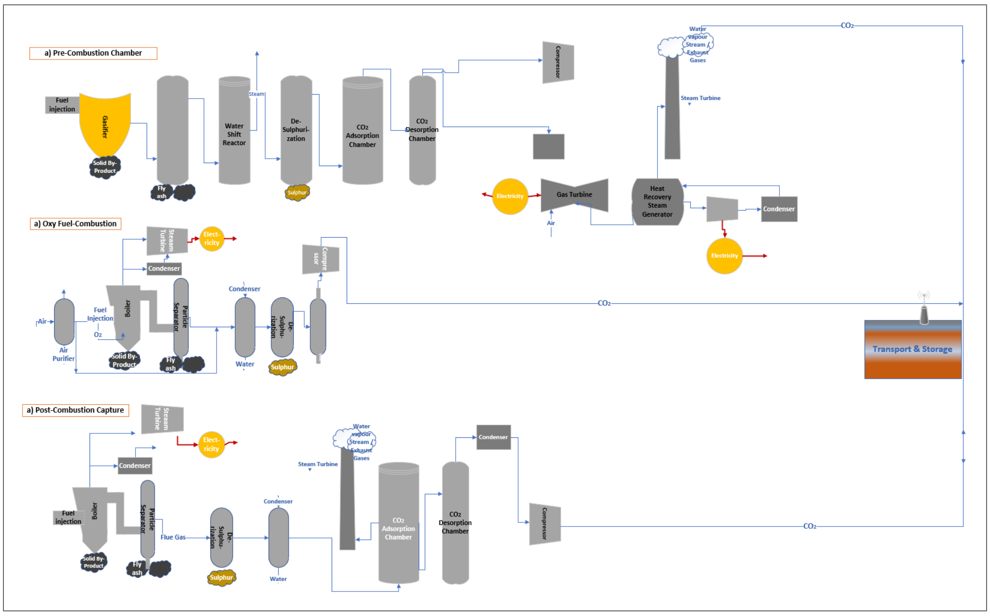


Figure 1. Carbon capture technologies, **(a)** pre-capture, **(b)** oxyfuel combustion, **(c)** post-capture [13]. (changed)

Table 1. Some characteristics of carbon capture technologies [13].

Characteristics	Pre-combustion carbon capture	Post-combustion carbon capture	Oxy-fuel combustion carbon capture
Methods of carbon capture	Conversion of synthesis gas into CO and H_2 and capture of CO_2 before combustion.	The potential for separation of CO_2 from flue gas after fuel combustion is low.	It is the separation of CO_2 from the flue gas containing high levels of CO_2 as a result of combustion with pure oxygen.
Conditions of operation of carbon capture chamber	High pressure requirement (20-30 bar)	Low pressure requirement (0.15-1 bar)	Low pressure requirement (~1 bar)
Compatibility with industrial systems	Industrial systems need to be designed first and foremost, they are less adaptable.	Easily integrated into existing systems.	Air separation systems need to be designed, less compliant.
Cost of investment	Expensive due to redesign and synthesis gas production.	No redesign is required, only installation costs.	High cost for obtaining high purity oxygen.

uid is sent back to the absorption tower in a cyclic process [2]. Amine-based solvents-especially monoethanolamine (MEA)-are favored in reactive sorption due to their high selectivity, large capacity, and thermal/chemical stability [15]. However, intensive studies on solvent optimization and alternative reaction mechanisms have been carried out in recent years to reduce the high energy requirement in the desorption stage. In addition, CO_2 capture projects in the iron and steel sector are being developed based on absorption technology in different countries, and pilot applications are planned for the commercialization stage.

Common Solvents Used in Absorption Technology

Although monoethanolamine (MEA) has been widely used in post-combustion CO_2 capture processes in the steel industry for many years, it offers limited efficiency in this field due to its high regeneration energy (3.5-4.0 GJ/tCO_2) and corrosion problems. To overcome these limitations, secondary and tertiary amines, such as methyl diethanolamine (MDEA), piperazine (PZ) and MDEA/PZ mixtures have been developed. These solutions offer higher CO_2 absorption capacity and lower regeneration energy (2.0-2.7 GJ/tCO_2) compared to conventional MEA, while significantly reducing corrosion [16,17]. Moreover, new amine-based solvents formulated specifically for the steel industry minimize amine degradation and solvent losses by improving thermal and chemical stability; thus, CO_2 capture efficiencies of over 90% can be achieved [16–18]. Ammonia-based solvents have been the subject of research, especially in removing CO_2 in coke oven gases. Aqueous ammonia solutions are notable for their lower regeneration energy requirement, low cost, and reduced corrosion potential compared to MEA. Furthermore, the ability to utilize medium and low-temperature waste heat streams in steel plants improves process economics. However, the high evaporation tendency of ammonia and solvent loss-

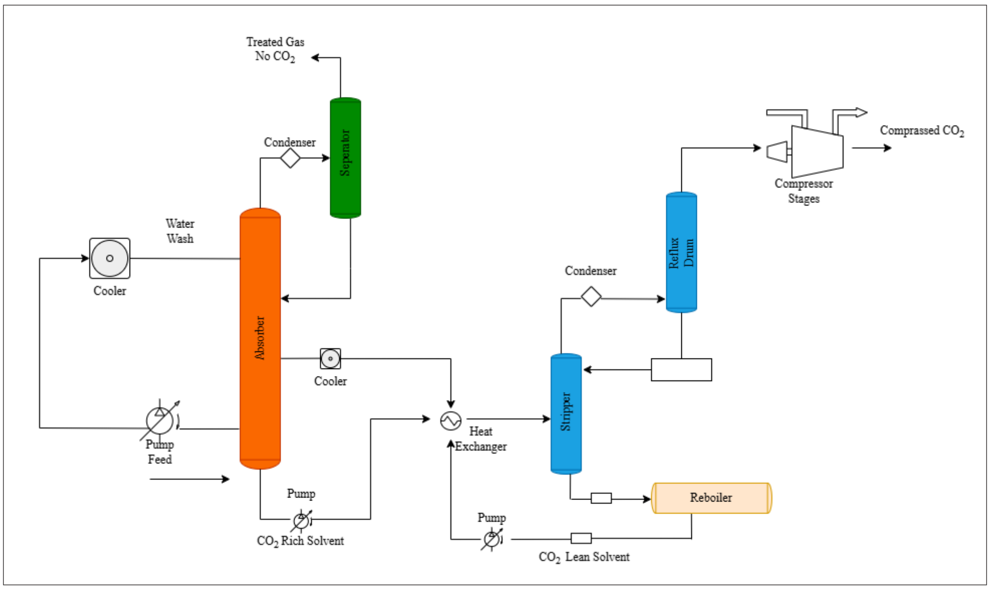


Figure 2. Flow chart of chemical absorption.

es through diffusion to the outside are the main challenges limiting the efficiency of the application [16]. In order to overcome these challenges, intensive studies on closed circuit designs, ammonia recovery technologies, and modified absorber-desorber configurations have been carried out.

Proprietary solvent technologies also offer high-performance solutions for the steel industry. For example, Carbon Clean's APBS-CDRMax® formulation requires 20-30% lower energy input compared to conventional amine systems and reduces investment costs by providing long solvent life and reduced equipment size. Furthermore, these solvents improve the quality of recovered combustible gases by increasing CO and H_2 concentrations in the gas stream after CO_2 removal, resulting in additional efficiency gains in integrated energy recovery cycles [18]. The comparison of commonly used chemical solvents is as shown in Table 2.

Adsorption Technology In CO_2 Capture For The Iron and Steel Industry

Adsorption is an important method used for CO_2 capture in various industrial sectors, including the iron and steel industry. This technology relies on the ability of certain materials (adsorbents) to selectively trap CO_2 molecules on their surfaces. The two main types of adsorption processes are Pressure Swing Adsorption (PSA) and Temperature Swing Adsorption (TSA). Among these, given that Figure 3, PSA has gained more attention due to its relatively low energy requirements, flexibility under different pressure and temperature conditions, and ease of operation. However, its large-scale application in the steel industry is still under development [19].

In PSA systems, gas mixtures are passed through columns packed with solid adsorbents. These materials selectively bind CO_2, while other gases like nitrogen, hydrogen, or carbon monoxide pass through. Once the adsorbent becomes saturated, it is regenerated by lowering the pressure, allowing the CO_2 to be released and collected. Key to the efficiency of this process is the choice of adsorbent, which must offer strong selectivity for CO_2, high capacity, good thermal and mechanical stability, and the ability to be regenerated many times without degradation. A notable example of PSA application is seen in Japan's COURSE50 project, where a two-stage PSA system was developed for CO_2 recovery from blast furnace gas [20]. In this system, the gas is first cleaned and then directed through PSA units for CO_2 separation. Although specific performance data is not fully disclosed, the system was able to recover a significant portion of CO_2 at a reasonably high purity level. The adsorbent used was a modified type of zeolite, a porous mineral material known for its strong affinity for CO_2. In China, another PSA-based system was implemented to capture CO_2 from lime kiln flue gases. The recovered CO_2 is reused within the steel production process, reducing the need for other gases like argon and nitrogen. This not only reduces pollutants but also enhances cost-efficiency within the facility [21].

PSA systems are also often paired with Top Gas Recycling Blast Furnace (TGR-BF) technologies. In this approach, the gas emitted from the top of the blast furnace, which contains CO_2 along with valuable reducing gases such as CO and H_2, is processed to separate and recycle

Table 2. Solvent comparison table

Solvent category	Examples	CO_2 capture effiency	Regeneration energy (GJ/tCO_2)	Advantages	Disadvantages
Amine solvents	MEA (traditional) MDEA, PZ, MDEA/PZ blends Specialized steel-grade amines	MEA: <80–90% Advanced: >90%	MEA: ~3.5–4.0 Advanced: 2.0–2.7	-High CO_2 absorption capacity (especially with PZ) -Lower corrosion in advanced blends -Improved thermal & chemical stability	- High energy demand and corrosion with MEA - Amine degradation & solvent losses (traditional)
Ammonia solvents	Aqueous NH_3	Typically ≥85% (process-dependent)	~1.8–2.2 (using waste heat)	- Low regeneration energy - Integration with plant waste heat - Less corrosive & lower cost	- High volatility and solvent losses - Requires NH_3 emissions control
Proprietary technologies	APBS-CDRMax® (e.g., Carbon Clean)	>90%	~1.5–2.0	- Very low energy requirement - Long solvent life & low degradation - Smaller equipment footprint & CAPEX savings - Enriched CO/H_2 off-gas for reuse	- Higher licensing/ supply costs - Access restrictions due to proprietary nature

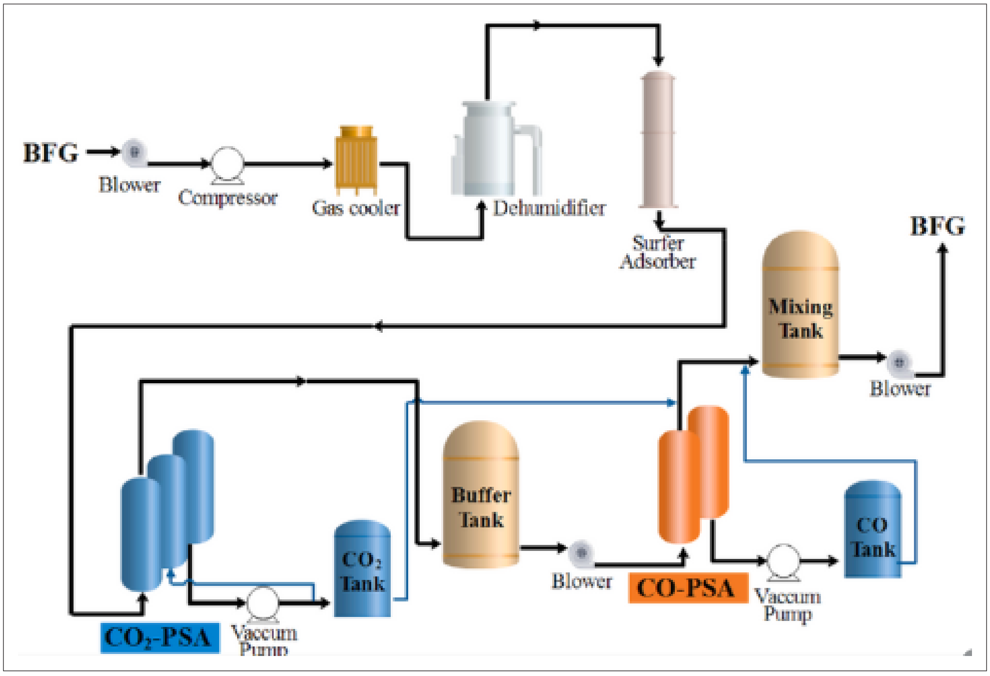


Figure 3. Flow chart of PSA process.

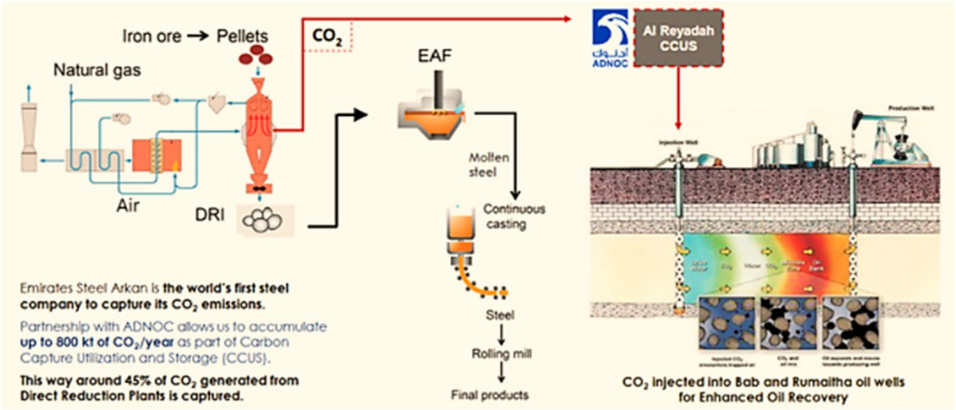
these components. The recycled CO and H_2 are returned to the furnace, reducing the demand for coke and lowering overall CO_2 emissions. Trials in Europe and China have shown that this method can significantly reduce carbon emissions, though full-scale commercial adoption is still progressing.

The performance of PSA systems heavily depends on the properties of the adsorbent materials. Zeolites, due to their high surface area, strong CO_2 binding capacity, and structural stability, are among the most studied. However, standard zeolites can have limitations, especially when exposed to industrial conditions involving high humidity, varying gas compositions, and temperature fluctuations. To overcome these limitations, researchers have explored various modification techniques. For example, amine-functionalization—where amine groups are added to the surface of the zeolite—has been shown to enhance CO_2 capture by promoting chemical interactions with CO_2 molecules. Similarly, impregnating zeolites with ionic liquids can improve selectivity and capacity, though these methods are still being refined and tested in controlled environments [22]. Ion exchange is another promising approach, where different metal ions are introduced into the zeolite structure to improve its affinity for CO_2 over other gases. Additionally, hybrid materials—combinations of zeolites with polymers or metal oxides—have been developed to improve overall performance. While these materials have shown improved CO_2 adsorption properties in laboratory settings, challenges remain in translating these results to real-world industrial applications. Large-scale production, long-term stability, cost-effectiveness, and resistance to impurities in the gas stream are all important factors that need to be addressed before widespread adoption [23].

Corrosion in CO_2 Capture Processes

Corrosion in CO_2 capture processes can vary significantly depending on the capture technology used. These technologies are generally categorized based on the combustion stage into three types: pre-combustion, post-combustion, and oxy-fuel combustion. Each method presents different corrosion risks and equipment durability concerns. Pre-combustion capture, commonly used in Integrated Gasification Combined Cycle (IGCC) systems, involves reacting coal with steam under high-pressure, oxygen-enriched conditions to produce a gas mixture mainly consisting of hydrogen and carbon monoxide. This mixture undergoes a catalytic shift reaction to form CO_2 and hydrogen. CO_2 is then removed using physical absorption, a method that operates at low temperatures and high pressures. This approach offers advantages such as high absorption capacity, no need for absorbent regeneration heating, and minimal corrosion, making it suitable for pre-combustion systems [24].

Post-combustion capture targets CO_2 in flue gases after fossil fuel combustion. The most widely applied method is chemical absorption, typically using solvents like ammonia, hot potassium carbonate, and especially monoethanolamine (MEA). MEA is one of the most established CO_2 capture agents. However, this method has several drawbacks, including high energy demands, solvent losses, and significant equipment corrosion due to acidic by-products formed during the process, especially in amine-based systems. In oxy-fuel combustion, fossil fuels are burned in



Emirates Steel Arkan is **the world's first steel company to capture its CO_2 emissions.**

Partnership with ADNOC allows us to accumulate **up to 800 kt of CO_2/year** as part of Carbon Capture Utilization and Storage (CCUS).

This way around 45% of CO_2 generated from Direct Reduction Plants is captured.

CO_2 injected into Bab and Rumaitha oil wells for Enhanced Oil Recovery

Figure 4. Al Reyadah CCUS plant [26].

pure oxygen, producing a flue gas composed primarily of CO_2 and water vapor. Upon cooling and condensation, nearly pure CO_2 can be obtained and subsequently stored or transported. CO_2 separation in this method typically relies on adsorption and membrane technologies.

Three Alternative Approaches to Carbon Reduction in Steel Production

There are many alternatives for reducing carbon emissions in the iron and steel industry The Strategic Research and Innovation Agenda (SRIA) document published by the Clean Steel Partnership (CSP) is based on the following 3 key technologies.

Direct carbon emission avoidance strategies: The aim of this technology is to promote and develop steel production in the iron and steel industry without the use of fossil fuels. Examples include the production of H_2-DRI-EAO using green hydrogen and the integration of electricity from renewable sources into the process.

Smart carbon utilization strategies: This technology involves process optimization, carbon capture, utilization and storage, and process optimization without radical changes to the steelmaking processes already in operation [25]. Al Reyadah, the first CCUS plant established in the steel industry, schematically shown in Figure 4, produces steel with an electric arc furnace, while the CO_2 generated is captured and stored in oil fields [26]. The investment cost of this plant is approximately \$122 million and approximately 800 thousand tons of CO_2 is adsorbed.

Circular economy practices: In steel production, the waste heat intensity from flue gases is quite high. This waste heat can be reintegrated into the process through certain transformations. This reduces energy consumption and therefore carbon emissions. In addition, if the slags generated during steel production are melted and used in the process in the same way, the amount of raw material is reduced and a contribution to the circular economy is made [27].

COMMERCIAL-SCALE CCUS PROJECTS

Al Reyadah CCUS

In the Mussafah region of Abu Dhabi, Emirates Steel, in partnership with ADNOC and Masdar, has been operating the world's first commercial-scale steel CCUS plant since 2016. An amine-based process captures 800,000 tons of CO_2 annually from reduced iron flue gas, which is injected into nearby oil fields for Enhanced Oil Recovery, significantly reducing the plant's net emissions [28,29].

Steelanol (ArcelorMittal Gent & LanzaTech)

Inaugurated in late 2022 in Ghent, Belgium, with an investment of around €180-200 million, this plant converts blast furnace gas into 80 million liters of ethanol (Carbalyst®) per year thanks to LanzaTech›s microbial fermentation technology, thus avoiding CO_2 emissions of around 125 000 tons per year. The first commercial production of ethanol was realized in 2023 and expansion work is underway to bring the plant to full capacity [[30].

Gary Works CCU (SkyCycle™)

U.S. Steel's plant in Gary, Indiana, USA, will use CarbonFree's SkyCycle™ technology to capture 50,000 tons of CO_2 annually from blast furnace gas, and this CO_2 is precipitated and mineralized as calcium carbonate (calcite). Hydrochloric acid (HCl) is obtained as a by-product in this process. The plant is scheduled to be operational in 2026 [31,32].

CONCLUSION

The iron and steel industry remains one of the most carbon-intensive sectors worldwide, contributing approximately 2.6 gigatonnes of CO_2 emissions annually—about 7% of total global energy-related emissions. This is primarily due to the sector's reliance on coal-based technologies such as the Blast Furnace–Basic Oxygen Furnace (BF–BOF) route, which requires high-temperature processes and fossil fuels as reductants. While steel is a critical material for global development, addressing its environmental impact is essential for meeting international climate goals and achieving carbon neutrality.

Carbon Capture, Utilization, and Storage (CCUS) has emerged as one of the most promising short- to medium-term decarbonization solutions for the steel sector. Unlike more disruptive measures such as full electrification or fuel switching, CCUS can be retrofitted onto existing infrastructure, enabling continued steel production while significantly reducing CO_2 emissions. Among the various capture technologies, post-combustion systems—particularly those based on amine solvents—are the most mature and readily deployable. Commercial-scale demonstrations such as the Steelanol project in Belgium and Al Reyadah in the UAE highlight the feasibility of CCUS in real industrial settings. However, the adoption of these systems remains limited due to several technical and economic challenges, including the high energy penalty of solvent regeneration, solvent degradation, process integration issues, and the lack of supporting infrastructure for CO_2 transport and storage.

In light of these findings, several key actions are recommended. First, government support through well-designed incentive mechanisms is essential to drive CCUS deployment. This includes the implementation of carbon pricing, tax credits, and direct funding for demonstration projects. Simultaneously, the development of national and regional CO_2 transport and storage infrastructure must be prioritized to ensure that captured emissions can be permanently sequestered or utilized effectively. Continued investment in research and development is also crucial—particularly in advancing low-energy solvents, solid sorbents, membranes, and hybrid capture systems that can reduce operational costs and improve system performance.

Furthermore, CCUS should be viewed as a component of a broader, integrated decarbonization strategy rather than a stand-alone solution. It should be implemented alongside complementary approaches such as the use of green hydrogen in Direct Reduced Iron (DRI) processes, the integration of biomass-based reductants, and the promotion of circular economy strategies like increased steel recycling through Electric Arc Furnace (EAF) technologies. Knowledge sharing and capacity building across the global steel industry will also be critical to overcoming barriers and accelerating adoption, especially in developing countries where steel demand continues to grow.

As a result, the most suitable method for achieving satisfactory results in the use of carbon capture technology in the iron and steel industry is post-combustion carbon capture technology. Looking at studies conducted using this method, the carbon capture process with the highest efficiency is the amine-based carbon capture process. This method can be integrated without disrupting the established operations of businesses, thus not harming the sector's production and allowing for rapid adaptation. The captured carbon can be actively used in sectors such as construction, chemistry, and energy.

In conclusion, while deep decarbonization of the iron and steel sector is undeniably complex, the strategic implementation of CCUS offers a viable and impactful path forward—particularly when integrated with parallel innovations and supported by coordinated policy, infrastructure, and investment frameworks. By embracing a systems-level approach that combines capture technologies with clean energy inputs, material efficiency, and industrial collaboration, the steel sector can play a vital role in building a climate-resilient and sustainable global economy.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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Review Article

The role of CCUS technologies in electricity generation: A comparative analysis of Türkiye and the World

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ABSTRACT

The share of renewable energy sources in electricity generation is increasing day by day. However, being an intermittent resource, it is not enough to completely end the use of fossil fuels. In the current situation, the use of fossil fuels continues, but the amount of carbon they release into the air during combustion is at a point that cannot be ignored, and carbon capture, storage and transportation technologies gain importance at this stage. In this study, examples of Carbon Capture, Utilization, and Storage (CCUS) technologies used in the electricity generation sector in the world and in Türkiye are examined. The CCUS techniques used in the plants and the working principle of these techniques are mentioned. The efficiency of the plants before and after CCUS is analyzed according to the fuels used. The situation in Türkiye and the world is analyzed technically, economically and politically and the potentials are evaluated. According to the data obtained, it is seen that the use of amine-based carbon capture technology (monoethanolamine (MEA)) is more appropriate in the electricity generation sector. Carbon capture from flue gas after combustion has been found to slightly reduce the total system efficiency. As a result, in addition to the few examples in the world, the applications in Türkiye are at the pilot stage and it is seen that there is already a high potential for carbon capture when the installed natural gas and coal plants are considered.

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INTRODUCTION

Electricity generation, as a key pillar of modern economies, is one of the main contributors to global carbon dioxide (CO_2) emissions, primarily due to its heavy reliance on fossil fuels. Approximately 40 % of global CO_2 emissions stem from fossil fuel combustion in power plants [1]. While renewable energy investments have grown, fossil fuels still maintain a significant share in both global and national energy portfolios, including Türkiye. For instance, in 2024, coal and natural gas accounted for over 50% of Türkiye's electricity generation.

The deployment of smart electricity grid technologies has the potential to reduce these emissions. Carbon Capture, Utilization, and Storage (CCUS) technologies play a

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critical role to reduce these emissions. CCUS applications in the electricity sector include the processes of capturing, transporting and safely storing emissions at source. The electricity generation sector plays a critical role in terms of energy supply security, economic growth and technological transformation both on a global scale and in Türkiye.

At global and national level, the electricity generation sector has a strategic importance in terms of energy security and economic development. Increasing investments in renewable energy sources contribute to diversifying the energy portfolio and reducing external dependence. However, the still significant share of fossil fuels requires careful and balanced management of the energy transition process. This information provides a basic framework for understanding the current state and future potential of the electricity generation sector. Keeping abreast of developments in the sector is important for the effectiveness and sustainability of energy policies. In 2024, data released by the Turkish Ministry of Energy and Natural Resources indicated that electricity generation in Türkiye was composed of 35.2% coal, 18.9% natural gas, 21.5% hydraulic energy, 10.5% wind, 7.5% solar, 3.2% geothermal, and 3.2% other sources.

While the transition to renewables is accelerating, fossil fuels still dominate electricity generation in many countries, making emission mitigation technologies like CCUS essential for reaching climate The Paris Agreement aims to limit the increase in global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit it to 1.5°C [2]. Achieving this goal requires global carbon emissions to reach net zero by 2050. However, given the current energy infrastructure and the continued reliance on high-carbon industrial processes, renewable energy and energy efficiency technologies alone appear insufficient to meet this target. In this context, carbon capture, utilisation and storage (CCUS) technologies play a crucial role, particularly in emission-intensive sectors such as electricity generation.

To achieve net-zero targets, substantial reductions in emissions from the energy sector and energy-intensive industries such as cement, iron and steel, and chemicals are essential. CCUS stands out as one of the few available solutions capable of directly capturing and reducing emissions from these sectors [3]. According to the International Energy Agency's (IEA) Net Zero by 2050 Roadmap, CCUS technologies are expected to account for approximately 15% of the total global CO_2 emission reductions required by mid-century, equivalent to about 7.6 billion tonnes annually. Furthermore, CCUS is seen as a key enabler in low-carbon hydrogen production, particularly in the form of "blue hydrogen" derived from natural gas [4].

The growing adoption of advanced carbon pricing mechanisms, such as the EU Emissions Trading System, is enhancing the economic viability of CCUS projects. However, in countries like Türkiye, where such mechanisms are not yet fully implemented, government incentives are critical to accelerate the deployment of these technologies.

Highlights

- The article analyzes the integration of Carbon Capture, Utilization, and Storage (CCUS) technologies within the iron and steel industry, addressing its role as a critical sector for global CO2 emission reduction.
- It provides a comprehensive assessment of various capture methods—pre-combustion, post-combustion, and oxy-fuel—comparing their technical efficiencies and economic feasibility for large-scale steel production.
- The study outlines necessary regulatory frameworks, infrastructure requirements, and strategic recommendations to overcome implementation barriers and achieve net-zero targets in the industry.

This study aims to examine the current status, challenges, and future potential of CCUS technologies in the electricity generation sector through a comparative analysis of Türkiye and global practices**.** The goal is to contribute to policy and investment strategies that align with both national energy security and international climate commitments.

LITERATURE REVIEW

Decarbonization of high-emitting sectors, such as the electricity generation sector, is vital in the fight against climate change. Around 40% of carbon dioxide (CO_2) emissions worldwide come from electricity generation, and this proportion is even higher in countries where fossil fuel-based systems such as coal and natural gas are predominant. In this context, carbon capture and storage (CCS) technologies offer a transition strategy that makes it possible to achieve climate goals without threatening security of energy supply by both continuing to use existing infrastructure and reducing carbon emissions. The main carbon capture technologies used in electricity generation include absorption, adsorption, membrane separation and cryogenic separation. These technologies can be applied at different stages such as pre-combustion, post-combustion and oxy-fuel, and are particularly preferred due to their high efficiency and ability to be integrated into existing infrastructure. Internationally, CCS investments have gained great momentum.

According to the Global CCS Institute (2024), there are 50 active plants and 44 new plants under construction worldwide, bringing the total number of plants to 628, an increase of 60% in one year. This growth is the result of government-backed policies, carbon pricing mechanisms and financial incentives. CCS technologies are generally classified into three main categories: post-combustion, pre-combustion and oxy-fuel combustion [5]. In addition, advanced and experimental technologies such as direct air capture (DAC), bioenergy carbon capture and storage (BECCS), and chemical loop capture (CLC) are gaining importance, especially for negative emissions targets [6-7]. CCS technologies in the electricity sector are categorized under four main headings to reduce CO_2 emissions: absorption, adsorption, membrane separation and cryogenic processes. Post-combustion capture technologies in particular stand out in terms of retrofit applicability to existing coal and natural gas power plants. Pre-combustion capture is mostly preferred in integrated gasification systems. Carbon mitigation strategies include the use of renewable energy, energy efficiency, carbon-free transportation and afforestation activities. In addition, innovative models for carbon management (e.g. Carbon Transport & Storage-as-a-Service - T&SaaS) facilitate access to CCS for small producers. Next-generation technologies such as BECCS (carbon capture and storage with bioenergy) and direct air capture (DAC) are increasing the solution capacity in the sector, especially for negative emission targets. The allocation of large-scale budgets for these technologies under the European Union's Horizon Europe program is also a critical incentive for investments.

Table 1 provides a comparative summary of literature studies on Carbon Capture and Storage (CCS) systems applied across various sectors, highlighting key aspects such as capture method, facility type, storage option, and annual CO_2 capture capacity, along with technical and economic evaluation approaches.

CARBON CAPTURE TECHNOLOGIES IN THE ELECTRICITY GENERATION SECTOR

Fossil fuel-based electricity generation remains one of the leading contributors to global carbon emissions. Accordingly, carbon capture technologies that aim to mitigate CO_2 emissions from power generation facilities have become a critical focus within the energy sector. As shown in Figure 1, carbon capture methods are broadly categorized into three main approaches: pre-combustion, post-combustion, and oxy-fuel combustion systems [8]. In addition to these conventional methods, advanced carbon management strategies such as Direct Air Capture (DAC), Bioenergy with Carbon Capture and Storage (BECCS), carbonate mineralization, carbon utilization, and geological storage have also been evaluated in recent studies as complementary or alternative solutions [5-7].

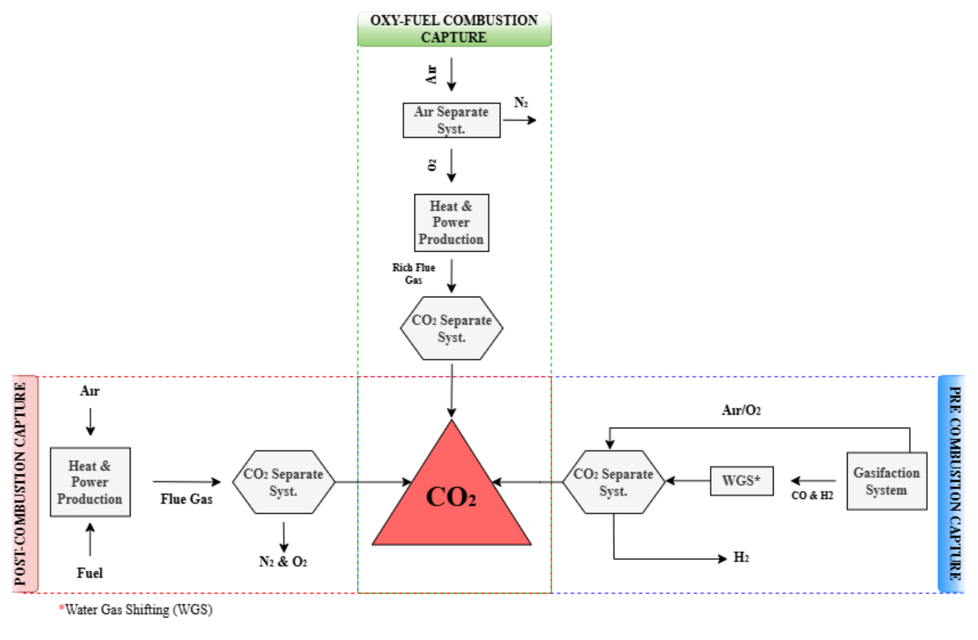
Conventional CO_2 Capture Methods

Pre-combustion capture

Pre-combustion carbon capture, particularly applied in Integrated Gasification Combined Cycle (IGCC) power plants, is based on the gasification of fossil fuels [8].The main advantage of this method lies in converting the fuel into synthesis gas (syngas) prior to combustion, which allows for more efficient separation of carbon dioxide from the system. In the process illustrated in Figure 2, in the initial stage, pure

Table 1. Studies reviewed

Pub. date	Authors	Facilty type	Review method		Capture method			Storage type	Captured CO_2 (tCO_2/yr)
			Tech.	Econ.	PCC	PrCC	OFC		
2021	Beiron, J. et al.	Energy Production	x	-	x	-	-	-	150K
2021	Reyes-Lúa, A. et al.	Oil Refinery	x	-	x	-	-	Geological Storage	0.48~1.44 M
2018	Sawada, Y. et al.	Hydrogen Production	x	-	x	-	-	Geological Storage	100K
2018	Zhang et al.	Energy Production	x	x	x	-	-	Geological Storage	8.44M
2016	Cormos, C.C	Energy Production	x	x	-	-	x	-	-
2016	Hetland, J. et al.	Energy Production	x	-	x	-	-	Geological Storage	-
2016	Yuan Wang	Energy Production	x	x	x	-	-	Geological Storage	-
2015	Rubin, S.E. et al.	Energy Production	x	x	x	x	x	Geological Storage	4.56M
2001	Byre, C. et al.	Energy Production	x	x	x	-	-	Geological Storage	-



*Water Gas Shifting (WGS)

Figure 1. Convantional carbon capture methods.

oxygen or oxygen-enriched air obtained from the air separation unit is fed into the gasification reactor, where it reacts with fossil fuel. This reaction results in a syngas primarily composed of carbon monoxide (CO), hydrogen (H_2), and water vapor (H_2O). The resulting gas is then cleaned via a cyclone unit to remove ash, soot, and other particulates. Subsequently, the CO and H_2O components in the syngas undergo a chemical reaction within a Water-Gas Shift (WGS) reactor, producing additional hydrogen (H_2) and carbon dioxide (CO_2). .This method offers high efficiency and energy recovery but is primarily feasible for newly constructed facilities [9]. Retrofitting costs and infrastructure requirements limit its integration into existing plants.

The chemical reactions that occur during this process are presented in Equations (1) and (2)

Water-Gas Shift Reaction:

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad (1)$$

Partial Oxidation and Gasification of Carbon:

$$2C + O_2 + H_2O \rightarrow H_2 + CO + CO_2 \qquad (2)$$

Oxy-fuel combustion

Oxy-fuel combustion technology involves burning fuel with pure oxygen instead of atmospheric air, resulting in a flue gas stream primarily composed of CO_2 and water vapor, significantly reducing nitrogen content and thereby simplifying CO_2 separation [10]. In this process, high-purity oxygen is first produced via an air separation unit (ASU) and subsequently reacts with the fuel in a controlled combustion environment. The resulting flue gas is then cooled and condensed to remove water vapor, leaving behind a CO_2-rich stream that can be captured at high purity [11].

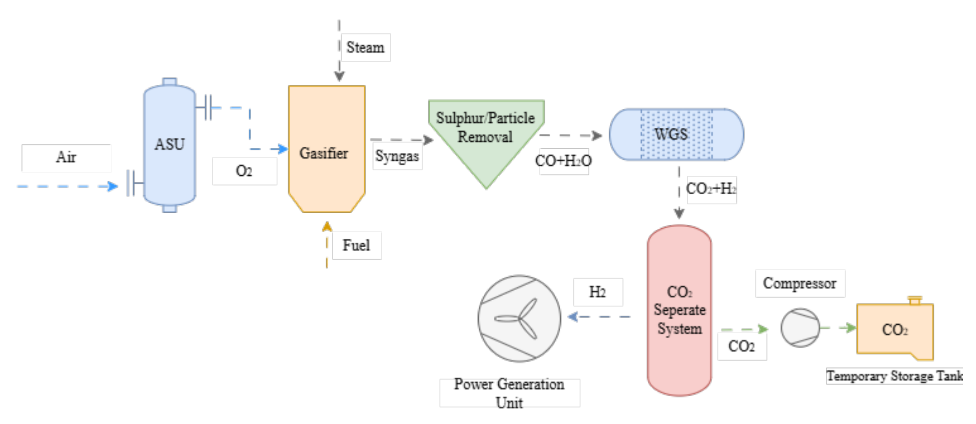


Figure 2. Pre-combustion capture method.

While this method facilitates the direct compression and storage of CO_2, it is also associated with significant energy consumption, primarily due to the operation of the ASU and the compression units such as pumps and compressors. Although integrated system designs in the literature indicate potential improvements in boiler efficiency, studies report an overall net efficiency penalty of up to 10% and a possible increase in electricity generation costs by as much as 70% compared to conventional systems [12]. Consequently, oxy-fuel combustion remains largely limited to specific coal- and natural gas-fired power plants, and is currently implemented at pilot or small-scale facilities, as identified in recent literature surveys.

Post-combustion capture

Post-combustion carbon capture is one of the most widely deployed technologies in fossil-fuel-based power generation facilities, aiming to prevent the release of CO_2 into the atmosphere by separating it from the flue gas after combustion [13]. In this method, the flue gas is contacted with chemical solvents that selectively interact with CO_2 in absorption columns prior to atmospheric release. Among the most commonly used solvents are amine-based compounds such as monoethanolamine (MEA), methyldiethanolamine (MDEA), piperazine, and AMP, which react with CO_2 to form carbamate-type intermediate compounds via covalent bonding [13-14].

In this study, a process example based on an MEA solution system is considered [8]. In the first stage of the process, the flue gas is cooled to approximately 40 °C to reach the absorption temperature. The cooled gas is then fed from the bottom of the absorption column with the help of a fan, while the amine solution is introduced from the top in a counter-current flow. As a result of the reaction between CO_2 and the amine, carbamate is formed (Equation 3):

$$2R{-}NH_2 + CO_2 \rightarrow R{-}NH_3^+ + R{-}NH{-}COO^- \qquad (3)$$

The saturated solution is subsequently transferred to a stripping column operating at 100–120 °C, where the CO_2 is released from the solvent by the application of heat, and the amine solution is regenerated for reuse in the system (Equation 4):

$$R{-}NH{-}COO^- + R{-}NH_3^+ + \text{heat} \rightarrow CO_2 + 2R{-}NH_2 \qquad (4)$$

Following regeneration, the recovered CO_2 is cooled to 40–45 °C, compressed to approximately 20 bar, and liquefied for temporary storage or transportation [15]. The efficiency and viability of this method depend on several factors, including solvent stability, the impurity level of the flue gas composition, and the overall energy requirement of the process. In cases where the flue gas contains high concentrations of SO_2, integration of a desulfurization unit is generally required to prevent amine degradation [16]. In retrofit projects, post-combustion carbon capture is considered one of the most commercially feasible options [17]. Its ability to be retrofitted into existing power plants makes it the most widely adopted carbon capture technique. The Boundary Dam project in Canada and the Petra Nova project in the United States serve as examples of large-scale implementations [18].

Next-generation carbon capture technologies (overview)

In recent years, alongside conventional methods such as pre-combustion, post-combustion, and oxy-fuel capture,

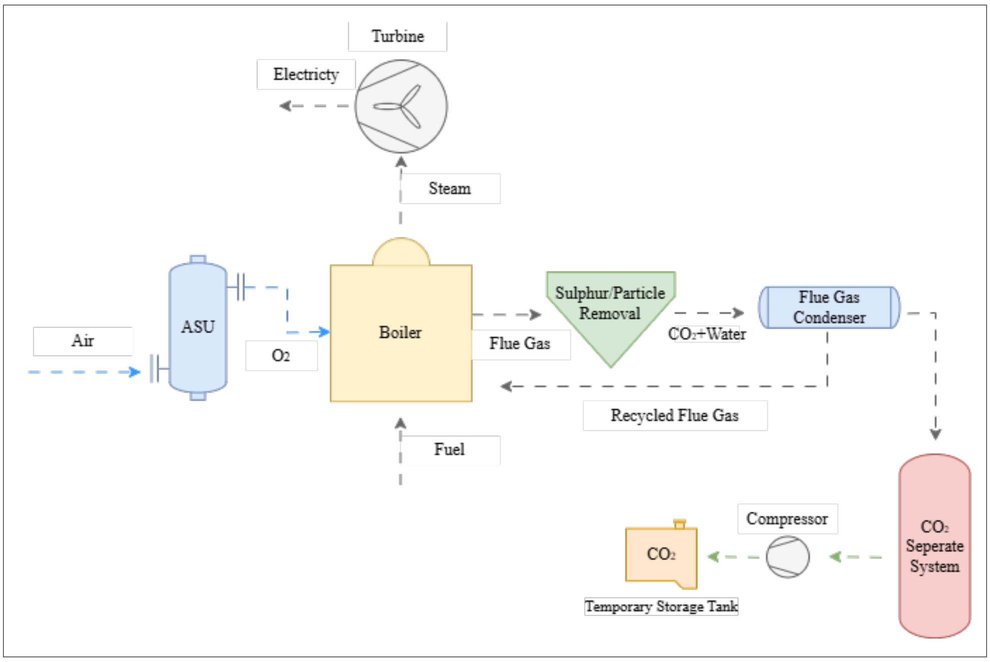


Figure 3. Oxy-fuel combustion capture method.

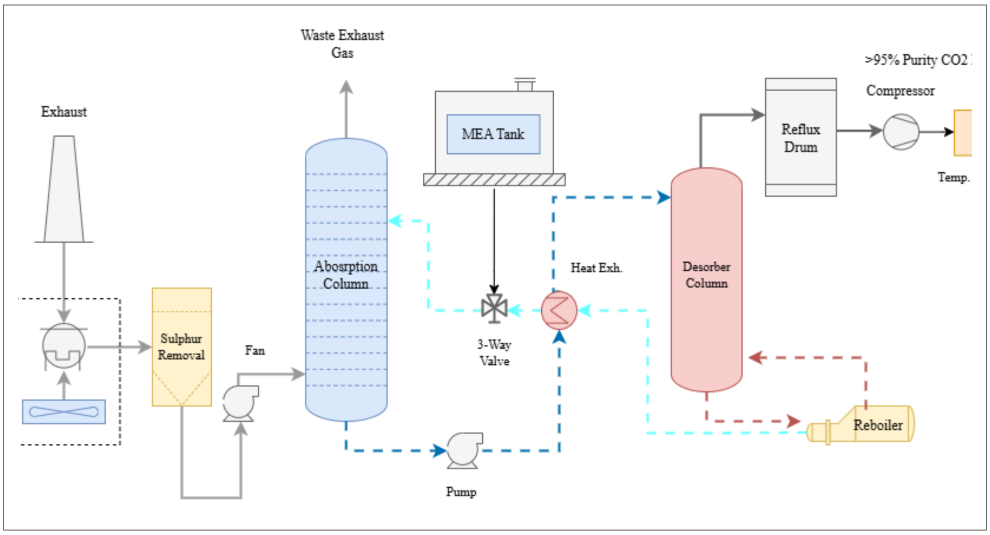


Figure 4. Flow chart of chemical absorption.

a range of next-generation carbon capture technologies have emerged. These approaches aim to address the energy and cost limitations of traditional systems, while offering enhanced flexibility and environmental compatibility. Although most are still at early development stages, their conceptual potential is noteworthy.

Chemical Looping Combustion (CLC)

CLC is an emerging combustion technology that enables inherent CO_2 separation by using solid oxygen carriers, thereby eliminating nitrogen from the flue gas. This results in a stream composed primarily of CO_2 and H_2O, simplifying downstream capture. While CLC offers thermodynamic advantages and high theoretical capture efficiency, it currently remains at the pilot scale due to technical and economic challenges [18-19]. These techniques remain in the research and development phase (Technology Readiness Level (TRL) 5–6) but hold promise for long-term carbon sequestration. Mineralization and geological storage offer significant opportunities for permanent carbon storage [20].

Membrane-Based CO_2 Separation

Membrane-based systems use semi-permeable materials to selectively separate CO_2 from flue gas without chemical solvents. These systems reduce environmental impact and maintenance costs; however, low gas pressures in power plants necessitate additional compression, increasing energy demand and limiting large-scale applicability [20-21].

Cryogenic CO_2 Capture

Cryogenic technologies separate CO_2 by cooling gas streams to very low temperatures, exploiting phase changes to isolate high-purity CO_2. Although suitable for streams with high CO_2 concentrations, their high energy consumption limits their feasibility in conventional flue gases from power plants [18-22].

Direct Air Capture (DAC)

DAC targets the separation of low-concentration CO_2 directly from the atmosphere using solid adsorbents or liquid solvents [6]; Despite its high energy consumption (5–11 GJ/ton CO_2), its ability to operate independently of emission sources is a key advantage. The Orca facility, operated by Climeworks in Switzerland, represents one of the first commercial DAC applications [23].

Bioenergy with Carbon Capture and Storage (BECCS)

BECCS combines CO_2 capture from biomass combustion with geological storage, enabling negative emissions [24]. It is one of the few technologies capable of removing carbon from the atmosphere. The Drax Power Station in the United Kingdom is a leading example of BECCS implementation [25].

Carbon Transport, Storage and Utilization

After the carbon capture stage, CO_2 must be conditioned for transport to suitable storage sites. Typically, the captured gas is converted into a supercritical phase, achieving a liquid-like density that facilitates both transportation and storage [8]. For large-scale CO_2 sources, pipeline transport is the most cost-effective and widely used method. Cryogenic tankers and ships are generally reserved for smaller volumes or geographically isolated storage locations. Transport costs typically account for 10–30% of the total CCS system costs, though this can be significantly reduced by repurposing existing natural gas infrastructure [18] For short pipelines (approximately 50–200 km), transportation costs average between \$1–5 per ton of CO_2 per 100 km [4]. Once delivered, CO_2 is primarily injected in supercritical form into geological formations such as depleted oil and gas reservoirs, deep saline aquifers, or unmineable coal seams [8]. The cost of storage depends on site-specific characteristics, but typically ranges from $1 to $15 per ton of CO_2. CO_2 is injected into geological formations, such as saline aquifers or depleted reservoirs, for permanent isolation [18]. The Gorgon Project in Australia exemplifies large-scale geological storage, injecting millions of tons of CO_2 annually as part of one of the world's largest CCS initiatives (Chevron Australia, 2024). As an alternative to geological storage, mineral carbonation offers a pathway for permanent sequestration by reacting CO_2 with naturally occurring rock minerals. The CarbFix project in Iceland is a notable demonstration of this approach, where CO_2 is mineralized by reacting with basalt formations, resulting in stable carbonate compounds [26]. In addition to storage, CO_2 utilization has gained attention as a complementary strategy for climate mitigation. Captured carbon can be converted into synthetic fuels or chemical products, such as through Fischer–Tropsch synthesis. The Norsk e-Fuel project in Norway exemplifies this pathway by integrating Direct Air Capture (DAC) with fuel production to create sustainable aviation fuel, showcasing a practical and value-added use of captured CO_2 [27].

International Projects

As of 2024, approximately 50 operational Carbon Capture and Storage (CCS) facilities worldwide successfully capture millions of tons of CO_2 annually [18]. However, economic feasibility, high initial costs, and scalability issues remain ongoing challenges (Table 2).

Table 2. Summary of CCUS Technologies International Projects

Project Name	Start/Features	CO_2 Capture (Annual)	Technology	Integration	Storage& Use	TRL Level
Boundary Dam (Canada)	First integrated CCS facility leading CCUS innovation	~1M	Amine-based solvents with post-combustion capture	Coal-fired power plant	Enhanced Oil Recovery (EOR)	9
Petra Nova (USA)	One of the largest carbon capture projects in the US	~1.4M	Amine-based solvents with post-combustion capture	Coal-fired power plant	EOR	9
Drax BECCS (UK)	Major negative emissions project aims for atmospheric CO_2 removal	Not specified	BECCS technology capturing CO_2 from biomass combustion	Biomass power plant	Geological Storage	7-8
Sleipner (Norway)	First offshore carbon storage project active since 1996	~1M	CO_2 separation using amine solutions, pressurized, and offshore injection	Natural gas processing	Subsea Formation Injection	9
Net Zero Teesside (UK)	Large-scale industrial CCS project in UK	Not specified	Post-combustion technology for CO_2 separation	New natural gas-fired power plant	Geological Storage	6-7
Taizhou BECCS (China)	Generating energy from agricultural waste while capturing carbon	Not specified	Biomass combustion and BECCS technology for CO_2 capture	Energy production	Geological Storage	6-8

Carbon Capture, Utilization, and Storage (CCUS) Projects and Implementations in Türkiye

As of 2024, Türkiye's electricity production totals 348.9 TWh, with 35.2% from coal and 18.9% from natural gas. The energy sector accounts for 71.3% of total emissions. Türkiye has set a 41% emission reduction target for 2030 and a net-zero goal for 2053. However, 54.1% of electricity generation remains fossil fuel-based (Table 3).

Carbon capture technologies are advancing globally, offering significant emission reduction potential [5]. In Türkiye, widespread adoption requires identifying geological storage potential, establishing carbon pricing, enhancing public-private collaborations, and increasing public awareness [28]. High costs, limited technical capacity, and regulatory uncertainties remain critical barriers.

RESULTS AND DISCUSSION

Carbon Capture and Storage (CCS) technologies have gained significant momentum globally, particularly in countries such as the United States, Canada, and Norway, where supportive regulatory frameworks and financial incentives have enabled large-scale implementation. These countries benefit from mature infrastructure and institutional capacity, allowing CCS to effectively reduce emissions from fossil fuel-based power generation. In contrast, CCS development in Türkiye remains at an early stage, largely limited to research, feasibility studies, and small-scale pilot projects. Although Türkiye's centralized energy infrastructure and emission profile are technically compatible with CCS, the lack of a comprehensive national strategy and regulatory framework

Table 3. Carbon Capture, Utilization, and Storage (CCUS) Projects and Implementations in Türkiye

No	Project Name	Entity	Features	Technology/ Methods	Integration	Status	TRL Level
1	TUBITAK ACT3	TUBITAK	One of Türkiye's most comprehensive R&D projects on carbon capture and storage technologies aims to reduce carbon emissions from electricity generation.	Post-combustion and pre-combustion carbon capture methods	Electricity generation	Lab and Pilot Studies	4-5
2	SOCAR NEFERTITI Project	SOCAR Türkiye	Aims to convert CO_2 into chemical products using solar energy-supported photocatalytic systems	Solar energy-supported CO_2 conversion	Indirectly related to electricity generation	R&D Phase	3-4
3	EUAS Hybrid Systems	EUAS	Reducing emissions from coal-fired thermal power plants using with Hybrid Membrane-Adsorbent CO_2 Capture System	Membrane and adsorbent technologies for CO_2 separation	Coal-fired thermal power plants	Pilot Studies	4-5
4	REC Türkiye	REC Türkiye	Mapping Türkiye's geological carbon storage potential and developing data-driven strategies for CO_2 storage from electricity generation.	Infrastructure analysis for CO_2 transportation and underground injection	Electricity generation	Analysis Phase	3-4

poses a major barrier to deployment. Furthermore, high investment costs and limited public awareness exacerbate the challenges of adoption. [29–33]. Nevertheless, CCS presents a strategic opportunity for Türkiye to meet its 2053 net-zero emissions target and participate in global carbon markets. Aligning with international climate finance mechanisms, such as the EU Green Deal and Horizon Europe, could enhance Türkiye's capacity to scale CCS technologies. Addressing regulatory, technical, and social acceptance issues will be crucial for narrowing the gap between Türkiye and leading countries in CCS deployment (Table 4).

To articulate CCUS (Carbon Capture, Utilization, and Storage) technology in economic terms, the economic feasibility of Carbon Capture and Storage (CCS) fundamen-

Table 4. Opportunities and challenges of CCUS technologies in power generation: A SWOT perspective (IEA – International Energy Agency - IEA)

SWOT Analysis of CCS Technologies in the Electricity Sector	
Strengths	***Weaknesses***
Enables up to 90% reduction in CO_2 emissions	High investment and operational costs
Can be integrated into existing fossil fuel infrastructure	Efficiency loss due to additional energy consumption
Applicable in high-emission sectors	Uncertainties regarding long-term storage security
Opportunities	***Threats***
Creates new job opportunities	Public acceptance issues (NIMBY effect)
Contributes to carbon markets	Insufficient legal regulations and investment uncertainties
Technology transfer and cross-border collaborations are developing	Risk of CO_2 leakage and potential environmental impacts

Table 5. Cost overview [29]

No	Progress	Method	Average Cost (US$/t$CO_2$)
1	Capture	Chemical Absorption	50–90
2	Capture	Physical Absorption	40–70
3	Capture	Cryogenic	>100
4	Transportation (Ship)	Medium Pressure (10k t)	~41
5	Transportation (Ship)	Medium Pressure (50k t)	~28
6	Transportation (Ship)	Low Pressure (50k t)	~18
7	Transportation – (Pipeline)	Intensive Phase (130-150 bar, 250 km)	25–50
8	Storage (Geological)	Saline Aquifer / Reservoir	5–20
9	Storage (Storage Tank)	Medium Pressure Tank	25–35
10	Storage (Storage Tank)	Low Pressure Tank	10–20

Table 6. CO_2 Capture method and efficiency [4-18-30]

CO_2 Capture Method	CO_2 Capture Efficiency (%)	Energy Consumption (MJ/kg CO_2)	Cost ($/ton CO_2)
Post-combustion	85–90	2–4	50–80
Pre-combustion	90–95	1.5–3	40–60
Oxy-fuel combustion	90–95	3–5	60–100

tally depends on the aggregated costs of its three principal components: capture, transportation, and storage. These components collectively determine the overall economic viability and scalability of the technology. Based on the literature review and related analyses, the average unit costs of CO_2 capture, transportation, and storage vary depending on the method and operational conditions, and these ranges are summarized in Table 5. These costs vary depending on the technology type, process configuration, and project scale. Among capture technologies, post-combustion MEA-based systems typically range from 50–90 USD/tCO_2, primarily due to high energy consumption and solvent losses [33]. Pre-combustion systems, which rely on gasification and subsequent chemical conversion, tend to be more complex and costly, averaging 60–100 USD/tCO_2 [34]. Oxy-fuel combustion, by using pure oxygen instead of air, simplifies CO_2 separation but requires capital-intensive infrastructure such as air separation units (ASUs), resulting in costs between 40–80 USD/tCO_2.Transport costs, influenced by distance, pressure, and mode (pipeline or ship), range from 18 to 50 USD/tCO_2, while geological storage in saline aquifers or depleted reservoirs typically adds 5–20 USD/tCO_2. An overview of these cost ranges is provided in Table 5, based on international benchmarks [8-18-29].

These findings emphasize the importance of selecting appropriate CCS technologies and integrating them effectively into energy systems. In the case of Türkiye, where fossil fuels still account for a large portion of electricity generation, the targeted deployment of CCS—particularly in emission-intensive sectors and coal-dominated regions—could significantly contribute to long-term climate targets [31]. However, this requires not only technological readiness but also supportive regulatory frameworks, investment incentives, and infrastructure planning to ensure large-scale implementation.

According to the data, Post-Combustion management can be integrated more easily than other methods.

CONCLUSION

In conclusion, the electricity generation sector is very important for the use of CCUS technologies as it is the sector with the highest carbon emissions. In the power generation sector, carbon capture technologies that are easy to integrate later should be used due to the old installation of fossil fuel plants. Post Combustion method leads to exergy losses as it partially prevents the utilization of waste heat in flue gases. When all methods are evaluated in terms of capture efficiency, economic feasibility, ease of integration and energy losses, it is understood that the Post-Combustion method with amine-based chemicals (MEA) is the most suitable capture technology for the power generation sector.

Although numerous examples of carbon capture exist globally, Türkiye currently lacks any fully commercialized carbon capture initiatives. However, Türkiye has significant potential with its existing large-scale fossil fuel-based facilities. In terms of carbon storage, the oil and gas reserves in Türkiye are highly suitable for injecting carbon dioxide. There are examples of these reserves in the Southeast, Black Sea and Thrace regions. Storage is also actively practiced in Türkiye with the Batı Raman field in Batman.

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Review Article

Carbon capture technologies and sustainable transformation in fertilizer production

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ABSTRACT

The fertilizer sector is vital for Türkiye's agricultural sustainability but poses significant carbon emission challenges. Intensive energy use and direct emissions, especially in ammonia and urea production processes, increase the carbon footprint of this sector; therefore, technological solutions to reduce carbon emissions become a priority. In this paper, Carbon Capture, Utilization and Storage (CCUS) technologies stand out as a strategic tool to reduce emissions and ensure compliance with international regulations. In this report, the applicability of CCUS technologies is assessed within the framework of Türkiye's sectoral emission profile and the most suitable capture technologies are analyzed, especially in the context of fertilizer production processes. Post-combustion carbon capture technology came to the forefront due to its compatibility with the existing industrial infrastructure and ease of implementation, and it was determined that this technology has high applicability in the short and medium term. Furthermore, recommendations for policy makers and industry are presented, considering the Turkish legislation, the need for economic incentives and international developments. The results show that CCUS practices in the fertilizer sector will play a critical role both in achieving emission reduction targets and maintaining the competitiveness of the industry.

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INTRODUCTION

The need for increasing food demand has increased day by day due to the rapid rise in the population. So, the sustainable transformation of agricultural industry is essential in this situation. The agricultural industry tries to improve crop efficiency and product yield by applying fertilizers, which are good nutrients for plants. However, they have certain environmental impacts such as climate change by the release of carbon dioxide (CO_2) and nitrous oxide emissions.

Food security, national revenue, employment, international trade, and agriculture-dependent industries are all bolstered by the agricultural sector. By 2050, the world population is predicted to reach 9.8 billion people, exacerbating the world's food security and making sustainable development one of the most crucial goals [1]. The agriculture sector is 3.2 times more effective than other sectors at reducing poverty [2].

There are 18 essential nutrients, three of which are carbon, hydrogen, and oxygen sourced from air (as CO_2) and water [3]. The other nine elements called micronutrients provide a small amount of effect on the growth of plants (Fig. 1).

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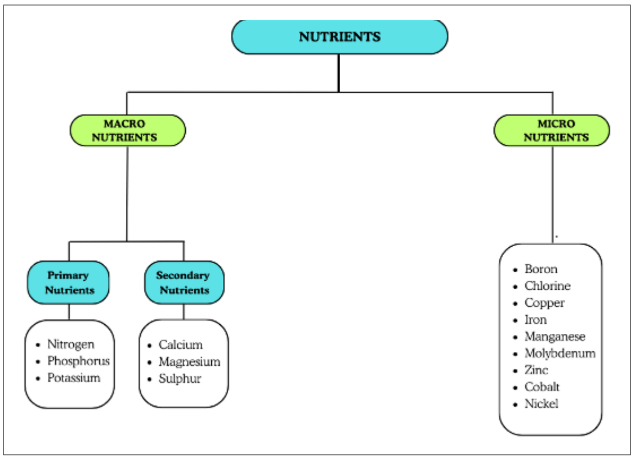

Figure 1. Essential nutrients for plants [3].

Highlights

- CCUS technologies offer a promising pathway to reduce carbon emissions in the fertilizer industry.
- Post-combustion carbon capture stands out as the most feasible option for short-term implementation.
- Integrating CCUS into fertilizer production can support Türkiye's emission reduction targets and industrial competitiveness.

Fertilizers are used as a supplementary product to create nutrient-rich environment for plants and are commonly applied in agriculture due to a lack of essential minerals in the soil. There are two types of fertilizers: organic fertilizers and inorganic (i.e. synthetic) fertilizers. Organic fertilizers are derived from natural sources such as compost and animal manure. This type of fertilizers is important for its recycling properties. But organic fertilizers release the nutrients more slowly to feed the soil. Otherwise, inorganic fertilizers are produced from chemical processes (generally known as nitrogen (N), phosphorus (P), and potassium (K) fertilizers (NPK) and blended with other materials and provide specific nutrients to feed the plant.

Nitrogen (N) is the most essential and limited nutrient in soil, playing a critical role in plant growth, chlorophyll formation, and protein synthesis. For this reason, nitrogen fertilizers, especially urea, are the most important and most frequently used fertilizers in agriculture. However, urea is lost in large quantities through evaporation, leaching, and emissions due to its high solubility, low molecular weight, and low thermal stability. [4]. A large portion of nitrogen in the urea is lost through evaporation, leaching, and emissions, especially when applied to the soil surface in alkaline conditions [5]. These losses contribute to environmental issues, such as water pollution and eutrophication. Due to these side effects, mitigation methods such as controlled-release fertilizers and the development of green ammonia technologies have increased globally to prevent the environmental risk of emissions from leaching.

The global fertilizer market was valued at $184.60 billion in 2021 and is expected to reach $251.57 billion by 2030, growing at a CAGR of 3.55% from 2022 to 2030 [6]. Major producers include China, India, Russia, the U.S., and Canada (Fig. 2).

Nitrogen leads global NPK production, accounting for 57% of total production in 2020, with 123.5 million tons produced globally [7]. Around 54.8% of this came from China, India, the U.S., and Russia. Russia and the U.S. increased nitrogen production by 67% and 38% respectively, while China's production decreased by 17% in 2020 [7].

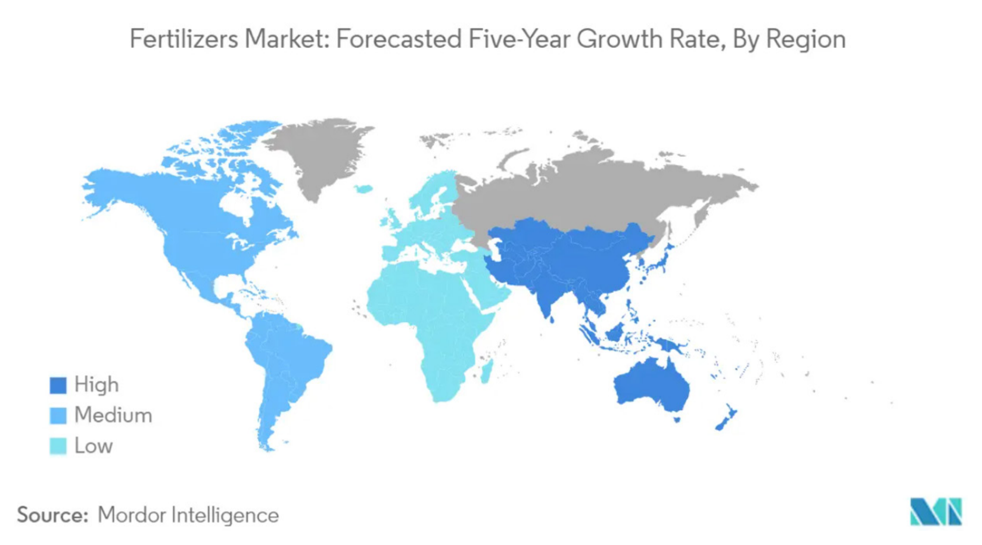

Figure 2. Distribution of the fertilizer industry worldwide [6].

The fertilizer market includes several product segments: straight fertilizers, complex fertilizers, conventional fertilizers, and controlled-release fertilizers (CRFs). Although straight fertilizers dominate the market in 2024 with a 72% share, CRFs are the fastest-growing segment due to their efficiency and environmental benefits [6].

In Türkiye, the fertilizer production began in 1939 and significantly developed after the 1970s due to increased investments. The first production took place at the Karabük Iron and Steel Factories through the reaction of ammonia gas with sulfuric acid, resulting in ammonium sulfate (21% N) [5]. Fertilizer exports from Türkiye remain low compared to other countries, primarily due to its high dependency on imports of certain raw materials.

On the other hand, the rising inflation and falling national currency have further made fertilizer imports expensive, negatively impacting Turkish farmers in recent years [7]. According to the Ministry of Agriculture and Forestry [7], Türkiye has consumed 7.03 million tonnes of fertilizers in 2023, with 5.2 million tonnes being imported due to limited domestic raw materials, except for phosphate in Mardin Mazıdağı. The country relies on imports of nitrogen, phosphate, and potassium fertilizers from various regions like Oman, China, North Africa, and the EU [7].

In Türkiye, The Ministry of Agriculture and Forestry banned ammonium nitrate in 2016 for security reasons and restricted the use of ammonium sulfate because it affects on soil pH [7]. These were largely replaced by urea-based and nitrogen-phosphate-potassium (NPK) compound fertilizers like 25-5-10 NPK (25% N, 5% P2O5, 10% K2O).

Climate change and environmental pollution are the main global threats. In response to these issues, the European Union launched the European Green Deal on December 11, 2019, aiming to reach a more sustainable future. A key component of the deal is the carbon border adjustment mechanism (CBAM), which will significantly affect international trade [8]. The EU emissions trading system (ETS) is the world's largest carbon pricing system and plays a central role in this regulation. According to trade map (2023), in 2022, the EU-27 accounted for 48.76% of Türkiye's fertilizer exports, alongside major shares in electricity, steel, cement, and aluminum exports.

With a projected 9% increase in global population, the demand for food and energy is rising, leading to higher emissions. As fertilizers are essential for food production, their usage—and related emissions—are also increasing.

The fertilizer industry currently accounts for around 5% of global greenhouse gas emissions [9]. Studies show that agriculture sector emit about 2.6 gigatonnes of CO_2 equivalent annually, exceeding emissions from global aviation and shipping combined. In synthetic fertilizer production, ammonia production is the main source of emissions. In Türkiye, the production of ammonia and nitric acid, which are key raw materials in fertilizer, is 50–65% more emission-intensive than that in the EU. To address this, most of the countries aim to reduce emissions by adopting innovative technologies like alternative processes and carbon capture systems. In line with the European Green Deal, global fertilizer and chemical producers are setting interim targets for 2030 and aiming to achieve carbon neutrality by 2050

LITERATURE REVIEW

Soil is one of the largest carbon stocks and plays an important role in combating climate change by storing carbon through the soil carbon sequestration process. Carbon sequestration involves capturing and storing atmospheric CO_2, playing a significant role in mitigating climate change. Also, this process has benefits such as increasing agricultural yields, improving water quality and enhancing soil health [10].

Furthermore, CO_2 is known to accelerate plant growth by increasing the rate of photosynthesis while minimizing water loss through transpiration [11]. CCU (Carbon Capture and Utilization) is the process of capturing CO_2 and converting it into useful products, so that it can be utilized instead of being buried underground. In agriculture, this refers to the reuse of CO_2 in agricultural production. Although CO_2 obtained with direct air capture can provide a decline in both greenhouse gases emitted from the sector and in imports of fertilizers, this technology is not yet widespread [12].

International Roadmaps and Strategies for Fertilizer Industry

By 2050, the European Green Deal [13] aims to achieve climate neutrality and build a resource-efficient and low-carbon economy. As part of this global transformation, during the COP (Conference of the Parties), countries have published their INDCs (Intended Nationally Determined Contributions) on the UNFCCC (United Nations Framework Convention on Climate Change) platform to demonstrate their commitments to combat climate change [14]. For example, the EU has targeted a 40% reduction compared to 1990 levels, while Canada, Korea, Australia, and Türkiye have also committed to reducing greenhouse gas emissions in line with their economic conditions. These targets necessitate the development of specific strategies and roadmaps for carbon-intensive sectors [15-19]. The Carbon Border Adjustment Mechanism (CBAM), developed for this purpose, aims to prevent carbon leakage by equalizing the carbon-related costs of imported products with those of domestically manufactured products within the EU [13]. Therefore, the European Union has developed various policy and financing instruments to accelerate the transformation of carbon-intensive industrial sectors. Within the framework of the European Green Deal, especially through the Innovation and Research Fund, CCUS projects have been supported at the industrial scale, and fertilizer and chemical industries are among the priority areas [20]. In addition, the applicability of CCUS technologies in the agri-food chain is also addressed in projects carried out under the Horizon Europe program. Carbon management has also started integrating into climate policies in developing countries. Major economies such as China, India, and Brazil are developing national strategies for CCUS technologies; while China focuses on infrastructure investments under the 14th Five-Year Development Plan, India supports carbon reduction targets with the National Hydrogen Mission [21]. However, structural barriers such as infrastructure deficiencies, high costs, and policy uncertainties limit the spread of CCUS applications in these countries [22]. Therefore, it is important to support these technologies with mechanisms such as carbon pricing, emission trading systems, and public incentives [22]. In Türkiye, sustainable transformation policies for the fertilizer sector aim to promote low-emission technologies, to encourage organic and microbial fertilizer production, and to integrate biogas and landfill gas facilities into production processes. In addition, steps such as supporting green and blue ammonia production and increasing energy efficiency in existing facilities could play a critical role in reducing the sector's carbon footprint. This transformation process also includes workforce requalification, social inclusion, and support for carbon-reducing practices. These national initiatives are integrated with global roadmaps and strategic frameworks in the fertilizer sector. Arrangements such as the Paris Agreement and the European Green Deal encourage countries towards carbon capture and low-emission technologies in line with their greenhouse gas emission reduction targets. Türkiye is investing in N_2O catalysts and aims to reduce emissions by promoting the use of green-blue ammonia [23]. Similarly, the International Energy Agency's "Ammonia Technology Roadmap" report presents three scenarios for decarbonizing ammonia production and assesses the viability of low-carbon technologies. International roadmaps focus not only on technological transformation but also on financial support mechanisms, multi-stakeholder governance structures, and just transition principles [24].

CCUS TECHNOLOGIES FOR FERTILIZER INDUSTRY

Carbon Capture, Utilisation and Storage (CCUS) Systems

Carbon capture, utilisation and storage (CCUS) systems, one of the most critical technological tools in the fight against climate change, play a strategic role in the decarbonisation of high emission sectors. In line with Türkiye's net zero carbon emission target, transformation of high carbon emitting sectors such as power generation, cement, steel and fertiliser industries is of great importance. Considering that the majority of carbon emissions in these sectors come directly from the production processes, there is a need not only for reduction technologies but also for conversion technologies. CCUS systems play a critical role in this transformation; they reshape the carbon cycle by capturing CO_2 before it enters the atmosphere, converting it into an input with economic value, or storing it safely [25].

CCUS systems are structured around a value chain consisting of four main stages: carbon capture, transport, utilisation and storage. Each stage includes different technological methods and operational solutions. For example, carbon capture can be achieved by pre-combustion, post-combustion, oxy-fuel and direct air capture (DAC) technologies. Among these methods, post-combustion is the most widespread and stands out especially for its easy integration into existing industrial infrastructures [25].

Carbon capture technologies aim to capture CO_2 gas from the atmosphere and then store or utilise it [25]. CO_2 is emitted into the atmosphere together with other gases as a result of industrial processes, hydrocarbon-fired power generation, steel and cement production, hydrogen production, fertiliser production and fuel production in refineries. Carbon capture technology refers to the separation of CO_2 from other gases emitted into the atmosphere. There are many different technologies used in the capture, transport and geological storage of carbon. These processes are technologies that will help reduce greenhouse gases. It has a key role in combating climate change [26].

There are four main carbon capture technologies. These technologies can be used before combustion, after combustion or with oxy-fuel.

- Absorption: It is the separation of CO_2 with chemical solvents by dissolving it in liquid medium.
- Adsorption (Surface Retention): The retention of CO_2 by binding to a solid surface (e.g. activated carbon, zeolite or MOF). This method is particularly favoured at low CO_2 concentrations (e.g. direct air capture).
- Membrane Separation: It is the separation of CO_2 through special polymeric or inorganic membranes by utilising molecular permeability differences.
- Cryogenic Separation: It is the separation of CO_2 from other gases by turning it into liquid or solid at low temperatures. Although this method is energy intensive, high purity CO_2 can be obtained when combined with hybrid systems [26].

Carbon capture technologies in blue ammonia and fertilizer sector

Ammonia is an essential chemical, especially in the production of agricultural fertilizers, and 85% of its production is directed to this field. However, since 95% of the production is based on fossil fuels, and the production process consumes large amounts of energy, ammonia production generates high levels of CO_2 emissions. This process accounts for about 2% of global energy demand and 1.3% of CO_2 emissions [27].

To address this issue, blue ammonia production involves the integration of carbon capture and storage systems into the Haber-Bosch process, which uses hydrogen produced by conventional steam methane reforming (SMR). Through this integration, CO_2 generated during production is separated by absorption technologies (e.g. MEA solutions) and either injected underground or converted into a reusable form. The product obtained by this method is called "blue ammonia" [27].

Blue ammonia systems fall into two main categories: Gen 1 systems integrate carbon capture into existing fossil-based production, while Gen 2 systems utilise renewable energy sources to produce hydrogen, making the process lower emission. However, the integration of CCS technology alone is not sufficient; the emission impact of the entire production system must be assessed through life cycle analysis. In particular, the risk of "fossil lock-in" may give the impression that production is only decarbonised on the surface [27].

Carbon capture and utilization (CCU) systems have the potential to reduce climate impact, but risk fossil lock-in if production processes remain based on fossil resources. As stated in the TfS guidelines, the system extension approach attributes CO_2 emission reductions only to by-products, while the main product (e.g. ammonia) continues to carry the same climate burden as conventional production. This increases the risk of making fossil-based production structurally unsustainable [27]. Furthermore, in scenarios with high methane leakage, the short-term climate impact of blue ammonia production may be more negative compared to green alternatives [28]. Therefore, in CCU applications, not only the CO_2 benefit but also the energy profile and long-term impacts of the whole system should be considered.

In the system depicted in Figure 3, CO_2 capture technology is integrated directly into the ammonia production process. The CO_2 gas generated during the production of blue ammonia exits the reactor as a gas stream. This CO_2 is directed to an absorption tower containing a solution of monoethanolamine (MEA). MEA chemically reacts with the CO_2, keeping it in solution. This solution is then sent to a separator unit to recover the CO_2. Here it is heated and the CO_2 is separated again, resulting in high purity captured CO_2. The CO_2 captured in this system is treated as a by-product of the production process. No system expansion or allocation procedure is applied; the multiple output is accepted directly [27].

When direct air capture (DAC) technology is added to blue ammonia systems, the system boundaries are further extended; CO_2 captured from the atmosphere replaces CO_2 generated in the production process, resulting in a lower net emission structure. Modelling studies in Germany have shown that such integrated systems reduce climate change impact by up to 20% compared to grey ammonia production [27].

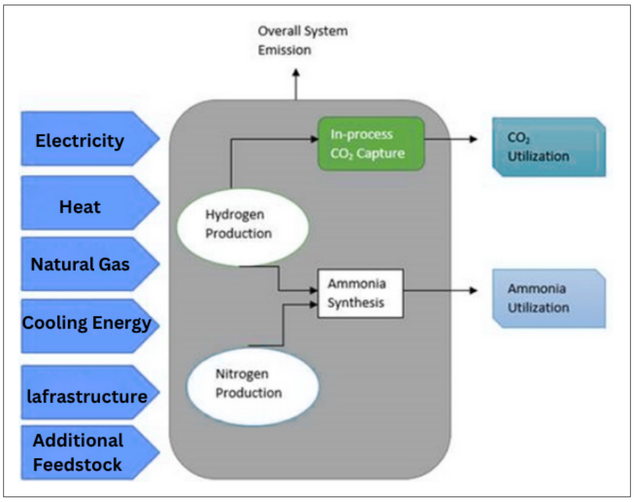

Figure 3. System boundaries for blue ammonia production.

The conventional SMR (steam methane reforming) method produces 1 kg of grey ammonia without CO_2 capture. CO_2 capture is integrated into the ammonia production process. When producing 1 kg of blue ammonia, CO_2 is captured at the same time. Three different production approaches are compared in the study. Gray ammonia production is based on conventional steam methane reforming (SMR), does not involve CO_2 capture and its functional unit is 1 kg of ammonia. The production of blue ammonia includes CO_2 capture technology integrated into the process, with the functional unit defined as 1 kg of blue ammonia along with the CO_2 captured during production. In addition, in the production of blue ammonia where direct air capture (DAC) is incorporated, in-process CO_2 capture as well as CO_2 obtained through DAC replaces the byproduct, so that the functional unit is 1 kg of blue ammonia and the associated CO_2 capture. In this case, in order to solve the multiple output problem, the limits are expanded to include DAC and the environmental impacts of ammonia and CO_2 are examined separately [27].

In research projects and industrial applications, the most common method in carbon capture processes are amine-based technologies, particularly based on monoethanolamine (MEA) sorption. These methods generally achieve CO_2 capture efficiencies of 85-90% in environments. The amine solutions saturated with CO_2 are separated from CO_2 by thermal treatment; thus, both CO_2 and the amine solution are obtained and made suitable for reuse. The captured CO_2 is compressed and transported by pipelines to storage or utilisation areas. A detailed life cycle inventory including transport of storage processes was presented; 90% of CO_2 purity, 30 years capture unit and 18 years compressor lifetime were assumed in the analysis [27].

Direct (airborne) carbon capture (DACC) captures CO_2 from air. This reduces the level of CO_2, helps to reduce emissions and stabilise the amount of CO_2 in the air [25].

Figures 3 and 4 represent the system boundaries used in the life cycle analysis (LCA) to assess the climate impacts of blue ammonia production. Figure 3 presents a system boundary limited to the production process, including only the in-process carbon capture unit, while Figure 4 reflects a scenario where the captured CO_2 is replaced by an external direct air capture (DAC) system, thus expanding the environmental contribution of the system [27].

This approach, in line with TfS guidelines, defines the benefit of captured CO_2 not as a direct reduction, but also in terms of avoided GHG emissions. CO_2 is thus included in the functionality of the system as a by-product and not just waste, which more realistically reflects the distribution of impacts between products in multifunctional processes. Thanks to the system extension, the climate benefit of the CO_2 generated during the production of blue ammonia can be analysed [27].

However, the environmental impacts of this systematic framework largely depend on methane leakage in the natural gas supply chain. Leakage rates in the production and transportation of natural gas are particularly decisive for short-term climate impacts. Indeed, TWP (Technology Warming Potential) analyses show that blue ammonia production can only be climate competitive with green ammonia under low leakage rates. For example, even at a leakage rate of 2.2%, the total thermal impact of the blue ammonia system is higher than the green alternative and can only be equalized at very low rates of 0.2% [28]. These system boundaries therefore reveal not only the technical flux, but also the impact of methodological choice in climate assessment on climate outcomes. Redefining the role of CO_2 within system boundaries could offer a strategy to reduce fossil lock-in, but only if the energy source is low-carbon and methane leakage is under control.

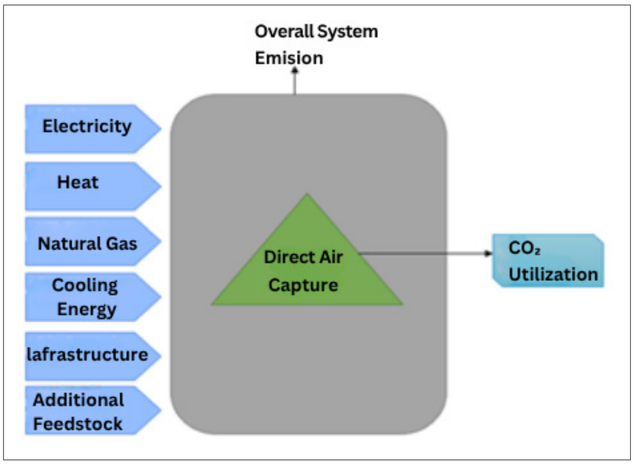

Figure 4. System boundaries for CO_2 production from DAC.

Carbon storage technologies

Geological storage methods are used for the long-term disposal of CO_2. In this context, CO_2 is injected into deep underground reservoirs in a supercritical state. The main storage environments are depleted oil and gas fields, deep saline aquifers and coal seams. The Enhanced Oil Recovery (EOR) method traps CO_2 underground, simultaneously increasing oil productivity. ADNOC Shah Gas project stores 2.3 million tonnes of CO_2 per year with this method. Effective storage requires >1000 m depth, porous reservoirs, seal rocks and leakage risk management [26].

CCUS projects

Large-scale projects demonstrating the feasibility of carbon capture, utilisation and storage (CCUS) technologies have been implemented around the world. These projects are remarkable in terms of integration of technologies into sectors, geographical suitability and cost-effectiveness.

Yara – Sluiskil Plant – Netherlands (2022)

Part of the Northern Lights project in Norway, this facility liquefies CO_2 emissions from the steam methane reforming (SMR) process used for hydrogen production by sequestering them through chemical absorption and transporting them to geological formations beneath the North Sea. The project aims to permanently store approximately 800,000 tonnes of CO_2 per year. This project is one of the first full-scale CCS applications directly integrated into the fertiliser sector and serves as a pioneering example in the sector's transition to carbon neutrality [29].

CF Industries – Yazoo City Facility –USA (2024)

At the ammonia production facility, CO_2 generated by the steam methane reforming (SMR) process is separated by chemical absorption. It is typically captured from the CO_2 gas stream using solvents such as monoethanolamine (MEA), then compressed and injected into underground formations through ExxonMobil's infrastructure. This project, planned to permanently store approximately 500,000 tons of CO_2 annually, is one of the pioneering applications in the US fertilizer industry aimed at reducing carbon emissions [30].

Saudi Aramco Blue Ammonia Shipment - Saudi Arabia - Japan (2020)

Saudi Aramco successfully delivered the world's first shipment of carbon capture and utilisation (CCU)-based blue ammonia to Japan in 2020. In this process, CO_2 generated during blue ammonia production was captured and transported for use at the Uthmaniyah oil recovery pilot plant in Saudi Arabia and the methanol production plant in Jubail [27].

Pupuk Indonesia - Pertamina - Mitsubishi Joint Venture - Indonesia

Pupuk Indonesia, Pertamina, Mitsubishi Corporation Located in Southeast Asia, this initiative aims to assess the feasibility of establishing a supply chain for hydrogen and ammonia through carbon capture, utilisation and storage (CCUS) [27].

Pupuk Indonesia Production Capacity- Indonesia

It is a major facility in Indonesia with an annual production capacity of over five million tonnes, accounting for approximately 3% of global ammonia production [27].

Mexico Technical Research Project- Mexico

The environmental impacts of carbon capture, utilisation and storage (CCUS) in an ammonia plant for applications such as an advanced oil recovery system, carbonated beverages and urea synthesis were investigated in detail [27].

CCU Based Blue Ammonia Modelling- Germany

In a modelling study conducted in present-day Germany, it was shown that the impact of CCU-based blue ammonia on climate change is reduced by 20% compared to grey ammonia [27].

ADNOC Shah Gas CCS Project- Shah, Abu Dhabi, United Arab Emirates (2019)

Under KBR's responsibility, this project has the capacity to capture, utilise and store 2.3 million tonnes per annum (MTPA) of carbon at ADNOC's ultra-acidic gas production facilities [31].

Northern Lights CCS Project- Eastern Norway (2017)

With an annual capacity of 1.5 million tonnes of CO_2, the project includes an onshore CO_2 receiving and storage terminal, an offshore pipeline and a subsea injection system [31].

Quest CCS Project- Canada (2013)

Located at Shell's Scotford complex, this project is designed to capture 1.1 million tonnes of CO_2 per year in a steam methane reformer. The captured CO_2 is sent to underground storage at a depth of 2,300 metres, 80 km from the plant [31].

Gorgon CCS Project- Barrow Island, Western Australia (2005)

The Gorgon Project is one of the largest CCS projects in the world with an annual injection capacity of 3.4 to 4.0 million tonnes of CO_2. CO_2 separated from natural gas production and liquefaction processes is injected into the saline aquifer layer 2.3 km below ground via a 7 km long pipeline [31].

Carbon Capture Efficiency of Processes and Carbon Emission Amount

CCUS systems differ greatly in cost, energy usage, CO_2 capture efficiency, and scalability [32]. Hanson et al.[33]'s study assessed different carbon capture technologies from various perspectives and evaluated parameters such as cost, efficiency and scalability for comparison. Parameters for different technologies including absorption, membrane separation, adsorption, direct air capture, cryogenic capture, and bio-based technologies are given in Table 1 [33].

According to the Fertilizer Sector Policy Document prepared by TOB-TAGEM, the Turkey Sectoral Low Carbon Roadmaps prepared by the Ministry of Industry and Trade of the Republic of Turkey, and data from the Directorate-General for Agricultural and Rural Development prepared by the European Commission, 547,000 tons of urea-based fertilizer and 234,400 tons of NPK-based fertilizer are produced in Turkey, while 5.4 million tons of urea-based fertilizer and 17.3 million tons of NPK-based fertilizer are produced in Europe. In a study conducted by TOB-TAGEM to calculate the carbon footprint of fertilizer, emission intensity data were reported as 1.49 tons CO_2/tons product for urea-based fertilizers in Türkiye [7], 1.05 for NPK based fertilizers in Türkiye, 1.34 tons CO2/tons product for urea-based fertilizers in Europe, and 0.54 tons CO_2/tons product for NPK based fertilizers in Europe [34-36].

Table 1. Parameters for absorption, membrane separation, adsorption, direct air capture, cryogenic capture, and bio-based technologies.

CCUS technologies	Cost (USD/ton CO_2)	Energy consumption (MJ/ton CO_2)	CO_2 capture efficiency (%)	Scalability (TRL)
Absorption	50-100	3-5	90-95	9
Adsorption	30-80	2-4	70-85	7
Membrane separation	60-120	2-3	85-90	6
Cryogenic capture	70-150	4-6	95-99	5
Bio-based technologies	40-90	1-2	60-80	4
Direct air capture	100-600	8-12	80-90	5

MATERIALS AND METHODS

One of the parameters that is effective in finding the optimum carbon capture process based on fertilizer sector is carbon capture capacity. The level of development of countries causes differences in the amount of carbon emissions. Therefore, in this study, carbon capture capacities for different processes were calculated based on the carbon emission amounts of Turkey and the European Union for urea and NPK based fertilisers and the efficiency of the processes was analyzed by using Equation 1.

$$CO_2\ \textit{Capture Capacity} = \textit{Fertilizer Amount} \times \textit{Emission Intensity} \times \textit{Process Efficiency} \qquad [1]$$

RESULTS AND DISCUSSION

In the study, the efficiency, energy consumption, and carbon capture capacities of carbon capture technologies in the fertilizer industry were taken into consideration and the technologies were compared for the fertilizer sector. Carbon capture capacities specific to the fertilizer sector could not be found in the literature, so carbon emission and carbon capture capacities were calculated according to the urea and NPK based fertilizer production amounts in Türkiye and Europe. The data and calculations from the literature are summarized in Table 2 and 3. According to Table 2 and 3, the absorption process has an efficiency of 90–95%, with an energy consumption of 3–5 MJ/ton CO_2, a carbon capture capacity of 0.73–0.77 million tons for urea and 2.22–2.34 million tons for NPK in Türkiye, and 6.51–6.87 million tons for urea and 8.41–8.87 million tons for NPK in Europe. Adsorption has an efficiency of 70–85%, energy consumption of 2–4 MJ/ton CO_2, a capture capacity of 2–4 million tons for urea and 1.72 – 2.09 million tons for NPK in Türkiye, and 5.07–6.15 million tons for urea and 6.54–7.94 million tons for NPK in Europe. Membrane separation shows an efficiency of 85–90%, energy consumption of 2–3 MJ/ton CO_2, a carbon capture capacity of 0.69–0.73 million tons for urea and 2.09–2.22 million tons for NPK in Türkiye, and 6.15 – 6.51 million tons for urea and 7.94–8.41 million tons for NPK in Europe. Cryogenic capture has an efficiency of 95–99%, energy consumption of 4–6 MJ/ton CO_2, a capture capacity of 0.77–0.81 million tons for urea and 2.34–2.44 million tons for NPK in Türkiye, and 6.87–7.16 million tons for urea and 8.87–9.25 million tons for NPK in Europe. Bio-based technologies have an efficiency of 60–80%, energy consumption of 1–2 MJ/ton CO_2, a carbon capture capacity of 0.49–0.65 million tons for urea and 1.48–1.97 million tons for NPK in Türkiye, and 4.34–5.79 million tons for urea and 5.61–7.47 million tons for NPK in Europe. Direct air capture has an efficiency of 80–90%, energy consumption of 8–12 MJ/ton CO_2, a carbon capture capacity of 0.65–0.73 million tons for urea and 1.97 – 2.22 million tons for NPK in Türkiye, and 5.79–6.51 million tons for urea and 7.47–8.41 million tons for NPK in Europe.

The comparative evaluation of Carbon Capture, Utilization and Storage (CCUS) technologies reveals significant variation in terms of efficiency, energy consumption, maturity, and carbon capture capacity— each influencing their

Table 2. Carbon capture performance of CCSU processes for urea production.

CCSU process	Efficiency (%)	Energy consumption (MJ/ton CO_2)	Carbon Capture capacity in Türkiye (Mt)	Carbon capture capacity in Europe (Mt)
Absorption	90–95	3–5	0.73–0.77	6.51–6.87
Adsorption	70–85	2–4	0.57–0.69	5.07–6.15
Membrane separation	85–90	2–3	0.69–0.73	6.15–6.51
Cryogenic capture	95–99	4–6	0.77–0.81	6.87–7.16
Bio-based technologies	60–80	1–2	0.49–0.65	4.34–5.79
Direct air capture	80–90	8–12	0.65–0.73	5.79–6.51

Table 3. Carbon capture performance of CCSU processes for NPK production.

CCSU Process	Efficiency (%)	Energy consumption (MJ/ton CO_2)	Carbon capture capacity in Türkiye (Mt)	Carbon capture capacity in Europe (Mt)
Absorption	90–95	3–5	2.22–2.34	8.41–8.87
Adsorption	70–85	2–4	1.72–2.09	6.54–7.94
Membrane separation	85–90	2–3	2.09–2.22	7.94–8.41
Cryogenic capture	95–99	4–6	2.34–2.44	8.87–9.25
Bio-based technologies	60–80	1–2	1.48–1.97	5.61–7.47
Direct air capture	80–90	8–12	1.97–2.22	7.47–8.41

suitability for implementation in the fertilizer sector. Furthermore, the carbon capture capacities estimated for urea and NPK production plants in Türkiye and Europe demonstrate clear differences that reflect both the scale of production and the nature of each process. Overall, NPK plants exhibit a higher carbon capture potential compared to urea plants across all CCSU methods. This higher capture potential of NPK plants is associated with the generation of high-concentration, stable CO_2 process streams from nitric and phosphoric acid production units, which are technically more suitable for efficient CCS deployment [37].

Carbon absorption stands out as the most mature and widely used method (TRL 9), particularly in post-combustion applications. With a CO_2 capture efficiency of 90–95% and a moderate energy consumption rate (3–5 MJ/ton CO_2), it offers both technical viability and operational compatibility with existing fertilizer production infrastructure. As shown in Table 2 and 3, this method also has one of the highest potentials of carbon capture capacities in Türkiye (0.73 – 0.77 million tons for urea and 2.22 – 2.34 million tons for NPK) and Europe (6.51 – 6.87 million tons for urea and 8.41 – 8.87 million tons for NPK). However, the trade-off lies in its high operating costs, primarily due to solvent degradation, corrosion, and energy required for solvent regeneration [38].

Membrane separation technology provides an attractive alternative with lower energy consumption (2–3 MJ/ton CO_2) and a solid efficiency range of 85–90%. Its estimated capture capacity in Türkiye is also significant (0.69 – 0.73 million tons for urea and 2.09 – 2.22 million tons for NPK). Despite being less mature (TRL 6), it offers the advantage of modular design and chemical-free operation, positioning it as a promising candidate for future integration, particularly where cost and space efficiency are critical [39].

Cryogenic capture exhibits the highest efficiency (95–99%) and recovery purity, making it suitable for applications requiring ultra-pure CO_2. As seen in the table, it offers the highest carbon capture potential for both Türkiye (0.77 – 0.81 million tons for urea and 2.34 – 2.44 million tons for NPK) and Europe (6.87 – 7.16 million tons for urea and 8.87 – 9.25 million tons for NPK). However, its high energy demand (4–6 MJ/ton CO_2) and low maturity level (TRL 5) restrict its practicality for widespread industrial deployment, relegating it primarily to a final purification role [40].

Adsorption technologies, with efficiencies ranging from 70–85% and moderate energy consumption (2–4 MJ/ton CO_2), strike a balance between performance and cost (50–150 USD/ton CO_2). Their carbon capture potential in Türkiye is between 2 – 4 million tons for urea and 1.72 – 2.09 million tons for NPK. However, limitations such as the need for frequent regeneration and reduced sorbent performance over time hinder their long-term stability and scalability [41].

Bio-based technologies and Direct Air Capture (DAC) remain less commercially viable due to lower maturity levels and energy challenges. Bio-based systems show the lowest energy requirement (1–2 MJ/ton CO_2) but also the lowest efficiency (60– 80%), and their maximum estimated capture capacity in Türkiye is only 0.49 – 0.65 million tons for urea and 1.48 – 1.97 million tons for NPK. DAC, although offering a capture efficiency of 80–90%, suffers from the highest energy consumption (8–12 MJ/ton CO_2), and its economic feasibility is still limited despite its long-term climate potential [42].

Table 2 and 3 highlights that while cryogenic and absorption methods provide the highest capture capacities, membrane and adsorption offer more energy-efficient solutions with potential for mid-term cost-effective adoption. Meanwhile, bio-based and DAC approaches, though promising for long-term innovation and negative emission goals, currently face barriers in scalability and affordability. Carbon absorption remains the most strategically advantageous option for immediate deployment in the fertilizer sector due to its maturity, integration ease, and high efficiency. Membrane technologies may serve as a compelling next-generation solution pending further R&D. Hybrid solutions combining multiple methods or regionally tailored systems are also recommended to optimize performance and cost across diverse industrial scenarios. Ultimately, expanding integrated CCUS infrastructure and investing in innovation will be key to ensuring sustainable decarbonization in fertilizer production [43].

According to Table 2 and 3, Türkiye's carbon capture capacity grows from 0.49 to 0.81 million tons for urea and from 1.48 to 2.44 million tons for NPK, whereas Europe's capacity spans from 4.34 to 7.16 million tons for urea and from 5.61 to 9.25 million tons for NPK. This steady trajectory shows a proportionate alignment, with better carbon capture capacity in Türkiye corresponding to enhanced capacities in Europe. The data show that regional carbon capture potential scales in tandem, indicating a consistent pattern that might represent common technical improvements or linked regulatory frameworks across both areas.

CONCLUSION

Carbon Capture, Utilization, and Storage (CCUS) technologies stand out as a strategic tool in the fight against climate change. Considering Türkiye's current industrial structure and GHG emission profile, the most appropriate sector-based CCUS approaches are concentrated in areas with high emission intensity, such as power generation, cement, iron-steel and petrochemicals. The post-combustion technology applied in these sectors stands out as the most logical option in terms of ease of integration into existing infrastructure, technological maturity and economic viability. Especially in fossil fuel fired power plants and industrial facilities, this method is expected to be the most widespread and effective solution in the short term.

Current projections indicate that CCUS technologies will play an important role in both reducing carbon emissions and achieving sustainable economic transformation as they become more widely adopted over the next decade. However, the widespread adoption of the technology depends on many factors such as infrastructure investments, economic incentive mechanisms, and social acceptance. While there are already pilot studies in Türkiye, there is a need for comprehensive and integrated projects.

In this framework, among the recommendations for policymakers, increasing R&D activities on CCUS technologies, developing incentive mechanisms, establishing a legislative infrastructure and supporting cross-sectoral collaborations come to the forefront. In terms of industry, integrating CCUS solutions into the carbon management strategies of sectors with high emission intensity will both contribute to national emission targets and increase their competitiveness in the international market.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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