Clean Energy Technologies Journal
Web page info: https://cetj.yildiz.edu.tr
DOI: 10.14744/cetj.2026.0001

CLEAN ENERGY
TECHNOLOGIES
JOURNAL

Review Article

Carbon capture in the iron and steel industry

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ARTICLE INFO

Article history
Received: 25 May 2025
Accepted: 11 February 2026

Key words:
Amin-Based Solvents; Carbon; Capture; Iron; Post-Combustion; Steel.

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.

Cite this article as: Erenoğlu MA, Ünal FN, Başerli M, Şahin HY, Temizkan OB, Akpınar S. Carbon capture in the iron and steel industry. Clean Energy Technol J 2026;4(1):1–10.

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-

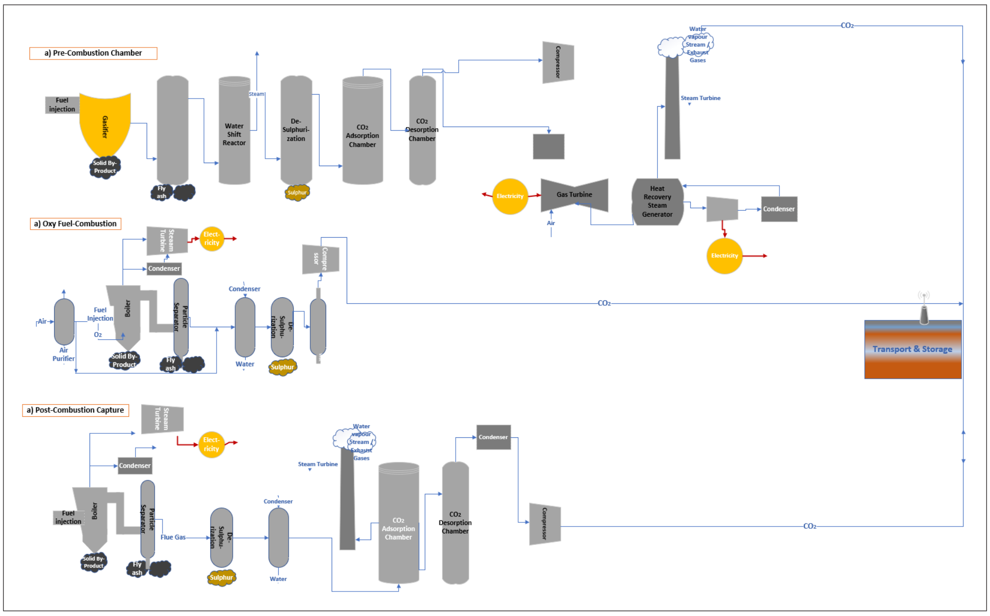


Figure 1. Carbon capture technologies, **(a)** pre-capture, **(b)** oxyfuel combustion, **(c)** post-capture [13]. (changed)

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-

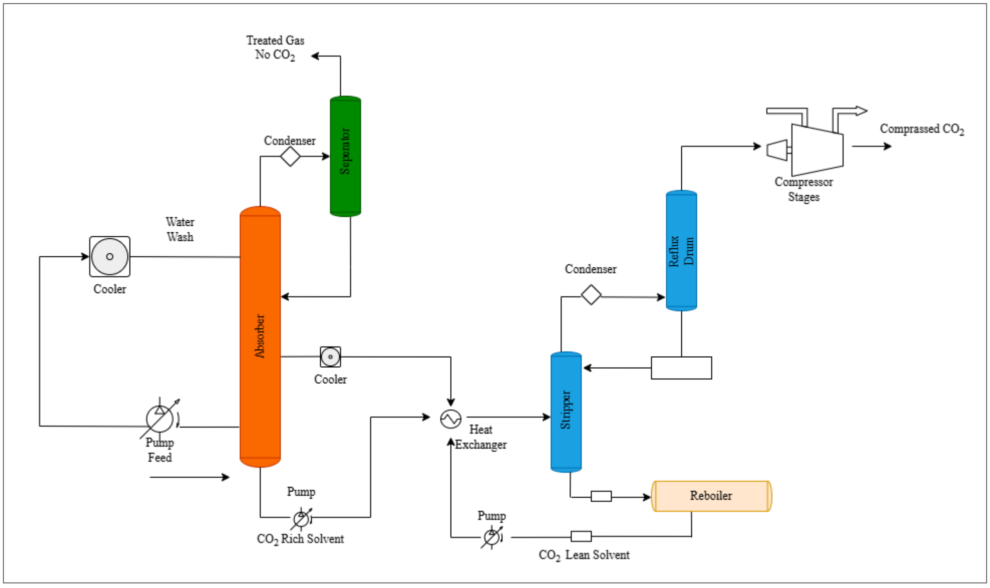


Figure 2. Flow chart of chemical absorption.

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

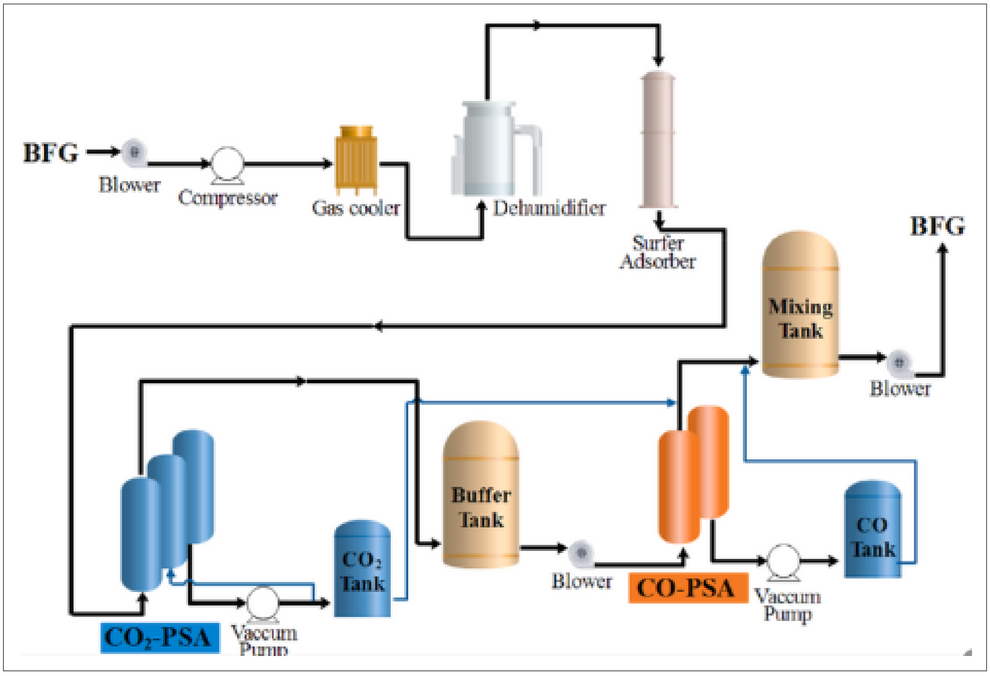


Figure 3. Flow chart of PSA process.

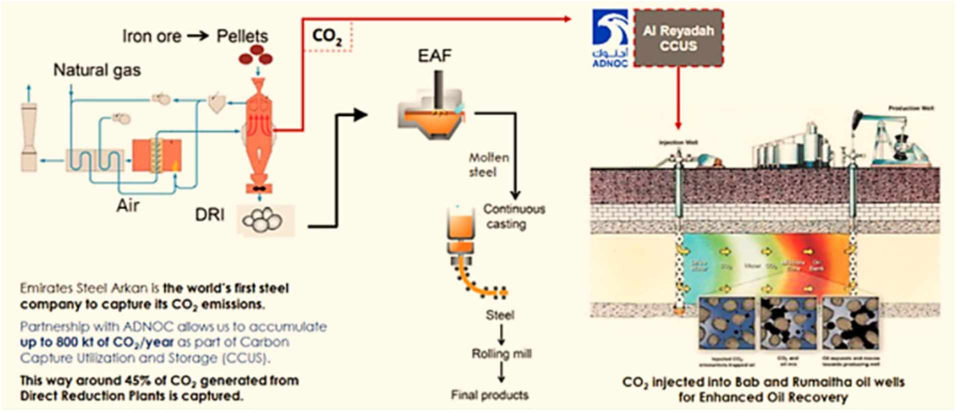
these components. The recycled CO and H_2 are returned to the furnace, reducing the demand for coke and lowering overall CO_2 emissions. Trials in Europe and China have shown that this method can significantly reduce carbon emissions, though full-scale commercial adoption is still progressing.

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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