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Carbon Capture for Steel?

CCUS will not play a major role in steel decarbonisation

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Key Findings

Over several decades of implementation in a range of sectors, carbon capture, utilisation and storage (CCUS) has accumulated a track record of underperformance and failure.

Capture rates at the world's only commercial-scale CCUS plant for gas-based steel production are very low. There are no commercial-scale CCUS plants for coal-based steelmaking anywhere in the world, with almost nothing in the pipeline.

Major steelmakers are turning increasingly to direct reduced iron (DRI)-based steelmaking to replace coal-consuming blast furnaces. CCUS faces being left behind as it was in other sectors like power generation.

Due to the poor performance of CCUS, it seems increasingly likely steel consumers will not want coal in their supply chains at all going forward. Investors should question steel company decarbonisation plans that maintain that CCUS will play a significant role.

Executive Summary

Carbon capture utilisation and storage (CCUS) looks unlikely to play a major role in decarbonising the global steel sector, despite support for the technology at the 2023 COP28 climate conference.

It is increasingly obvious to many, including the International Energy Agency (IEA), that the uptake of direct reduced iron (DRI)-based steelmaking – which can run on green hydrogen with very low emissions – is accelerating. This technology – along with electric arc furnaces (EAFs) associated with renewable electricity – offers steelmakers a far more promising pathway to reduce their emissions than CCUS.

Despite this, many major steelmakers around the world still maintain that CCUS will play a role in decarbonising their operations. Their plans for CCUS tend to push commercial-scale implementation of the technology off into the 2040s and lack detail. There are no commercial-scale CCUS plants for blast furnace-based steelmaking in operation anywhere in the world. The few pilot projects that exist have not proven the technology's feasibility.

CCUS's weak track record

CCUS technology has been around for nearly 50 years and has accumulated a history of significant underperformance. According to Bloomberg New Energy Finance (BNEF), CCUS currently captures just 0.1% of global emissions despite decades of implementation efforts. The IEA's updated *2023 Net Zero Roadmap* report noted that "The history of CCUS has largely been one of underperformance."

In 2022, IEEFA research showed that, out of 13 flagship, large-scale CCUS projects, five had materially underperformed, two were suspended, one was mothballed and two didn't provide data that allowed performance to be assessed. The study found almost three quarters of captured carbon dioxide (CO_2) was being used for enhanced oil recovery (EOR), enabling more fossil fuel extraction and therefore more carbon emissions.

CCUS is also susceptible to significant financial, technological and environmental risks, made worse by uncertainty over the long-term effectiveness of geological CO_2 storage. Transportation and storage of CO_2 in secure, dedicated geological sites pose significant challenges, requiring detailed studies for each project individually. The uniqueness of each CCUS project limits technological learning and cost reductions. The cost of carbon capture implementation has hardly reduced in 40 years while the cost of alternative technologies like renewable energy and battery storage has plunged, with further reductions to come.

One issue with CCUS that is often missed is its low rate of capture. CCUS projects have consistently struggled to reach targeted capture rates. Moreover, targeted carbon capture itself is often far below overall carbon emissions. Installations that capture low CO_2 levels cannot be viewed as "decarbonised" – as illustrated by the world's only commercial-scale CCUS facility for steelmaking.

Poor results at the only commercial-scale CCUS plant for steel

The Al Reyadah CCUS facility is the first and only commercial-scale plant in the steel sector. Commissioned in 2016, its primary objective is to receive captured CO_2 from a DRI-based steel plant owned by Emirates Steel Arkan and transport it for use in EOR operations. Based on Emirates Steel Arkan's disclosed emissions figures, and assuming the carbon capture facility was operating at full capacity (0.8Mt per annnum), the plant captured less than 20% of the total Scope 1 and Scope 2 emissions in 2020 and 2021.

In 2022, Emirates Steel Arkan was able to reduce its Scope 2 emissions significantly by procuring electricity produced from nuclear and solar power generation. This led to an increase in the percentage of overall Scope 1 and 2 emissions captured in 2022, though it was still only 26%. This rise was not attributable to the improved performance of the CCUS facility but rather to a greater proportion of clean electricity utilised in the total electricity consumption mix.

Despite being operational for seven years, and having a use for the captured CO_2 in EOR, no other commercial-scale carbon capture facilities for DRI-based steelmaking have been built. Meanwhile, Emirates Steel Arkan is now turning to alternative technology that it appears to consider is more effective for decarbonising steel. The company is establishing the first pilot project for DRI-EAF using green hydrogen in the Middle East, expected to start up in 2024.

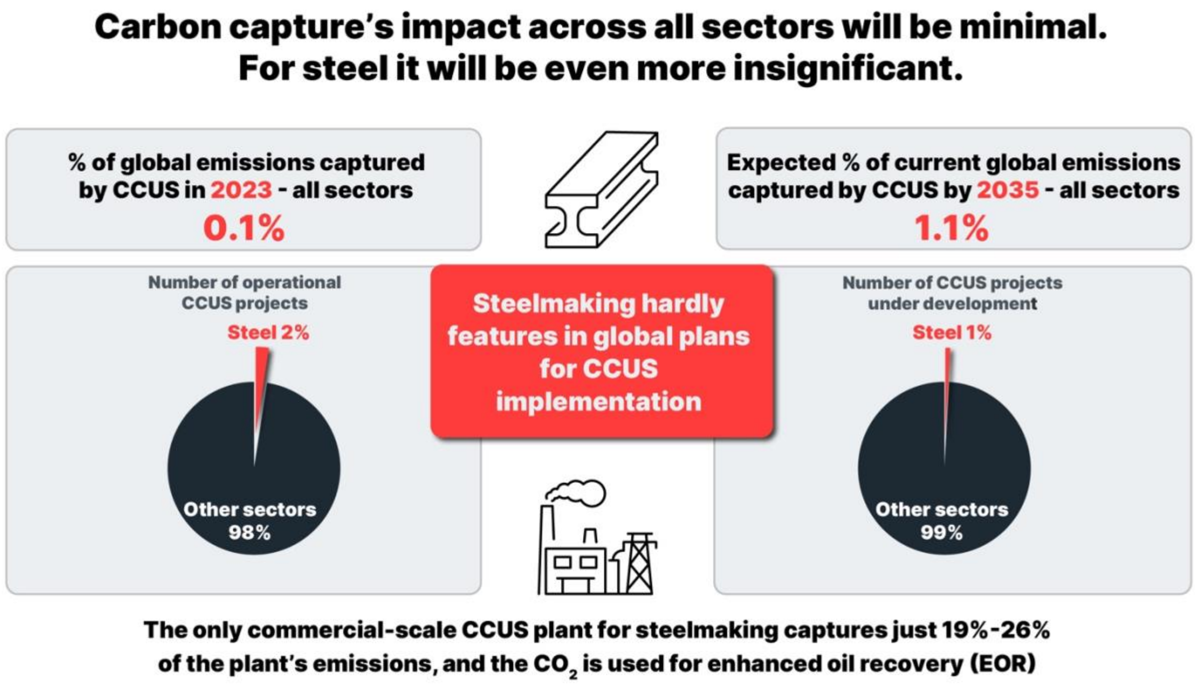
The outlook for steel CCUS

The Global CCS Institute (GCCSI) published its 2023 *Global Status of CCS Report* in November 2023. Despite carbon capture and storage (CCS) having been around for decades, the GCCSI is tracking just 41 commercial-scale projects in operation globally, with 351 in development. With the great majority of these categorised as being only in “early development” (i.e. a long way from final design or investment decision), IEEFA expects a large proportion to never reach commercial operation.

Of the combined 392 projects, just four are in the steel sector, including the operational Al Reyadah project. Three of these are for DRI-based steel plants, not for blast furnace-based steelmaking - the dominant and most carbon-intensive process. Two of the projects under development are only in the early development stage. Although the GCCSI's report highlights an increase in the carbon capture project pipeline, this rise appears to have passed the steel industry by.

The IEA has a track record of reliance on CCUS for decarbonisation in its scenarios, but recently this appears to have started to shift in its long-term view on steel decarbonisation. In its landmark 2021 report *Net Zero by 2050: A Roadmap for the Global Energy Sector*, the IEA saw CCUS-equipped processes making up 53% of global primary steel production in 2050. In this first iteration of the IEA's Net Zero Emissions by 2050 Scenario (NZE), 670 million tonnes (Mt) of CO_2 would be captured from these processes.

However, just two years later the IEA's view had already started to change significantly. In its 2023 update to the NZE Scenario, the IEA sees CCUS-equipped processes' 2050 share of iron production down to 37%. The amount of CO_2 captured in the global steel sector has been downgraded to 399Mt, from 670Mt in the 2021 version. At the same time, the share of hydrogen-based steelmaking has increased from 29% in 2021 to 44% in the 2023 update. IEEFA expects that the IEA will continue to decrease the role it expects CCUS to play in steel decarbonisation in future updates.



Source: Bloomberg New Energy Finance, Global CCS Institute, IEEFA calculations

CCUS will not play a major role in decarbonising blast furnace steelmaking

The majority of global steel is currently produced in integrated, blast furnace-based steel plants. One key reason why CCUS for blast furnace-based steelmaking has not made an impact – and is unlikely to going forward – is that these plants have multiple sources of carbon emissions. Retrofitting multiple CCUS systems to such plants would incur significant additional cost.

Due to the high cost of CCUS, potential developers of the technology often state that a significant carbon price is needed to stimulate its implementation. Despite a clear and significant carbon price signal in the EU, CCUS for steel in Europe has made little or no commercial progress. If steel CCUS cannot advance in Europe where there is a significant carbon price, it cannot be expected to make headway in developing Asia, the seat of major steel demand growth.

The German think tank Agora Industry highlights that, since 2020, commercial-scale project announcements for new DRI-based steel plants and for CCUS projects for blast furnace-based steelmaking have developed very differently. To date, virtually all steel companies that plan to build low-carbon steelmaking capacity at commercial scale have opted for hydrogen-based or hydrogen-ready DRI plants, not CCUS. The 2030 project pipeline of DRI plants has grown to 94 million tonnes a year (Mtpa), while the pipeline for commercial-scale CCUS on blast furnace-based operations amounts to just 1Mtpa. It is clear that CCUS for blast furnace-based steelmaking is already being left behind by alternative technology, just as has happened in other sectors such as power generation.

Long-term risks for coal-based steelmaking are growing

As well as low capture rates, CCUS for integrated, blast furnace-based steel plants does nothing to address the emissions associated with metallurgical coal mining, particularly methane emissions. Total methane emissions from coking coal mines globally totalled 10.5Mt in 2023, according to the IEA. This equates to up to 913.5Mt CO_2 equivalent over a 20-year impact timeframe. For comparison, global emissions from steelmaking amount to around 2,800Mt CO_2 per annum.

This, along with low capture rates at integrated steelmaking sites, will likely mean that any CCUS installations will not decarbonise steel production enough to satisfy the growing number of steel consumers demanding truly green steel. Car makers are already signing purchase agreements for green steel made using green hydrogen with virtually no emissions. Tighter definitions of what exactly constitutes “green steel” can be expected in the near future. There is a significant risk that the low capture rates of CCUS will mean steel produced this way will not meet such definitions. Steelmakers will become increasingly exposed to the risk that steel consumers will not want coal involved in their supply chains at all. Investors should have questions for steelmakers that continue to maintain that CCUS will play a significant decarbonisation role.

At COP28, parties agreed to accelerate the deployment of low- and zero-emissions technologies, including “carbon capture utilisation and storage, particularly in hard-to-abate sectors…” The phrases “hard to abate” and “carbon capture and storage” often go hand in hand. Some steelmakers seem to be using the phrase “hard to abate” as an excuse to justify indefinite plans for CCUS in future decades while continuing business-as-usual to a large extent.

Where better and more cost competitive alternatives exist, CCUS is unlikely to play a role in decarbonisation. Global steelmakers will increasingly shift from blast furnaces to recycling steel in EAFs and DRI-based processes that can shift to green hydrogen. This process is already well underway. Using green hydrogen in DRI and renewable energy to power EAFs enables the production of truly low-carbon steel, a feat CCUS looks unable replicate.

Introduction

In Dubai on 13 December 2023, almost 200 nations agreed on a need to increase climate action before the end of the decade, marking the key outcome of the 28th Conference of the Parties (COP28) climate conference.[1] For the first time at a COP, parties agreed to transition away from fossil fuels.[2]

As part of the same global stocktake, parties also agreed to accelerate the deployment of low- and zero-emissions technologies including "carbon capture utilisation and storage, particularly in hard-to-abate sectors…"[3]

Steelmaking is often termed a "hard-to-abate" sector despite the fact that some of the key technologies that can enable the decarbonisation of steel, such as scrap steel recycling and direct reduced iron (DRI) are mature and increasingly widely used. The key DRI technology providers – Midrex and Tenova/Danieli – have even made clear that their technology is ready to use green hydrogen. The phrase "hard to abate" is increasingly out of date when it comes to steel.[4]

Despite this, it is generally assumed that steel is one of the sectors being referred to in the global stocktake text on carbon capture utilisation and storage (CCUS), along with other industries such as cement and chemicals. Many major steelmakers and iron ore producers have CCUS as part of their long-term decarbonisation plans.[5]

However, the track record of CCUS in other sectors is one of persistent and significant underperformance.[6] One week before COP28 commenced, Fatih Birol – Executive Director of the International Energy Agency (IEA) – termed the oil and gas sector's idea that carbon capture can allow the continued production of fossil fuels while meeting climate goals an "illusion".[7]

Furthermore, there has been virtually no progress on commercial-scale CCUS for the decarbonisation of blast furnaces. CCUS will likely need to play a role in decarbonising truly hard-to-abate sectors like cement where other options are limited. In the steel sector, however, alternative decarbonising technologies are available and their uptake is accelerating. This report highlights why it is unrealistic to expect that carbon capture technology will play a major role in enabling steelmakers to reach net zero emissions.

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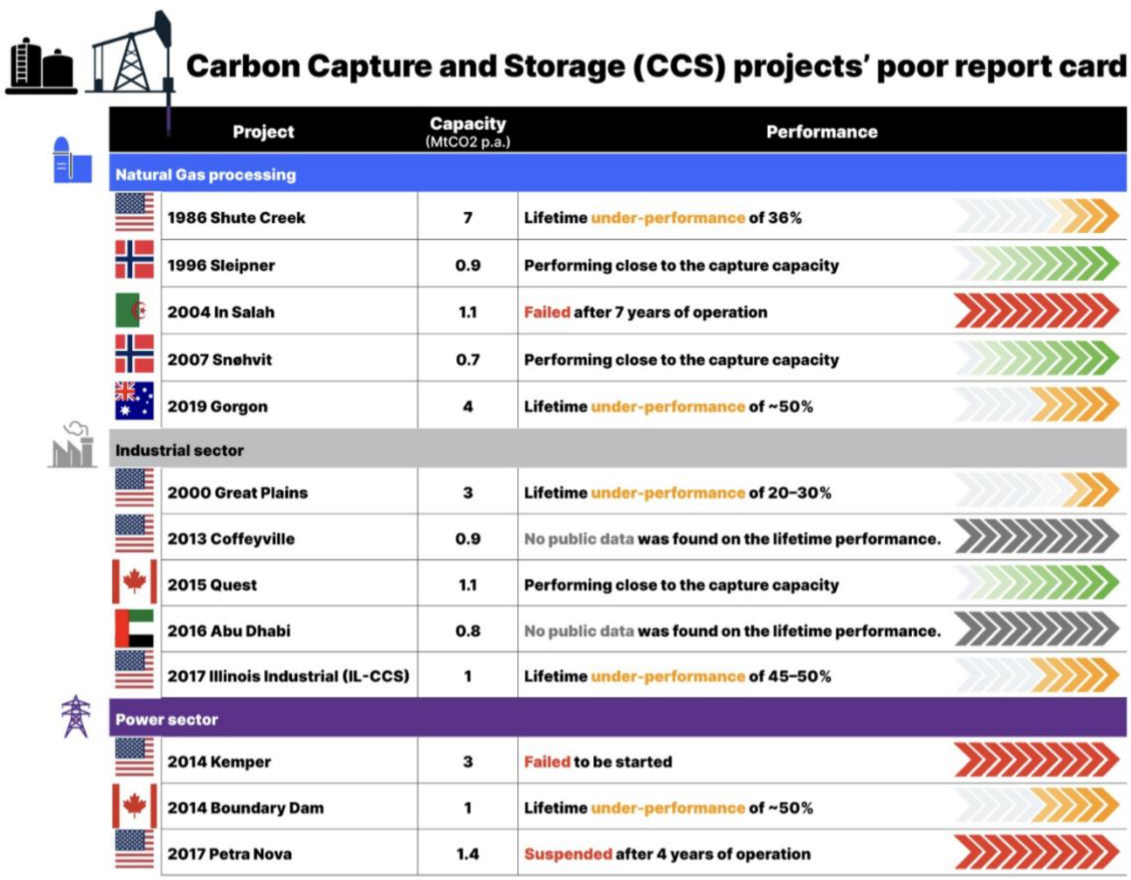
[1] United Nations Framework Convention on Climate Change (UNFCCC). COP28 Agreement Signals "Beginning of the End" of the Fossil Fuel Era. 13 December 2023.
[2] Financial Times. Countries reach 'historic' COP28 deal to transition away from fossil fuels. 14 December 2023.
[3] UNFCCC. Outcome of the first global stocktake. 13 December 2023. Page 5.
[4] IEEFA. "Hard-to-abate" must not become code for delaying steel decarbonisation. 24 January 2023.
[5] IEEFA. BHP quotes outdated figures as efforts to prop up carbon capture for steel start to get desperate. 15 December 2023
[6] IEEFA. The Carbon Capture Crux: Lessons Learned. 1 September 2022.
[7] IEA. Oil and gas industry faces moment of truth – and opportunity to adapt – as clean energy transition advances. 23 November 2023.

CCUS has a poor track record in other sectors

CCUS technology has been around for nearly 50 years and has accumulated a history of significant underperformance. Attempts have been made to apply CCUS in various sectors including oil and gas production, power generation, petrochemical, hydrogen production and industry. According to Bloomberg New Energy Finance (BNEF), CCUS capacity currently captures only 0.1% of global emissions despite decades of implementation efforts.[8] The IEA in its updated *2023 Net Zero Roadmap* report noted that: “The history of CCUS has largely been one of underperformance.”[9]

In 2022, IEEFA published research that showed that out of 13 flagship, large-scale CCUS projects, five materially underperformed, two were suspended, one was mothballed and two didn’t provide data that allowed performance to be assessed.

Figure 1: The poor track record of key carbon capture and storage projects globally



Carbon Capture and Storage (CCS) projects’ poor report card

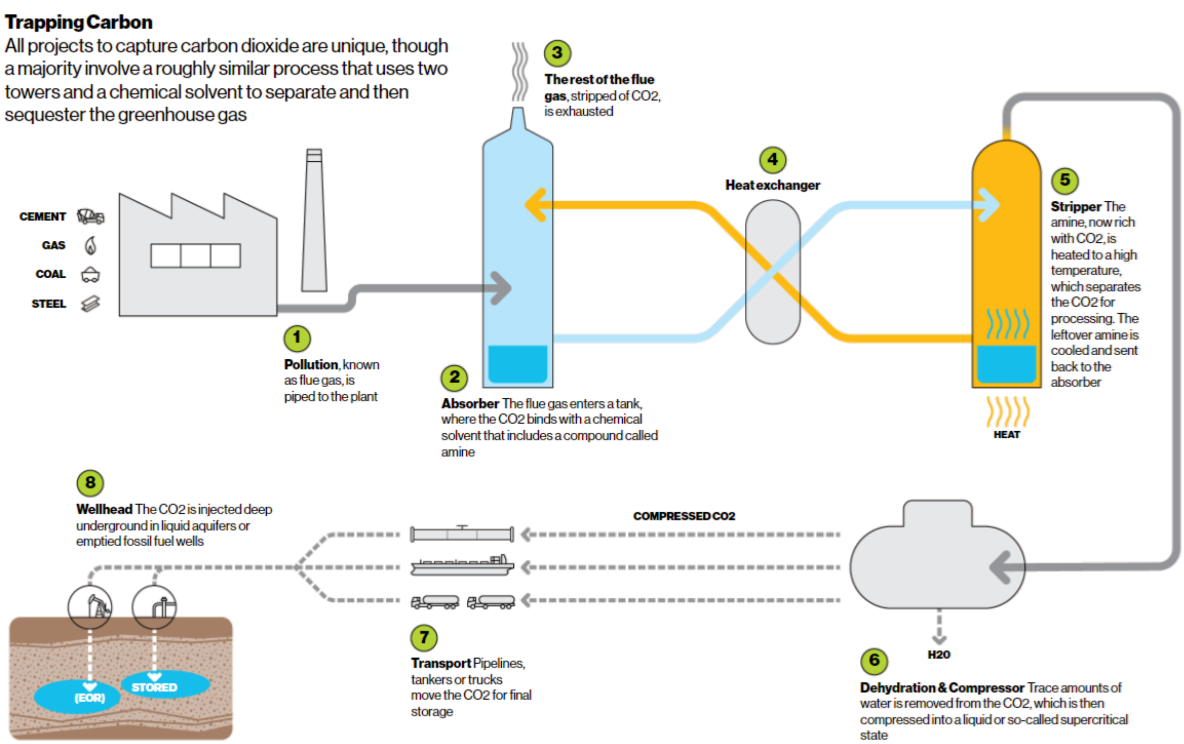
Project	Capacity (MtCO2 p.a.)	Performance
Natural Gas processing		
1986 Shute Creek	7	Lifetime under-performance of 36%
1996 Sleipner	0.9	Performing close to the capture capacity
2004 In Salah	1.1	Failed after 7 years of operation
2007 Snøhvit	0.7	Performing close to the capture capacity
2019 Gorgon	4	Lifetime under-performance of ~50%
Industrial sector		
2000 Great Plains	3	Lifetime under-performance of 20–30%
2013 Coffeyville	0.9	No public data was found on the lifetime performance.
2015 Quest	1.1	Performing close to the capture capacity
2016 Abu Dhabi	0.8	No public data was found on the lifetime performance.
2017 Illinois Industrial (IL-CCS)	1	Lifetime under-performance of 45–50%
Power sector		
2014 Kemper	3	Failed to be started
2014 Boundary Dam	1	Lifetime under-performance of ~50%
2017 Petra Nova	1.4	Suspended after 4 years of operation

Source: IEEFA. The Carbon Capture Crux, Lessons Learned, September 2022

[8] BNEF. CCUS Market Outlook 2023: Announced Capacity Soars by 50%. 6 November 2023.
[9] IEA. Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach. September 2023.

The study found that nearly three quarters of captured carbon dioxide (CO_2) is being used for enhanced oil recovery (EOR). Enabling the extraction of more fossil fuels cannot be regarded as an emissions reduction solution. Furthermore, the application of CCUS to oil and gas production does nothing to address the much greater Scope 3 emissions impact of these fossil fuels when used. (Scope 3 emissions amount to 80 to 95% of total oil and gas company emissions).[10] IEEFA's research affirmed that CCUS is susceptible to significant financial, technological and environmental risks, made worse by uncertainty over the effectiveness of geological CO_2 storage over decades.[11]

Figure 2: Carbon capture and storage steps



Source: Bloomberg.[12]

Occidental Petroleum's Century project is one example from a growing list of failed CCUS projects. Built in 2010, it was meant to become the biggest carbon capture project to date. CO_2 was to be captured at a gas processing plant in Texas and used for EOR. Over 13 years of operation, it was unable to operate at more than one third of its capacity, leading to the eventual sale of the project at a fraction of its cost. Occidental received around USD200 million, equivalent to less than a quarter of

[10] Wood Mackenzie. Few oil and gas companies commit to Scope 3 net zero emissions as significant challenges remain. 28 October 2022
[11] IEEFA. The carbon capture crux: Lessons learned. 01 September 2022.
[12] Bloomberg. Big Oil's Climate Fix Is Running Out of Time to Prove Itself. 13 September 2023.

the construction expenses. Between 2018 and 2022, the project managed to achieve less than 10% of its nameplate capacity of 8.4 million tonnes per annum (Mtpa).[13]

CCUS projects face various risks that can lead to failure. The Century failure stemmed from inaccurate estimates of gas processing capacity, particularly the lack of adequate contingencies for a gas market that experienced a significant price downturn in the years following the CCUS plant commission.

In addition to economic issues, many CCUS projects are grappling with technical hurdles. A list of projects that faced major technical issues, causing delays in their operation, such as the Gorgon project in Western Australia, or even halting operations due to concerns about CO_2 leakage, as seen in the In Salah project in Algeria, serves as an example of the challenges associated with transportation and storage.[14,15]

The Gorgon project, part of Chevron's 15.6Mtpa Gorgon liquefied natural gas (LNG) venture and one of the largest carbon capture and storage (CCS) initiatives (focusing on storing captured CO_2 rather than utilising it in EOR) has consistently under-performed. Originally designed to store at least 80% of the gas reservoir CO_2, the project fell well short.[16,17]

The project encountered technical hurdles during commissioning, particularly concerning pipeline corrosion. This issue required the installation of new instruments, resulting in a delay of approximately three years in the project's start-up. A significant challenge arose when Chevron failed to extract water from the underground formation quickly enough to create sufficient space for CO_2, leading to a hazardous increase in pressure.[18] The project has sequestered far less CO_2 than intended, storing only 34% of the CO_2 captured in the last fiscal year to 30 June 2023. Taking Scope 3 emissions into account, less than 4% of the total emissions that the Gorgon LNG project is responsible for are captured.[19]

The plight of the Gorgon project highlights that CCUS developers face an additional challenge in addressing the specifics of each project, exposing them to unforeseeable challenges. Unlike modular climate solution technologies like solar or wind for electricity generation or electrolysers for green hydrogen production, the nature of CCUS projects necessitates a more customised design. The chemical composition of effluents being addressed, the concentration of CO_2 within those effluents and even the physical location and environment where the process is being attempted requires a

[13] Bloomberg. An Oil Giant Quietly Ditched the World's Biggest Carbon Capture Plant. 23 October 2023.
[14] IEEFA. The carbon capture crux: Lessons learned. 1 September 2022.
[15] IEEFA. The Good, the Bad and the Ugly reality about CCS. 12 March 2024.
[16] The Guardian. Emissions from WA gas project with world's largest industrial carbon capture system rise by more than 50%. 21 April 2023.
[17] Chevron. Gorgon Gas Development and Jansz Feed Gas Pipeline Environmental Performance Report 2023. 7 November 2023. Page 64.
[18] The Sydney Morning Herald. World's biggest carbon storage project off WA coast burying only a third of what it promised. 14 November 2023.
[19] IEEFA. Australia's CCS expansion poses increased risks. 20 December 2023.

bespoke design every time, whether adsorption, absorption or membrane CO_2 removal processes are being used. There is no off-the shelf, turnkey solution for CO_2 removal.

> **The uniqueness of each CCUS project limits technological learning and cost reductions.**

The uniqueness of each CCUS project limits technological learning and cost reductions. The cost of carbon capture implementation has hardly reduced in 40 years, while the cost of alternative technologies like renewable energy and battery storage has plunged, with further reductions to come.[20]

The additional issue with CCS projects lies in the accessibility of appropriate geological storage locations near the point of CO_2 emission. In the steel sector, even if all steel mills were retrofitted with capturing facilities, the transportation and storage of CO_2 in secure, dedicated geological reserves pose a significant challenge, requiring detailed studies for each project individually. Few existing steel mills are likely to be located close to reliable geological storage for captured CO_2. Transporting CO_2 over large distances to storage sites entails significant additional costs and risks.

In addition, the permanency of CO_2 storage must be regularly checked through monitoring and field surveillance to detect potential leakage and ensure that stored CO_2 does not return to the atmosphere.[21] The process entails extra expense for decades even after the closure of projects.[22]

CCS hubs have been conceptualised in various locations globally to collaborate on a significant project, with a predominant focus on offshore storage sites such as the US Gulf of Mexico, Malaysia and the European North Sea. The technology involved necessitates in-depth studies and stringent regulations to ensure the long-term safety of storage.[23] The limited worldwide experience with CCS raises concerns about the feasibility of proposed offshore ventures, especially regarding environmental, health and safety risks linked to potential CO_2 leaks from underwater pipelines and storage sites. Targeting offshore CCS in oil and gas production zones, where the risk of leaks is heightened, is considered problematic. Historical challenges in monitoring industrial activities in the ocean cast doubt on the efficacy of oversight for offshore CCS. This approach also calls for reinforced regulatory frameworks to monitor long-term storage effectively.[24]

While the Sleipner and Snøhvit CCS facilities in Norway are frequently cited as successful instances of offshore CCS, challenges persist in the domain of long-term geological storage. Continuous surveying and monitoring are essential due to the unpredictable nature of extended storage beneath the ground. In the Sleipner project, the injected CO_2 inadvertently reached a large, shallow, risky

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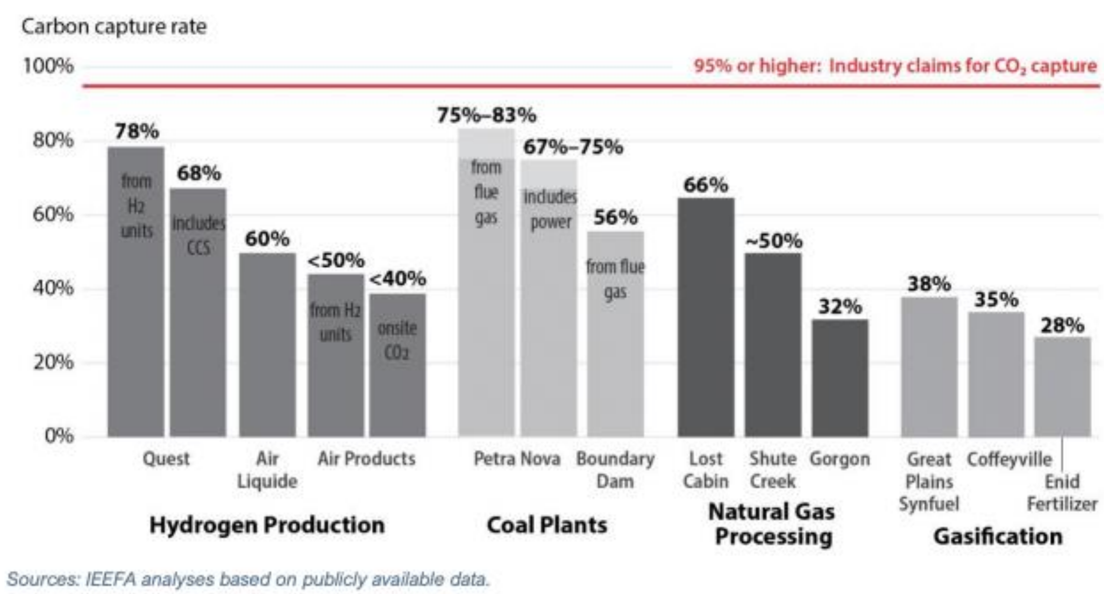
[20] Smith School of Enterprise and the Environment. Heavy dependence on Carbon Capture and Storage 'highly economically damaging', says Oxford report. 11 March 2024.
[21] Vista Projects. Carbon Capture and Storage Projects: Monitoring, Measurement, and Verification. Last updated 28 March 2022.
[22] IEEFA. Norway's Sleipner and Snøhvit CCS: Industry models or cautionary tales? 14 June 2023.
[23] Scientific American. The False Promise of Carbon Capture as a Climate Solution. 1 March 2024.
[24] CIEL. Deep Trouble. The Risks of Offshore Carbon Capture and Storage. June 2023.

underground layer that geophysicists completely missed during study and design, jeopardizing the project's containment goals. Similarly, the Snøhvit case necessitated prospecting for a replacement CO_2 storage site after the initially targeted storage pore space, thought to be ideal for years' worth of injections, stated rejecting CO_2 within months of operations, again despite extensive site studies and laboratory research.[25] While the Snøhvit project was fortunate enough to implement successful back-up plans after spending hundreds of millions of dollars not intended, initiatives like Gorgon faced major technical challenges, leading to long delays in commissioning and the purchase of carbon credits to bridge the gap between initial plans and actual results.[26]

There are questions about the extent to which governments are prepared and able to maintain the critical responsibility of ensuring the secure maintenance of stored CO_2 for decades, even after the project ends. The task entails precise regulations at governmental levels globally, as they may not be adequately prepared for it. The problems faced by Norway's two flagship CCS projects, Sleipner and Snøhvit, raise additional concerns about whether sufficient expertise exists to tackle the unprecedented technical challenges, necessitating a supportive regulatory framework and a commitment to guide efforts in ensuring the permanent burial of sequestered CO_2 beneath the seabed without any risk of leakages.[27]

Figure 3: CO_2 real-world capture rates at commercial-scale hydrogen production, coal-fired power plants, natural gas processing and gasification facilities



A key point about CCUS that is often missed is its low capture rates. Confronted with numerous technical and financial challenges, CCUS projects have consistently encountered difficulties in

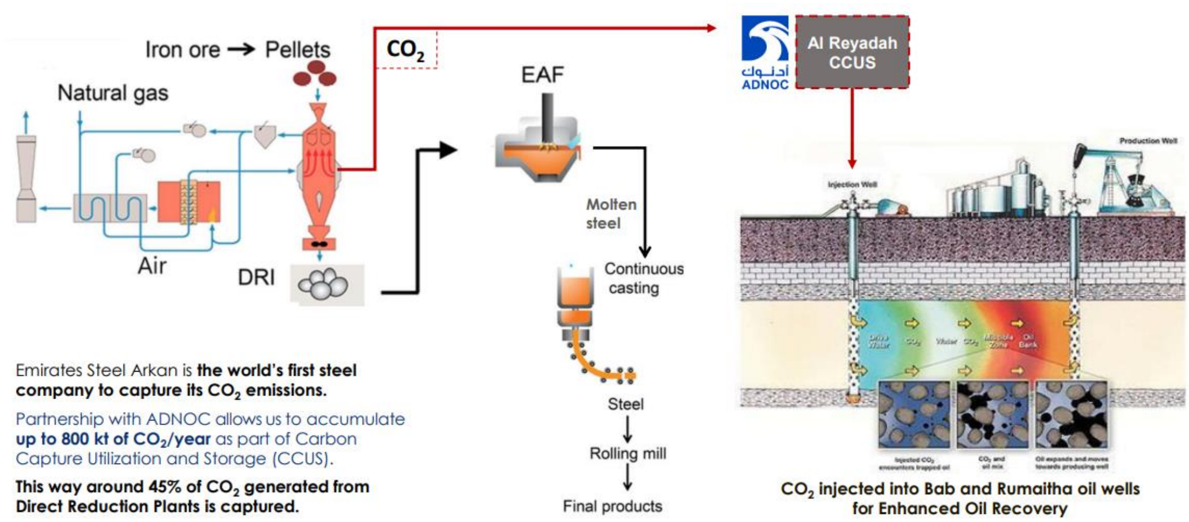
[25] IEEFA. Norway's Sleipner and Snøhvit CCS: Industry models or cautionary tales? 14 June 2023.
[26] AFR. Chevron to invest $40m, buy credits to offset CCS shortfall. 11 November 2021.
[27] IEEFA. Norway's Sleipner and Snøhvit CCS: Industry models or cautionary tales? 14 June 2023.

reaching their targeted capture rates. Furthermore, targeted carbon capture is itself often far less than overall carbon emissions. The amount of CO_2 captured by existing plants is significantly lower than the 85%-95% that industry claims is achievable (Figure 3).[28,29] Installations that see low levels of CO_2 captured cannot be considered "decarbonised." This issue is well illustrated by the performance of the world's only commercial-scale CCUS facility for steelmaking.

Al Reyadah: How is the world's only commercial-scale CCUS facility for steel performing?

The Al Reyadah facility in the United Arab Emirates (UAE) is the first and only commercial-scale CCUS plant in the steel sector and has a nominal capacity to capture 0.8Mt of CO_2 annually. Commissioned in 2016, its primary objective is to receive CO_2 from a steel facility operated by Emirates Steel Arkan and transport it for use in EOR operations. The steel plant is DRI-based rather than blast furnace-based. This facility was a joint venture with Abu Dhabi National Oil Company (ADNOC) and clean energy company Masdar, utilising the captured CO_2 in ADNOC's onshore oilfields – Rumaitha (43km away) and Bab (120km away) – to enhance oil production. In 2018, ADNOC acquired Masdar's 49% share, becoming the sole owner of the project.[30]

Figure 4: Al Reyadeh CCUS plant



Source: Emirates Steel Arkan.[31]

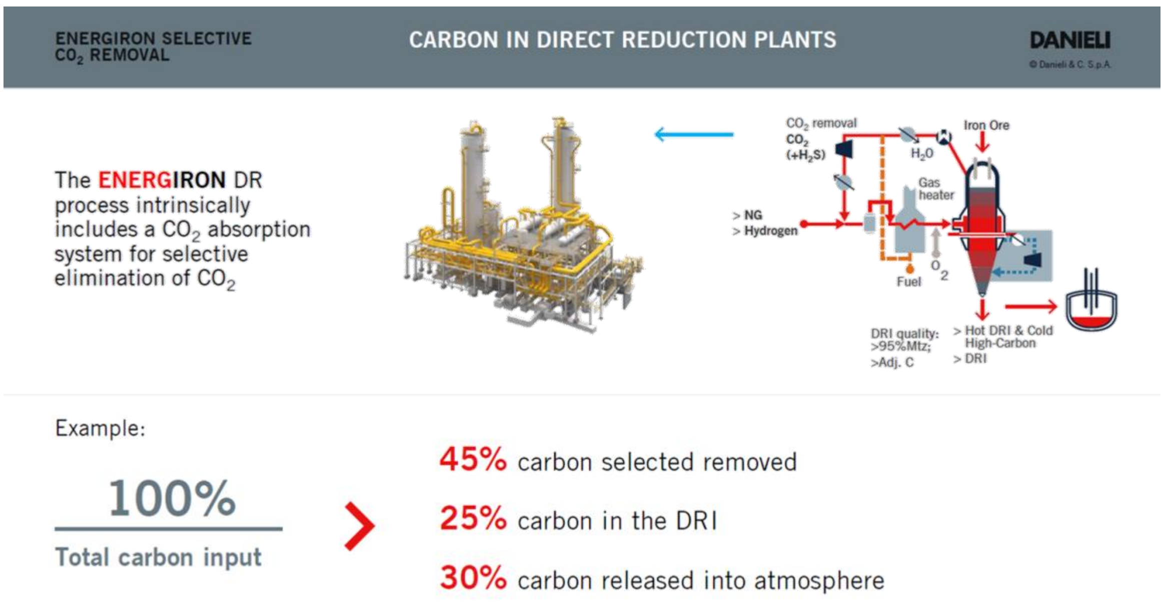
[28] IEEFA. Blue Hydrogen: Not Clean, Not Low Carbon, Not a Solution. 12 September 2023
[29] Smith School of Enterprise and the Environment. Assessing the relative costs of high-CCS and low-CCS pathways to 1.5 degrees. 4 December 2023. Page 17.
[30] Middle East Oil and Gas. ADNOC acquires remaining 49% share of Al Reyadah. 15 January 2018.
[31] Emirates Steel Arkan. Investor Presentation. November 2023. Page 14.

ADNOC receives wet CO_2 at atmospheric pressure and is responsible for compressing, dehydrating and pressurising it, transporting it via pipelines, and injecting it into the oil wells. The received CO_2 is approximately 89% pure, with the remaining content being water vapour. ADNOC dehydrates it to make it suitable for subsequent processes.[32]

DRI carbon capture

There are two main DRI technology providers globally – Energiron (a technology provided by Tenova and Danieli) and Midrex. Emirates Steel Arkan operates Energiron DRI technology, which includes a selective CO_2 removal system (Figure 5).

Figure 5: Energiron selective CO_2 removal



Source: Danieli.[33]

According to the carbon balance calculation, approximately 45% of the total carbon input from gas can be captured in the form of CO_2 through the selective removal system, with another 30% being vented in the flue gases. The remaining balance is combined with the final product in DRI. This is different from the other main direct reduction (DR) technology (from Midrex), which lacks an embedded facility for capturing CO_2 and essentially vents 86% of the carbon in the form of CO_2, with the remaining 14% being combined carbon in the DRI (Figure 6).[34]

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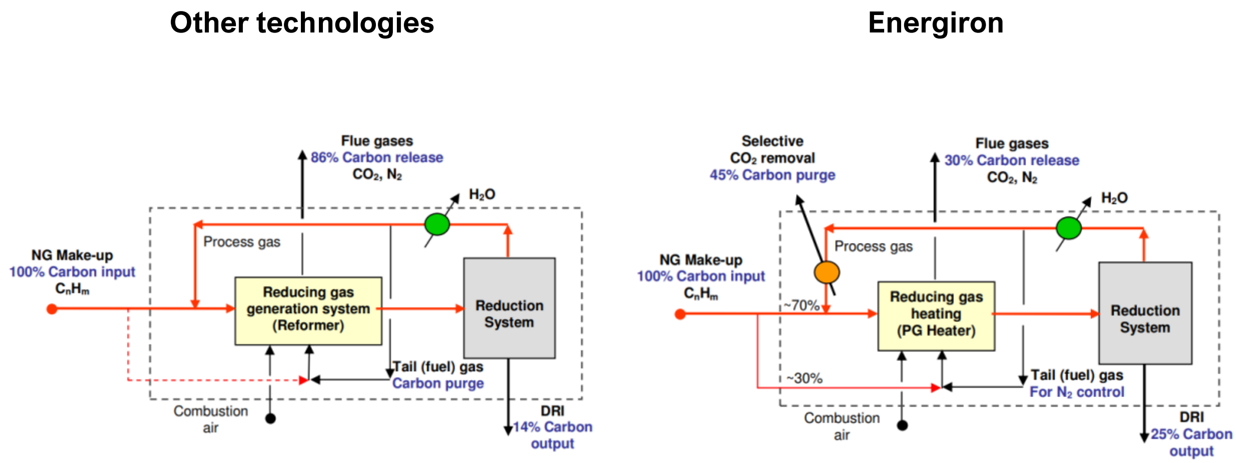
[32] The Global CCS Institute. CCS in the Middle East-present and future. 27 January 2022.
[33] Danieli. Green Steel Production Through Hydrogen-Based Energiron DRI Process. 17 November 2021. Page 11.
[34] Energiron. Achieving carbon-free emissions via the Energiron DR process.

Figure 6: The carbon balance in DR technologies



Source: Energiron.[35]

Even with Energiron, capturing all the CO_2 from various emissions points in the direct reduction process is not feasible. The technology provider has concentrated efforts on capturing CO_2 from only one specific emission point - the main direct reduction reactor. Based on the Energiron design, nearly 0.25 tonnes of CO_2 per tonne of DRI can be captured.[36,37] To increase the carbon capture rate, a separate carbon capture system would need to be added to capture the CO_2 vented with flue gases (encompassing 30% of the total carbon input), incurring extra expense. For DRI technologies, flue gas carbon capture would be a necessary addition to achieve any reduction in CO_2 emissions where the plant is based on natural gas.

Although Midrex technology lacks a carbon removal system in gas-based reduction shafts, the company asserts that CO_2 can be captured from two points within the system:

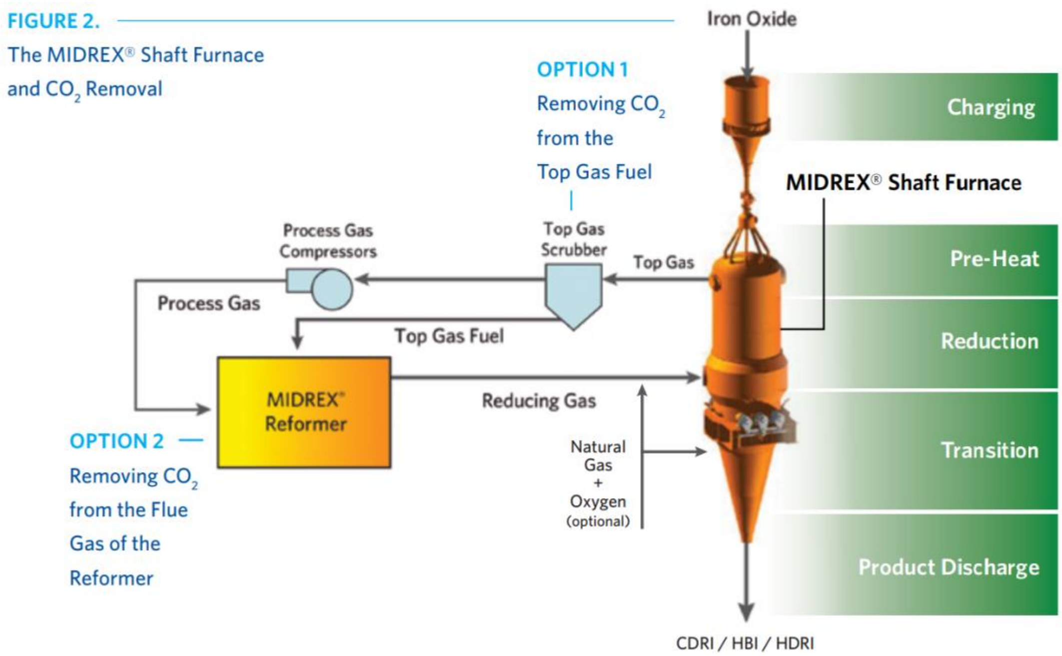
1. Remove CO_2 from the top gas fuel, which is used in the reformer for heating. CO_2 emissions can be reduced by 0.25-0.35 tonnes per tonne of DRI.

2. Remove CO_2 from the flue gas of the reformer, after heat recovery. CO_2 emissions can be reduced by about 0.5 tonnes per tonne of DRI. [38]

Capturing CO_2 from flue gas poses increased difficulty and potentially higher costs, given that the CO_2 concentration in flue gas is lower compared with the top gas stream.[39]

[35] Energiron. Achieving carbon-free emissions via the Energiron DR process. Page 6.
[36] Ibid. Page 7
[37] Danieli. Green Steel Production Through Hydrogen-Based Energiron DRI Process. 17 November 2021. Page 12.
[38] Midrex. MIDREX NG™ with H2 Addition: Moving from natural gas to hydrogen in decarbonizing ironmaking. March 2022.
[39] Green Steel World Magazine. Blue DRI for Greener Steel. February 2024.

Figure 7: Midrex carbon removal options



Source: Midrex.[40]

Assessing Al Reyadah's capture performance

Despite the fact that the Al Reyadah plant has been operating for eight years, detailed performance data remains undisclosed to the public. Nonetheless, in its investor presentation of November 2023, the company asserted that the CCS facility enabled them to capture approximately 45% of the CO_2 emissions from direct reduction plants (Figure 4).[41] In contrast, the investor presentation in May of the same year indicated a capture rate of only 30% was achieved in 2022.[42]

However, the direct reduction shaft furnaces are not the only point of CO_2 emissions at a DRI-based steel plant. Emirates Steel Arkan operates two Energiron DRI shafts, each with a nominal capacity of 2Mtpa, following a revamp in 2014. The plant has three steelmaking and five rolling mills facilities as well. The plant also incurs Scope 2 emissions from the consumption of electricity.

Table 1 shows the effectiveness of the CCUS plant in reducing Emirates Steel Arkan's total Scope 1 and 2 emissions. Based on emissions figures disclosed in Emirates Steel Arkan's Sustainability Report[43], and assuming the maximum CO_2 emissions of 0.8Mt per annum is being captured, CCUS

[40] Midrex. Ironmaking technology for a sustainable steel industry. Page 5.
[41] Emirates Steel Arkan. Investor Presentation. November 2023. Page 14.
[42] Emirates Steel Arkan. Investor Presentation. May 2023. Page 12.
[43] Emirates Steel Arkan. Sustainability Report 2022.

was capturing less than 20% of the total Scope 1 and 2 emissions in 2020 and 2021.[44] Given that carbon capture is limited to 0.8Mt per annum, the carbon capture rate would have been even lower if the plant was operating at full steelmaking capacity.

Table 1: Emirates Steel CCUS capture rates and increasing low-emissions electricity purchase

Description	Index	Unit	2020	2021	2022
Disclosed maximum CO_2 capture	A	tonne	800,000	800,000	800,000
Disclosed Scope 1	B	tCO_2e	1,904,805	2,094,888	2,024,973
Disclosed Scope 1 + 0.8Mt CO_2 as captured by CCUS plant	A+B	tCO_2e	2,704,805	2,894,888	2,824,973
Disclosed Scope 2 (market-based)	C	tCO_2e	1,434,462	1,120,521	249,220
Scope 1 and 2 + 0.8Mt CO_2 from the CCUS plant	A+B+C	tCO_2e	4,139,267	4,015,409	3,074,193
Rate of capture of total emissions	(A/(A+B+C))	%	19.3%	19.9%	26.0%

Source: Emirates Steel Arkan Sustainability Report, IEEFA calculations. tCO_2e = tonnes of carbon dioxide equivalent.
Notes:

Adding 0.8Mt of captured CO_2 to Scope 1 emission to determine the total emissions before using CCS.

As of 2022, Emirates Steel Arkan purchased a 2 million MWh clean energy certificate that covered 80% of the steel mill's total electricity consumption. While the CCUS facility at the Emirates Steel plant has limited capacity, the adoption of low-emissions power procurement in 2022 reduced Scope 2 emissions by 83% compared with 2020. As a result, there was an increase in the percentage of overall Scope 1 and 2 emissions capture in 2022.

Furthermore, the Emirates Steel Arkan plant lacks a pelletising facility and procures all its pellets from external sources. Other materials such as calcined lime and dolomite, produced with high CO_2 emissions methods, are also purchased. As such emissions from production of these materials would be considered Scope 3. The production of these materials can be carbon-intensive – for example, iron ore pellets entail 0.137 tonnes of CO_2 emissions per tonne, and limestone entails 0.440 tonnes

[44] Deloitte. Scope 1, 2 and 3 emissions

of CO_2 per tonne[45]. The carbon capture facility at Al Reyadah does nothing for reduction of emissions resulting from these processes.

In 2022, Emirates Steel Arkan was able to reduce its Scope 2 emissions significantly by procuring electricity produced from nuclear and solar power generation.[46] As a result, there was an increase in the percentage of overall Scope 1 and 2 emissions captured in 2022 (26%). It is important to note that this rise in the capture rate was not attributable to improved performance of the CCUS facility, but rather to a greater proportion of clean electricity utilised in the total electricity consumption mix.

A previous assessment of the amount of CO_2 captured at Al Reyadah in a report for the European Union estimated a capture rate of 25%. This figure was based on an estimate of the steel plant's total emissions of 3Mtpa, close to the actual, disclosed Scope 1 and 2 emissions in 2022.[47]

Although some CO_2 can be captured in Emirates Steel Arkan's Energiron DRI plant, it appears that other DRI facilities release it into the atmosphere, as they either do not have carbon storage or usage options, or the cost of doing so is too great. Despite Al Reyadah being operational for eight years, and having a use for the captured carbon in EOR, no other commercial-scale carbon capture facilities for DRI-based steelmaking have been built. ADNOC continues to invest in CCS technology across various global projects.[48,49] Part of ADNOC's sustainability strategy is to increase its carbon capture capacity to 10Mtpa by 2030.[50]

Meanwhile, Emirates Steel Arkan is planning to transition to green hydrogen. In collaboration with Masdar, which has already divested its shares in the Al Reyadah project to ADNOC, Emirates Steel Arkan is teaming up to establish the first pilot project for DRI-EAF steelmaking using hydrogen (H_2-DRI-EAF) in the MENA region.[51] The electrolysers have already been delivered, and the project is expected to start up in 2024. Eight years after commissioning the Al Reyadah carbon capture project, Emirates Steel Arkan appears to be shifting focus to an alternative that has a better outlook for true steel decarbonisation.

[45] Worldsteel. CO2 Data Collection User Guide, version 11. 23 August 2023.
[46] Emirates Steel Arkan. Investors Presentation. November 2023.
[47] Publications Office of the European Union. Technologies to decarbonise the EU steel industry. 2022.
[48] ADNOC. ADNOC Makes Strategic Investment in Storegga, Broadening its Carbon Management Portfolio. 08 January 2024.
[49] ADNOC. ADNOC to Invest in One of the Largest Integrated Carbon Capture Projects in MENA. 06 September 2023.
[50] ADNOC. Our 2030 Sustainability Strategy.
[51] Hydrogen Insight. Electrolysers already delivered for UAE's first green hydrogen-based steel project. 23 November 2023.

The outlook for steel CCUS

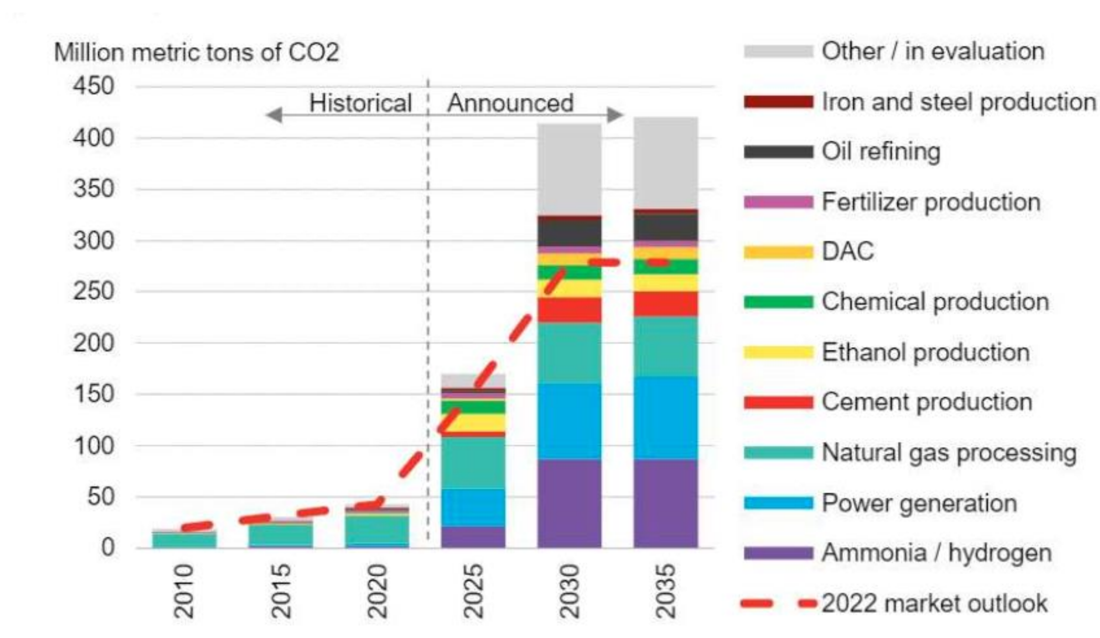
Some forecasts seem to suggest an optimistic role for CCUS in steelmaking going forward. However, when put into context, the outlook is highly doubtful.

Bloomberg New Energy Finance

In its most recent *CCS Market Outlook* report, published in November 2023, BNEF forecasts that CCUS is set for a more rapid expansion going forward, and that carbon capture capacity across all sectors is set to reach 420Mtpa by 2035. However, this figure represents a mere 1.1% of current global annual emissions from fossil fuel combustion and industrial processes.[52] On this basis, CCUS will barely be making a perceptible dent in global emissions in 2035.

Furthermore, just 1% of announced projects have started construction while 75% are only in the very early stages of development (i.e. a long way from final design or investment decision) according to BNEF. Given the cost of such projects and the low capture rates in many cases, IEEFA predicts that a large percentage of these early-stage CCUS developments will never reach construction.

Figure 8: Cumulative global carbon capture capacity by sector (Mt of CO_2)



Source: Bloomberg New Energy Finance.[53]

[52] BNEF. CCUS Market Outlook 2023: Announced Capacity Soars by 50%. 6 November 2023.
[53] Ibid.

The report highlights that CCUS projects are "diversifying rapidly" into sectors like steel and cement. However, in its chart of the cumulative announced project capacity, iron and steel capture capacity is barely visible within the 2035 pipeline (Figure 8). According to this forecast, CCUS will be making virtually no contribution at all to the reduction of global steelmaking emissions.

Global CCS Institute

The Global CCS Institute (GCCSI) published its *Global Status of CCS Report* in November 2023. The Institute's mission is to accelerate the deployment of CCS, and its members consist of fossil fuel producers, technology providers and consumers, including steelmakers ArcelorMittal and Kobe Steel.

Despite the technology having been around for decades, the GCCSI is tracking just 41 commercial-scale CCS projects in operation globally, with 351 in development.[54] Again, with the great majority of these only in the early development stages, IEEFA expects that a large proportion of these will never reach commercial operation.

Of the combined 392 projects, just four are in the steel sector, including the operational Al Reyadah project (which uses captured CO_2 for enhanced oil recovery). Three of these are for DRI-based steel plants. Only one (the Baotou Steel project) is for blast furnace-based steelmaking - the dominant and most carbon-intensive steelmaking technique. Two of the projects under development are in the 'early development' stage (Figure 9).

Figure 9: Global, commercial-scale CCS projects for steelmaking

Status	Facility	Country	Operational Date	Capture Capacity (Mtpa Co2)	Storage
Operational	ADNOC Al Reyadah	UAE	2016	0.8	Enhanced oil recovery
In construction	Baotou Steel	China	Under evaluation	0.5	Dedicated geological storage
Early development	Nucor Steel DRI	USA	2026	0.8	Under evaluation
Early development	ArcelorMittal Texas	USA	Under evaluation	Under evaluation	Under evaluation

Source: Global CCS Institute.[55]

[54] GCCSI. Global Status of CCS Report. November 2023.
[55] Ibid.

Despite both BNEF and GCCSI highlighting an increase in the carbon capture project pipeline in their reports, this rise appears to have passed the steel industry by. Meanwhile, the cumulative number of operational CCUS projects remains tiny even after decades of development.

International Energy Agency

The IEA has a track record of reliance on CCUS for decarbonisation in its scenarios. However, more recently this appears to have started to shift, including in the IEA's long-term view on steel decarbonisation.

In its landmark 2021 report *Net Zero by 2050: A Roadmap for the Global Energy Sector*, the IEA saw CCUS-equipped processes making up 53% of global primary steel production in 2050 (Figure 10). In this first iteration of the IEA's Net Zero Emissions by 2050 Scenario (NZE), 670Mt of CO_2 would be captured from these processes.

Figure 10: 2021 key milestones in transforming steel

	2020	2030	2050
Steel			
Recycling, re-use: scrap as share of input	32%	38%	46%
Hydrogen demand (Mt H_2)	5	19	54
with on-site electrolyser capacity (GW)	0	36	295
Share of primary steel production: hydrogen-based DRI-EAF	0%	2%	29%
iron ore electrolysis-EAF	0%	0%	13%
CCUS-equipped processes	0%	6%	53%
CO_2 captured	1	70	670

Source: IEA.[56]

However, just two years later the IEA's view had already started to change significantly. In its 2023 update to the NZE Scenario, the IEA noted: "… so far, the history of CCUS has largely been one of unmet expectations. Progress has been slow and deployment relatively flat for years. The current level of annual CO_2 capture of 45 Mt represents only 0.1% of total annual energy sector emissions. This lack of progress has led to progressive downward revisions in the role of CCUS in climate mitigation scenarios, including the 2023 NZE Scenario."[57]

For steel, the IEA sees CCUS-equipped processes in 2050 accounting for 37% of iron production in its 2023 update. The amount of CO_2 captured in the global steel sector is down to 399Mt, from

[56] IEA. Net Zero by 2050: A Roadmap for the Global Energy Sector. May 2021.
[57] IEA. Net Zero Roadmap: A Global Pathway to Keep the 1.5°C Goal in Reach. September 2023. Page 132.

670Mt in the 2021 version. At the same time, the share of hydrogen-based steelmaking increased from 29% in the 2021 version to 44% in the 2023 update (Figure 11).

Figure 11: IEA 2023 updated key milestones in transforming steel

Milestones	2022	2030	2035	2050
Steel				
Crude steel production (Mt)	1 880	1 970	1 970	1 960
Share of scrap in metallic inputs	33%	38%	40%	48%
Share of near zero emission iron production	0%	8%	27%	95%
CCUS-equipped	0%	3%	10%	37%
Electrolytic hydrogen-based	0%	5%	15%	44%
Iron ore electrolysis	0%	0%	2%	14%
CO_2 captured (Mt CO_2)	1	27	131	399
Low-emissions hydrogen demand (Mt)	0	6	17	41

Source: IEA.[58]

IEEFA expects that the IEA will continue to reduce the role it expects CCUS to play in steel decarbonisation in future updates.

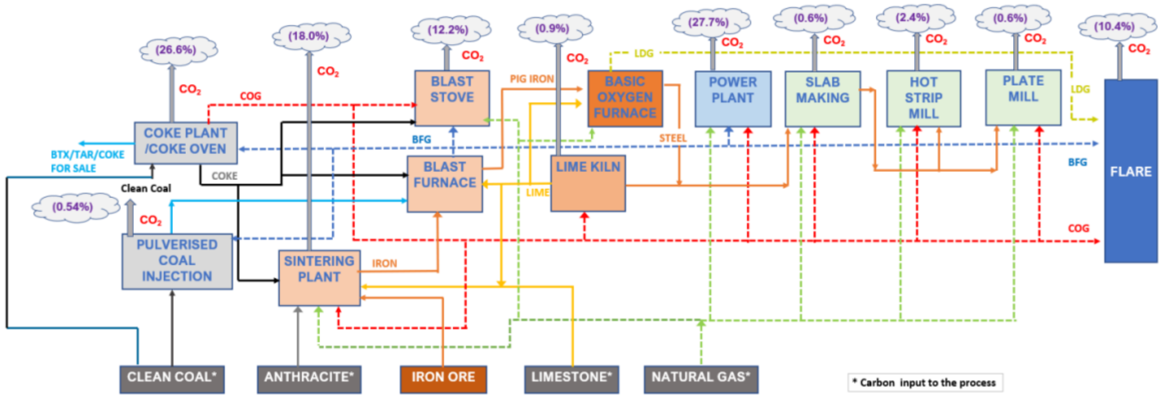
CCUS will not play a major role in blast furnace decarbonisation

The majority of global steel is currently produced in integrated, blast furnace-based plants.[59] However, there are no commercial-scale CCUS plants for blast furnace-based steelmaking in operation anywhere in the world, with only a small number of pilot plants underway or planned.[60] This looks unlikely to significantly change in the near future (Figure 9).

One of the key reasons why CCUS for blast furnace-based steelmaking has not made an impact – and is unlikely to going forward – is that such steel plants have multiple sources of carbon emissions (Figure 12). Retrofitting CCUS to just one of these sources can only result in a low percentage of the plant's overall emissions being captured. Attempting to improve the capture rate by adding multiple CCUS systems to the plant will clearly incur additional costs.

[58] IEA. Net Zero Roadmap: A Global Pathway to Keep the 1.5°C Goal in Reach. September 2023.
[59] IEEFA. The facts about steelmaking: Steelmakers seeking green steel. June 2022.
[60] BHP. Carbon capture in the steel industry: ArcelorMittal, Mitsubishi Heavy Industries Engineering, BHP and Mitsubishi Development sign collaboration agreement. 27 October 2022.

Figure 12: Carbon flow and CO_2 emissions sources in integrated BF-BOF steelmaking



Source: CO2CRC.[61] Note: BF = blast furnace; BOF = basic oxygen furnace.

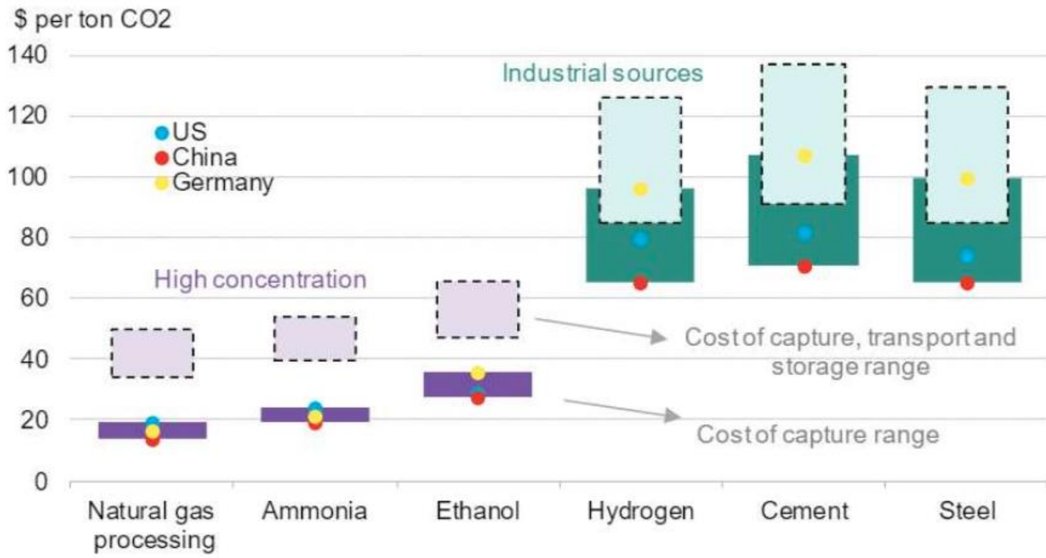
High cost is a problem holding back the deployment of CCUS globally across all sectors, but it is even more of a problem for industrial sectors like steel. Industrial CO_2 sources like steel, cement and hydrogen have a more dilute flue gas stream of CO_2 than that of natural gas, ammonia or ethanol. As a result, the cost of carbon capture is higher for these industrial sources (Figure 13).

BNEF foresees that a lack of carbon transport and storage capacity will be a bottleneck holding back the rollout of CCUS technology.[62] Transport and storage also adds to the cost of CCUS, another key factor that will continue to limit its role in decarbonisation. BNEF calculates a cost of carbon capture for steel of USD92-USD122 per tonne of CO_2 for a US plant in real 2021 US dollars, including the cost of transportation and storage.[63]

Due to the high cost of CCUS, potential developers of the technology often state that a significant carbon price is needed to stimulate its implementation.[64] Meaningful carbon prices are few and far between, with the EU's carbon price an exception. Even though carbon polluters in the European Union – including steelmakers – are currently given free permits, this is set to change with free allowances to be phased out from 2026.[65] Despite this clear carbon price signal in the EU, CCUS for steel has made little or no commercial progress in Europe. If steel CCUS cannot make progress in Europe where there is a significant carbon price, it cannot be expected to make headway in developing Asia, the seat of major steel demand growth.

[61] CO2CRC. Reduction of Greenhouse Gas Emissions in Steel Production. March 2020. Page 25.
[62] BNEF. CCUS Market Outlook 2023: Announced Capacity Soars by 50%. 6 November 2023.
[63] BNEF. Carbon Capture Cost Breakdown: Industrial Sources. 20 September 2023.
[64] Reuters. Explainer: Why carbon capture is no easy solution to climate change. 28 November 2023.
[65] S&P Global. EU steel emissions to see higher penalties as free allowances get taken away. 24 August 2023.

Figure 13: Cost of carbon capture for high concentration and industrial sources by country (USD per tonne of CO_2)



Source: Bloomberg New Energy Finance.[66]

In 2021, the Athos CCS proposal in the Netherlands was cancelled after project partner Tata Steel opted to for a switch from blast furnaces to DRI to decarbonise its operations, rather than CCS.[67]

More recently, when British Steel announced it will switch to EAFs from the end of 2025, it made clear it was unable to decarbonise its current blast furnace-based operations, stating: "We have engaged extensively with the public and private sector to understand the feasibility of producing net zero steel with our current blast furnace operations. However, thorough analysis shows this is not viable."[68] Clearly, carbon capture technology would have been the key technology that British Steel assessed in its analysis. The UK has its own carbon price, though it is not as high as the EU's.

The German think tank Agora Industry highlights that, since 2020, commercial-scale project announcements for new DRI-based steel plants and for CCUS projects for blast furnace-based steelmaking have developed very differently. To date, virtually all steel companies that plan to build low-carbon steelmaking capacity at commercial scale have opted for hydrogen-based or hydrogen-ready DRI plants, not CCUS. The 2030 project pipeline of DRI plants has grown to 94Mtpa, while the pipeline for commercial-scale CCUS on blast furnace-based operations amounts to just 1Mtpa (Figure 14)[69].

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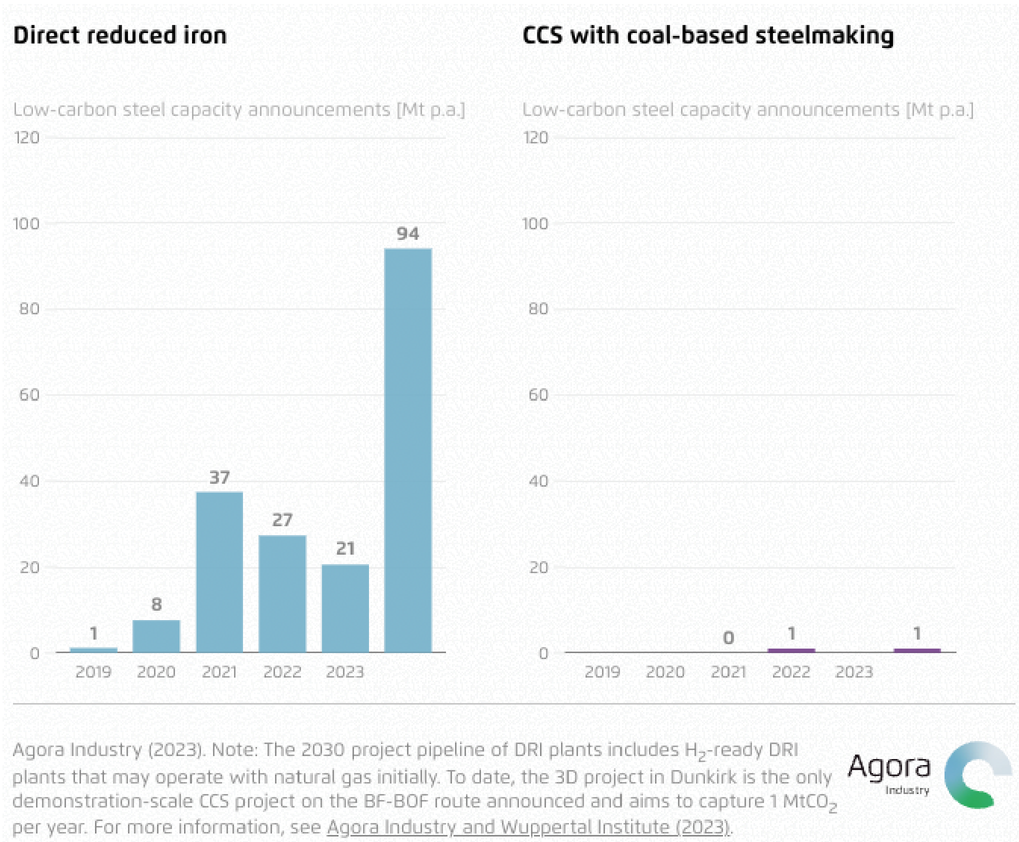
[66] BNEF. CCUS Market Outlook 2023: Announced Capacity Soars by 50%. 6 November 2023.
[67] S&P Global. Dutch CCS project scrapped after Tata Steel opts for hydrogen DRI production route. 21 September 2021.
[68] British Steel. British Steel today unveils £1.25 billion proposal to decarbonise its operations. 6 November 2023.
[69] Agora Industry. Global Steel Transformation Tracker.

Figure 14: 2030 pipeline of low-carbon steel announcements



Source: Agora Industry.[70]

It is clear that CCUS for blast furnace-based steelmaking is already being left behind by alternative technology, just as has happened in other sectors such as power generation. Furthermore, the shift from blast furnaces to DRI is accelerating.

DRI gains momentum as steel CCUS stalls

In an April 2023 column in the Financial Times, IEA chief Fatih Birol noted the acceleration in the steel technology transition, stating: “The transition to clean energy is also accelerating in other sectors, including those where emissions are most challenging to reduce, such as steel. The project pipeline for producing steel with hydrogen rather than coal is expanding rapidly. If currently announced projects come to fruition, we could already have more than half of what we need in 2030 for the IEA’s net zero pathway.”[71]

[70] Agora Industry. Global Steel Transformation Tracker.
[71] Financial Times. Clean energy is moving faster than you think. 14 April 2023.

Although Europe has led the way on new, low-carbon DRI development, steelmakers are increasingly turning to this technology globally, including in China[72] and the Middle East – where DRI technology based on gas is already well established.[73,,74] New, hydrogen-ready DRI plants are now being built at commercial scale, while CCUS for blast furnace-based steelmaking is tinkered with at pilot scale.

Many new DRI plants will begin operations on gas – producing iron with significantly lower emissions than via coal-consuming blast furnaces – before switching to hydrogen. German steelmaker Thyssenkrupp has begun the process of progressively replacing its blast furnaces with DRI plants, with the first to be operational from 2026. Starting based on gas, Thyssenkrupp is aiming to have it running on 100% hydrogen by 2029.[75]

However, where cheap clean energy is already plentiful, new DRI-based steelmaking can skip gas and use green hydrogen immediately.[76] H2 Green Steel will use green hydrogen powered by hydro power in northern Sweden for its new commercial-scale DRI plant, which will begin operations in late 2025. In January, H2 Green Steel raised EUR4.2 billion in debt financing for the plant to bring its total finance raised to EUR6.5 billion.[77] H2 Green Steel is already considering other green steel opportunities – the company is exploring the possibility of a USD6 billion plant in Quebec utilising the Canadian province's predominantly hydro power generation.[78]

The response from iron ore miners

Iron ore miners are already responding to the accelerating switch from blast furnaces towards DRI. Rio Tinto has signed an agreement with H2 Green Steel that will see it supply the green steelmaker with DR-grade iron ore from its Canadian operations.[79] Vale has a similar agreement with H2 Green Steel for the supply of ore suitable for DRI.[80]

With DRI-based steelmaking on the rise, iron ore majors are responding by changing their long-term strategies to ensure they can meet rising demand for iron ore that is suitable for DRI. The DRI-EAF steelmaking pathway requires a higher grade (higher iron content, lower impurities) than that suitable for blast furnaces. Developments by Vale, Rio Tinto, Fortescue and Anglo American clearly indicate that these iron ore miners see steelmakers increasingly switching from blast furnace to DRI going forward.

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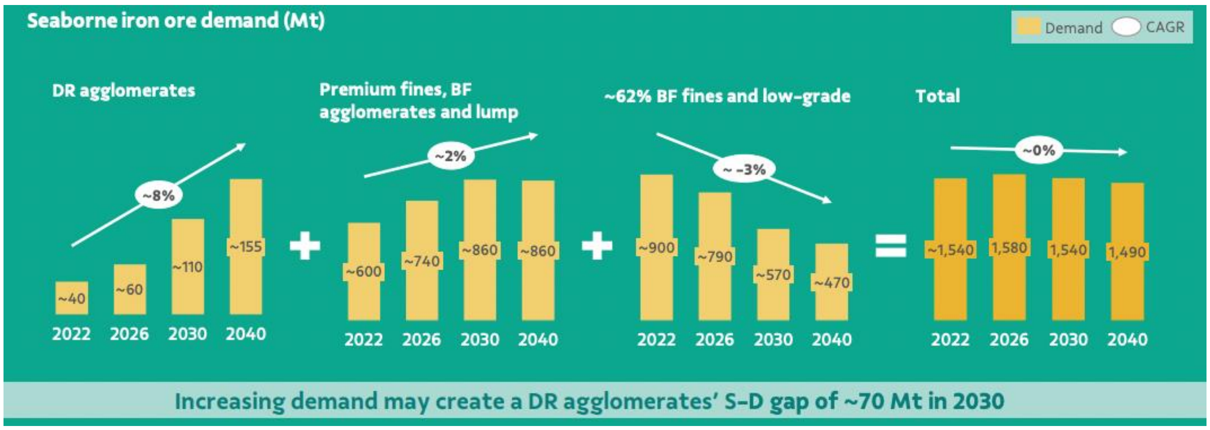
[72] Danieli. New Energiron DRI plant starts production at Baowu. 17 January 2024.
[73] IEEFA. Australia faces growing green iron competition from overseas. 1 September 2023.
[74] IEEFA. Green iron and steel offer MENA a chance to shine. 16 November 2023.
[75] Thyssenkrupp. Thyssenkrupp Steel is intensively pushing ahead with developing the hydrogen economy: Call for tenders for supplying hydrogen to the first direct reduction plant at the Duisburg location. 16 February 2024.
[76] IEEFA. Competing for Green Steel: national advantages and location challenges. 11 January 2024.
[77] H2 Green Steel. H2 Green Steel raises more than €4 billion in debt financing for the world's first large-scale green steel plant. 22 January 2024.
[78] Bloomberg. Swedish Industrialists Explore $6 Billion Green Steel Project in Canada. 9 October 2023.
[79] Rio Tinto. Rio Tinto and H2 Green Steel partner to accelerate the green steel transition. 9 August 2023.
[80] H2 Green Steel. H2 Green Steel and Vale in agreement for the supply of direct reduction iron ore pellets. 9 August 2023.

Vale is already the world's biggest supplier of DR-grade iron ore. It forecasts that by 2030, global DRI/HBI (hot briquetted iron) production will increase 55% to 200Mtpa, and demand for seaborne DR-grade iron ore will more than double to 110Mtpa. Vale sees DR-grade ore demand continuing to rise beyond 2030, while demand for benchmark 62% (blast furnace-grade) iron ore has now entered permanent decline (Figure 15).

Figure 15: Vale's iron ore segment forecast



Source: Vale.[81]

Rio Tinto has approved its investment in the world's biggest mining development – the Simandou iron ore projects in Guinea – which will increase the global supply of higher-grade ores.[82] Rio Tinto CEO Jakob Stausholm said in February 2024 that most of the ore extracted from its Simandou project can be used in DRI-EAF steelmaking, stating "it's good for the planet" due to the lower carbon emissions of this pathway relative to blast furnaces.[83]

Fortescue is also planning to increase supply of high-grade ore from Africa. December 2023 saw the company's first shipment from its Belinga iron ore project in Gabon – its first ever delivery from outside Australia.[84] Details about the quality of iron ore to be produced from this project have been thin, but Fortescue has previously insisted that "every indication we have, shows the project has the potential to be significant scale and very high-grade", and that "initial indications are that it could be similar in scale and size to Simandou in Guinea". [85,86] Meanwhile, Fortescue is already producing and shipping iron ore in Australia containing more than 67% Fe, which meets DR-grade.

In February 2023, Anglo American announced it had reached an agreement with Vale that will see Anglo expand its production of DR-grade iron ore from its Minas-Rio mine in Brazil. Anglo American

[81] Vale. Iron ore solutions webinar: Decarbonization of steel and impacts in iron ore supply. 14 April 2023.
[82] Financial Times. Rio Tinto approves world's biggest mining project in west Africa. 21 February 2024.
[83] Sky News. Simandou project 'good for the planet', says Rio Tinto CEO. 25 February 2024.
[84] Fortescue. Fortescue ships first product from Belinga iron ore project in Gabon. 4 December 2023.
[85] Fortescue. World Mining Congress Speech. 28 June 2023.
[86] Australian Financial Review. After years of fruitless drilling, Fortescue is ready to change tactic. 17 March 2023.

CEO Duncan Wanblad stated that the agreement offers the company “the scope to expand the production of the premium grade pellet feed products we sell to steelmaking customers as they focus on decarbonising their own processes for decades to come. The Minas-Rio DRI-grade product sells into one of the most attractive growth segments available in our industry today.”[87]

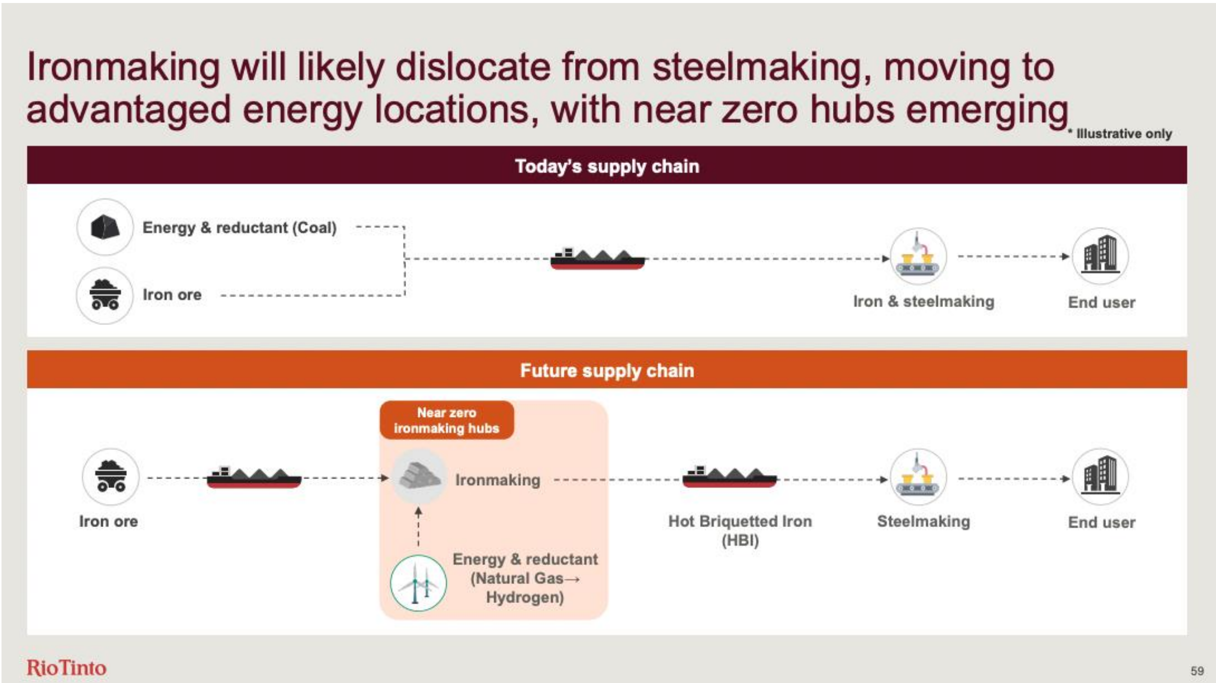
In contrast to its peers, BHP is not targeting increased high-grade iron ore production. Its focus remains on expanding production of blast furnace-grade ore in the Pilbara, and it is significantly more bullish on the role that CCUS can play in blast furnace-based steelmaking than other iron ore producers.[88] BHP’s insistence that CCUS will play a role in reducing steel emissions by decarbonising coal-consuming blast furnaces is hardly surprising – BHP is also the world’s largest shipper of metallurgical coal, the future of which is dependent on continued consumption of coal in blast furnaces.[89]

A global shift to DRI also raises the prospect of a geographical restructuring of the steel supply chain. Currently, iron ore and metallurgical coal are shipped to integrated, blast furnace-based steel plants situated close to centres of steel demand. Future reliance on green hydrogen-based DRI could see the ironmaking stage, which is currently highly emissions-intensive, move to sites where there is both suitable iron ore and plentiful renewable energy to make cheap green hydrogen. The ‘green iron’ produced could then be shipped as hot briquetted iron (HBI) to EAFs located close to the centres of steel demand to be processed into steel. The shipping of HBI would therefore increasingly displace the shipping of iron ore and metallurgical coal as the steel technology transition away from blast furnaces progresses.

Rio Tinto – which sold the last of its metallurgical coal mines in 2018[90] – is among the companies that foresee this restructuring (Figure 16). As part of its agreement with H2 Green Steel for its supply of DR-grade iron ore, Rio Tinto will purchase and on-sell HBI from the steelmaker in an early indication that this geographic restructuring is starting to take place.[91]

[87] Anglo American. Anglo American secures additional multi-billion tonne high quality iron ore resource at Minas-Rio. 22 February 2024.
[88] IEEFA. Big iron ore’s long-term strategies diverging in the face of steel decarbonisation. 5 February 2024.
[89] IEEFA. BHP quotes outdated figures as efforts to prop up carbon capture for steel start to get desperate. 15 December 2023.
[90] Rio Tinto. Rio Tinto completes sale of remaining coal assets. 1 August 2018.
[91] Rio Tinto. Rio Tinto and H2 Green Steel partner to accelerate the green steel transition. 9 August 2023.

Figure 16: DRI / green hydrogen switch drives geographic restructuring of steelmaking



Source: Rio Tinto.[92]

H2 Green Steel is investigating the feasibility of green industrial hubs in Brazil and North America with Vale. These would include the production and export of HBI.[93] Vale is also advancing its 'Mega Hubs' concept, which will see the miner co-locate DR-grade iron ore pellet production facilities with DRI-based steelmaking for the production of steel and HBI for export. Vale is planning such hubs in Brazil, Saudi Arabia, the UAE and Oman.[94]

Thanks to its established use of DRI and excellent green hydrogen potential, the Middle East is seeing interest in the production and export of HBI to steelmakers in Japan. Emirates Steel Arkan, the largest steel producer in the UAE, has formed a collaborative partnership with JFE Steel and Itochu Corporation. They aim to establish an ironmaking facility within the UAE, focused on producing low-emission iron materials like HBI for export. This collaboration will adopt gas-based DRI technology, though a later switch to hydrogen is planned. Additionally, there are plans to use CCUS technology while the DRI plant runs on gas, though the captured CO_2 would be used for EOR,

[92] Rio Tinto. Pilbara Site Visit. October 2023
[93] Vale. Vale and H2 Green Steel sign agreement to study the development of green industrial hubs in Brazil and North America. 6 September 2023.
[94] Vale. Vale advances on Mega Hubs project by signing off take agreement with Essar Group to supply iron ore agglomerates. 11 September 2023.

thereby aiding the release of more fossil fuel emissions.[95] DRI production is intended to begin in the second half of 2025.

South Korean Steel giant POSCO is also considering the potential for a geographic restructure of steelmaking. It has submitted plans for a DRI-based HBI production plant in Western Australia for environmental approval. The plan would see POSCO produce HBI from DR-grade magnetite ore and export it back to South Korea for processing into steel.[96]

While most major iron ore miners are increasing focus on DR-grade ores, there is also a need to find ways to use more plentiful blast furnace-grade ores in DRI-based steelmaking processes.[97] The leading technology solution to achieve this involves DRI with an addition melting step that allows the removal of impurities from the lower-grade ore. The DRI plant that Thyssenkrupp is building in Germany is the latter DRI/melter combination that will allow it to continue to use blast furnace-grade ore.[98] POSCO's HyREX technology is also intending to use a lower-grade ore in the form of iron ore fines processed with hydrogen fluidized bed reduction technology modelled on POSCO's FINEX.[99]

All of the major Australian iron ore producers are investigating technologies that will allow the use of their Pilbara, blast furnace-grade ores in DRI processes.[100] In February 2024, such efforts were bolstered by a new collaboration agreement between BHP, Rio Tinto and BlueScope Steel, who will now share what they have learnt so far and will likely bring forward the date by which Pilbara hematite is used in DRI-based steelmaking at commercial scale.[101]

At the announcement of the collaboration, Tania Archibald, BlueScope's Chief Executive Australia, said: "We believe DRI is the most prospective technology to decarbonise our Australian business." She made no mention of CCUS.[102]

The long-term risks for coal-based steelmaking are growing

As well as low capture rates, CCUS for an integrated, blast furnace-based steel plant does nothing to address the emissions associated with metallurgical coal mining, particularly methane emissions. Total methane emissions from coking coal mines globally totalled 10.5Mt in 2023, according to the IEA.[103] Assuming a global warming potential (GWP) of methane over a 100-year period of 30 tonnes CO_2 equivalent[104], 10.5Mt of methane amounts to 315Mt CO_2 equivalent. The GWP of methane over

[95] JFE Steel Corporation. JFE Steel, Emirates Steel and Itochu to Study Building Supply Chain of Ferrous Raw Material for Green Ironmaking with Low-carbon Emission. 1 September 2022.
[96] ABC. Multi-billion-dollar South Korean investment could make Port Hedland a green iron centre. 16 December 2023.
[97] IEEFA. Solving iron ore quality issues for low-carbon steel. 9 August 2022.
[98] IEEFA. German steel giant tech breakthrough to steer industry away from coal. 28 September 2022.
[99] POSCO. HyREX
[100] IEEFA. Big mining's downstream steel emissions. 12 October 2023.
[101] Rio Tinto. Australia's leading iron ore producers partner with BlueScope on steel decarbonisation. 9 February 2024.
[102] BlueScope Steel. Australia's leading iron ore producers partner with BlueScope on steel decarbonisation. 9 February 2024.
[103] IEA. Methane Tracker. 13 March 2024
[104] IEA. Global Methane Tracker 2024: Understanding methane emissions.

a 20-year impact period is higher (82-87).[105] On this basis, 10.5Mt of methane amounts to up to 913.5Mt CO_2 equivalent. For comparison, global emissions from steelmaking (excluding coal mine methane) amount to around 2,800Mt CO_2 per annum.[106]

A large share of metallurgical coal is produced in open-cut coal mines, which makes it hard to address methane emissions.[107] It is increasingly being recognised that action on methane needs to be a key part of efforts to reduce greenhouse gas emissions.[108] Coal-producing nations like Australia – by far the world's largest exporter of metallurgical coal – are only beginning to come to terms with scale of the coal mine methane leak issue and how to respond to it.[109] One thing is certain: pressure to act on methane emissions from fossil fuel production will only grow, and steel plant CCUS is unable to address it.

> “ **Steelmakers will be increasingly exposed to the risk that steel consumers will not want coal involved in their supply chains at all.**

This, along with low capture rates at integrated steelmaking sites, will likely mean that any CCUS installations will likely not decarbonise steel production enough to satisfy the growing number of steel consumers demanding truly green steel. Car makers are already signing purchase agreements for green steel made using green hydrogen with virtually no emissions.[110] Tighter definitions of what exactly constitutes "green steel" can be expected in the near future. There is a significant risk that the low capture rates of CCUS will mean steel produced this way won't meet such definitions. Steelmakers will be increasingly exposed to the risk that steel consumers will not want coal involved in their supply chains at all.

[105] Ibid
[106] IEA. Emissions Measurement and Data Collection for a Net Zero Steel Industry: Executive summary. April 2023
[107] IEEFA. Growth in Australian open-cut coalmining raises urgency of methane abatement. 5 February 2024
[108] European Commission. 2023 Global Methane Pledge Ministerial: decisive action to curb emissions. 4 December 2023.
[109] IEEFA. Growth in Australian open-cut coal mining raises urgency of methane abatement. 5 February 2024.
[110] H2 Green Steel. Porsche plans to use CO2-reduced steel from H2 Green Steel in sports cars from 2026. 31 October 2023.

Conclusion

Despite decades of implementation, CCUS has a poor track record across all sectors. CCUS projects have consistently struggled to reach targeted capture rates. Moreover, targeted carbon capture itself is often far below overall carbon emissions. Installations that capture low CO_2 levels cannot be viewed as "decarbonised" – as illustrated by the world's only commercial-scale CCUS facility for steelmaking.

The uniqueness of each CCUS project limits technological learning and cost reductions. The cost of carbon capture implementation has hardly reduced in 40 years, while the cost of alternative technologies like renewable energy and battery storage has plunged, with further reductions to come. Despite a clear and significant carbon price signal in the EU, CCUS for steel in Europe has made little or no commercial progress. If steel CCUS cannot advance in Europe where there is a significant carbon price, it cannot be expected to make headway in Asia, the seat of major steel demand growth.

CCUS has almost no track record in the steel sector. There are only four commercial-scale projects in existence globally, of which just one is operational and two others are only in the early stages of development. Three of the four are for DRI-based steelmaking, not the blast furnace-based technology that dominates global steel production and emissions. With both the key DRI technology providers making clear that their technology is hydrogen-ready, a progressive switch from gas to green hydrogen as it becomes cheaper and more available provides a more effective pathway to reduce DRI emissions than CCUS.

CCUS looks even less likely to play a role in the decarbonisation of blast furnace-based steelmaking due to the multiple sources of emissions of such operations. Where better and more cost-competitive alternatives exist, CCUS is unlikely to play a role in a sector's decarbonisation. Global steelmakers will increasingly shift from blast furnaces to recycling steel in electric arc furnaces and DRI-based processes that can shift to green hydrogen. This process is already well underway. Using green hydrogen in DRI and renewable energy to power electric arc furnaces enables the production of truly low-carbon steel, a feat CCUS appears unable to replicate.

Appendix

Despite the long history of failure and under-performance in other sectors, and the unproven nature of carbon capture technologies for steelmaking, some of the world's largest steelmakers persist in including the technology in their long-term decarbonisation plans. The phrases "hard to abate" and "carbon capture and storage" often go hand in hand. Some steelmakers are using the phrase "hard to abate" as an excuse to justify vague plans for CCUS in future decades while continuing business-as-usual to a large extent.

Investors should have questions for steelmakers that continue to maintain that CCUS will play a significant decarbonisation role.

ArcelorMittal

ArcelorMittal, the world's second-largest steelmaker, has a target to achieve net zero emissions by 2050. In the short term, the giant steel company aims for a 25% reduction in carbon dioxide equivalent (CO_2e) emissions intensity – not absolute emissions – by 2030 compared with a 2018 baseline. ArcelorMittal has set a more ambitious carbon intensity reduction target for Europe at 35%.[111]

ArcelorMittal is following two main pathways to reduce its carbon footprint: 'Innovative DRI'; and so-called 'Smart Carbon' (which can be read as code for CCUS). A third, longer-term technology pathway, direct iron ore electrolysis, is still a long way off from commercial viability.

'Smart Carbon' incorporates technologies including CCUS, biomass, capturing and utilising waste carbon monoxide and hydrogen, and recycling hydrogen-rich coke oven gas. The 'Smart Carbon' pathway currently encompasses four major projects, namely Steelanol, Torero, Top Gas Recycling, and 3D, most of which are being developed in the company's Ghent facility in Belgium. The primary CCS initiative in ArcelorMittal's portfolio is 3D, while the company's "flagship" carbon capture development is the Steelanol carbon capture and utilisation (CCU) project.[112]

The EUR200 million Steelanol project has the capability to capture up to 0.125Mt of CO_2 and transform it into 80 million litres ethanol. This equates to less than 2% of the total carbon emissions of Ghent plant.[113] Despite the fact that this is a tiny portion of the total CO_2 emissions of the plant, it can satisfy approximately half of the current advanced ethanol demand in Belgium. This limits the

[111] ArcelorMittal. ArcelorMittal Climate Action Report 2. July 2021.
[112] ArcelorMittal. ArcelorMittal and LanzaTech announce first ethanol samples from commercial flagship carbon capture and utilisation facility in Ghent, Belgium. 14 June 2023.
[113] Financial Times. Can the steel industry go green? | FT Climate Capital. 31 October 2023.

effectiveness of the technology as a more widespread carbon removal solution, as there is insufficient market demand for the final product.[114]

ArcelorMittal Ghent has two blast furnaces in operation. In 2021, the company announced plans to replace its blast furnace A with a 2.5Mt DRI plant and two new electric furnaces, at a cost of EUR1.1 billion. This initiative has the potential to reduce emissions by around 3Mt of CO_2 per year.[115]

The 0.125Mt of CO_2 captured by the Steelanol CCU project represents only 4% of the total emissions reduction expected to be achieved by the planned switch from blast furnace to DRI-EAF. However, the investment for the Steelanol project equates to 18% of the planned investment for the DRI-EAF transition. It is evident that these small-scale facilities cannot match the carbon abatement cost efficiency of more mature direct reduction technology, which is exhibiting significantly higher potential capacity for carbon reduction per dollar of investment.

The 3D CCU/S pilot project in Dunkirk – launched in 2019 – aims to capture blast furnace CO_2 using a chemical solvent for utilisation or storage. However, as a demonstration project it has very limited capacity, capturing only up to 4,400 tonnes of CO_2 annually. This pilot initiative, while potentially an advancement in capturing capacity at small scale, still represents a small fraction of emissions mitigation. The success of any sequestration is entirely reliant on the progress of North Sea CO_2 storage development.[116]

Even other solutions falling under the 'Smart Carbon' umbrella, like Torero, do not provide a significant reduction in carbon emissions. The company has inaugurated its EUR35 million Torero plant, designed to convert waste wood into bio-coal for utilisation in blast furnaces instead of coking coal. Despite this partial substitution of fuel, the Ghent steel mill can only achieve a reduction of 0.112Mt of CO_2. This figure represents around 1% of the plant's total carbon emissions per annum.[117]

The IGAR project is another solution being investigated by ArcelorMittal, aiming to produce syngas by combining natural gas with CO_2 from a blast furnace. The resulting syngas, containing carbon monoxide (CO) and hydrogen, can be utilised for iron reduction.[118] Other studies and small-scale projects, such as NEDO, are being developed to produce synthesis gas from captured CO_2.[119] This can be used as a reducing agent again in the ironmaking process, but these projects have a long journey ahead before reaching commercialisation.

[114] ArcelorMittal. ArcelorMittal and LanzaTech announce first ethanol samples from commercial flagship carbon capture and utilisation facility in Ghent, Belgium. 14 June 2023.
[115] ArcelorMittal. ArcelorMittal signs letter of intent with the governments of Belgium and Flanders, supporting €1.1 billion investment in decarbonisation technologies at its flagship Gent plant. 28 September 2021.
[116] ArcelorMittal. The 3D Project (DMX™ Demonstration in Dunkirk).
[117] ArcelorMittal. ArcelorMittal commissions a first for the European steel industry converting waste wood into bio coal to reduce fossil coal consumption. 20 December 2023.
[118] ArcelorMittal. IGAR process.
[119] ArcelorMittal. ArcelorMittal and SEKISUI CHEMICAL's Carbon Recycling Project achieves target ahead of schedule. 19 June 2023.

ArcelorMittal, Mitsubishi Heavy Industries Engineering (MHIENG), BHP and Mitsubishi Development Pty Ltd have entered into a collaborative effort for a multi-year trial of MHIENG's carbon capture technology at ArcelorMittal facilities. MHIENG, with its proprietary KM CDR Process for CO_2 capture, aims to deploy this technology in steel facilities, testing it in both DR and blast furnace plants. In Ghent, the project focuses on separating and capturing CO_2 from the blast furnace top gas at a rate of only around 100,000kg of CO_2 per year. The parties also intend to install a mobile test unit in one of ArcelorMittal's North American DRI plants to assess MHIENG's technology in this steelmaking route.[120]

In 2024, ArcelorMittal continues to seek carbon capture opportunities. In February, the company signed a Memorandum of Understanding (MoU) with Petrobras to jointly seek to identify carbon capture opportunities.[121]

While ArcelorMittal continues to work on various carbon capture technologies in Europe at small scale, the company's predominant decarbonisation focus lies in substantial investments in its 'Innovative DRI' pathway. ArcelorMittal facilities across Europe and Canada are planning investments of billions of euros in establishing DRI-EAF plants to replace blast furnaces. Operations including Dunkirk in France; Contrecoeur in Canada; Bremen, Eisenhüttenstadt and Hamburg in Germany; Gijon and Sestao in Spain; and Ghent in Belgium are planning a transition towards DRI-EAF technology. In February 2024, the European Commission approved a EUR1.3 billion grant from the German government to ArcelorMittal to support the decarbonisation of its German operations via the construction of a new DRI plant and three EAFs. This will replace two blast furnaces and two basic oxygen furnaces, leaving even fewer opportunities for any of the carbon capture projects the company is developing to decarbonise its blast furnace-based operations.[122]

ArcelorMittal appears to be undertaking a two-speed decarbonisation process in developed and developing nations. In IEEFA's opinion, there is a risk to the company that the 'Smart Carbon' pathway will increasingly be perceived as "greenwashing", used to justify the continued installation of new blast furnaces in developing nations.

China Baowu

State-owned China Baowu is the world's largest steelmaker. Baowu is targeting net zero emissions by 2050, ten years ahead of China's national target.[123]

The company's transition towards low-carbon steelmaking is already underway. In January 2024, production started at Baowu's first commercial-scale DRI plant running on methane, hydrogen and

[120] Mitsubishi Development Pty Ltd. Carbon capture in the steel industry: ArcelorMittal, Mitsubishi Heavy Industries Engineering, BHP and Mitsubishi Development sign collaboration agreement.
[121] ArcelorMittal. Petrobras and ArcelorMittal sign agreement for low carbon business studies and assessments. 27 February 2024.
[122] European Commission. Commission approves €1.3 billion German State aid measure funded under Recovery and Resilience Facility to support ArcelorMittal decarbonise its steel production. 23 February 2024.
[123] Reuters. China's top steelmaker Baowu Group vows to achieve carbon neutrality by 2050. 21 January 2021.

coke-oven gas.[124] The plant uses Energiron technology developed by Tenova and Danieli, who have made clear that their technology is ready to run on 100% hydrogen.[125]

Baowu is also considering embracing the potential for a geographical restructuring of the global steel industry as it shifts towards green hydrogen-based DRI. The company is looking at setting up a DRI facility in Australia that would export HBI back to China.[126] In June 2023, the company signed an MoU with Rio Tinto for the examination of a range of steel decarbonisation options including the use of low-grade Pilbara iron ore in DRI-based steelmaking and the potential for low-carbon iron production in Western Australia.[127] In the same month, Baowu signed an MoU with Fortescue that will see the two parties examine green hydrogen-based steel production in China using Fortescue's iron ore.[128]

Australia is being considered by the likes of Baowu for potential green ironmaking sites.[129] However, it faces competition from other places like Brazil and West Africa due to their reserves of higher-grade ore that is more immediately suitable for DRI-based steelmaking.

China Baowu's consideration of West Africa as a future ironmaking hub is made much more serious by its role in iron ore mining in the region. The company is one of the key owners of the Simandou iron ore mine and rail and port projects in Guinea, which is set to produce iron ore of a higher grade than the great majority of Pilbara production, including a significant amount of high enough grade for DRI-EAF steelmaking operations.[130] In January 2024, Baowu raised 10 billion yuan (USD1.4 billion) from a bond issue, most of which will be used to fund the Simandou projects, which are expected to commence operations in 2026.[131]

However, despite China Baowu's shift towards DRI and high-quality iron ore, as well as more scrap steel recycling in EAFs, the company still also maintains that CCUS will play a role in steel decarbonisation. In February 2024, Baowu announced it had signed an MoU with ExxonMobil on low-carbon solutions cooperation including CCS value chains.[132]

In 2023, Baowu signed a joint research agreement with Shell, German chemical firm BASF and Chinese state-owned oil company Sinopec to jointly assess the feasibility of an open-source, 10Mt CCUS facility in eastern China.[133] This follows an MoU signed by the four parties in November 2022 for the project.[134]

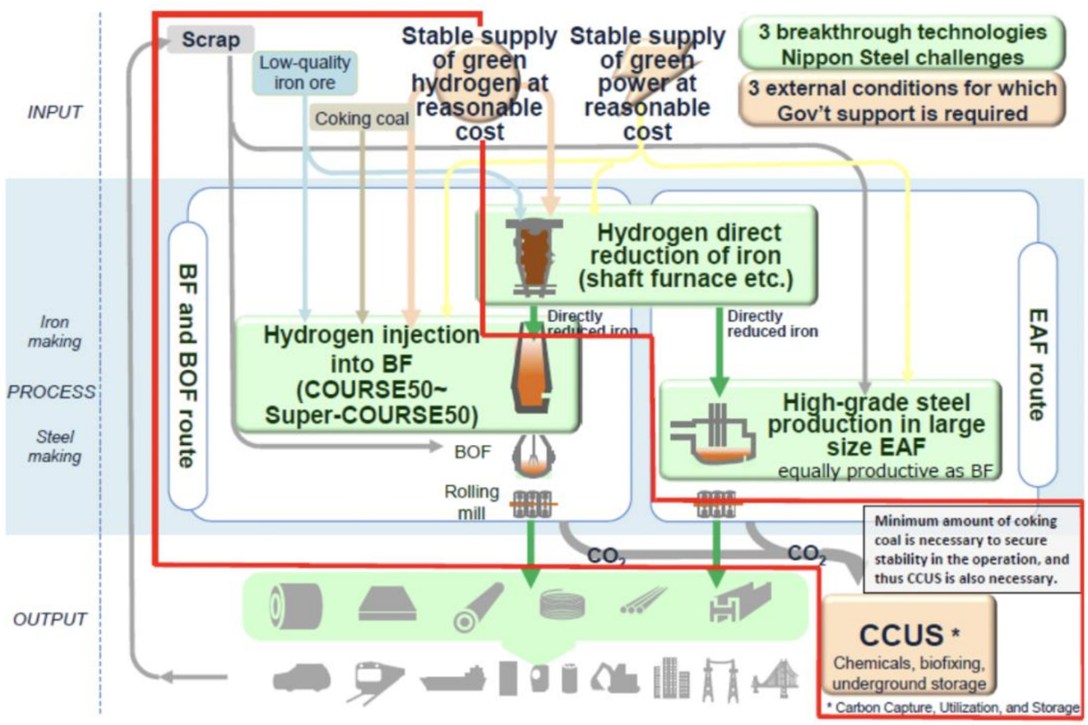
[124] Danieli. NEW ENERGIRON® DRI PLANT STARTS PRODUCTION AT BAOWU. 17 January 2024.
[125] Energiron. Hydrogen.
[126] Australian Financial Review. World's biggest steel maker looks to WA for massive green investment. 12 May 2023.
[127] Rio Tinto. China Baowu and Rio Tinto extend climate partnership to decarbonise the steel value chain. 12 June 2023.
[128] Fortescue. Fortescue partners with world's largest steel maker to reduce emissions across iron and steel making. 14 June 2023.
[129] Australian Financial Review. World's biggest steel maker looks to WA for massive green investment. 12 May 2023.
[130] Rio Tinto. Investor Seminar 2023 – Simandou.
[131] Reuters. China Baowu raises $1.4bn via bond, mostly for Simandou iron ore project. 30 January 2024.
[132] China Baowu. Baosteel and ExxonMobil Signed a Memorandum of Understanding on Cooperation. 5 February 2024.
[133] Reuters. Baosteel inks CCUS research agreement with Sinopec, Shell and BASF. 8 August 2023.
[134] Shell. SHELL, SINOPEC, BAOWU AND BASF TO EXPLORE OPEN-SOURCE CARBON CAPTURE, UTILISATION AND STORAGE PROJECT IN CHINA. 4 November 2022.

Despite its progress on real steel decarbonisation solutions, including DRI and the opening up of high-grade iron ore capacity, China Baowu is still involving itself with unproven CCUS projects in collaboration with oil and gas majors that continue to push such technology as cover for business-as-usual activities.[135]

Nippon Steel

Nippon Steel, Japan's largest steelmaker, aims to achieve a 30% reduction in carbon emissions compared with the 2013 baseline by 2030, as part of its commitment to reach carbon neutrality by 2050.[136] This target relies on technologies including hydrogen injection in blast furnaces, high-grade steel production in large-sized EAFs, and the use of hydrogen in the DRI process. However, as long as steel production with coal-based blast furnaces remains a significant part of its overall production set-up, emissions can only be partially reduced. The company's zero emissions roadmap also ultimately depends on CCUS.

Figure 17: Nippon Steel's 'Carbon Neutral Vision 2050



Source: Nippthis ion Steel.[137]

[135] IEA. Oil and gas industry faces moment of truth – and opportunity to adapt – as clean energy transitions advance. 23 November 2023.
[136] Nippon Steel. Nippon Steel Carbon Neutral Vision 2050. 30 March 2021.
[137] Nippon Steel. Nippon Steel to indirectly acquire a 20% interest in the steelmaking coal business of Teck Resources Limited. 14 November 2023.

The involvement of CCUS in Nippon Steel's plan is not surprising given the company remains highly committed to coal-based steelmaking. Nippon is adding to its existing investments in metallurgical coal mines by taking a 20% stake in the coal business of Teck Resources, which will become majority-owned by Glencore.[138] The November 2023 press release announcing the acquisition of the coal business now known as Elk Valley Resources made clear via a diagram entitled "Necessity of steelmaking coal to Nippon Steel's Carbon Neutral Vision 2050" that CCUS is a key part of the company's decarbonisation plans (Figure 17).[139]

Nippon Steel aims to secure a long-term offtake agreement with Elk Valley Resources to ensure a consistent supply of coking coal for its coal-based steelmaking. The company has explicitly stated that the purpose of this investment is to secure a stable coal supply "essential to Nippon Steel's carbon neutral strategy". It currently sources nearly 20% of its required coal (approximately 25Mt) from the invested mines. After acquiring the stake in Elk Valley Resources, this will rise to 30%.[140]

Nippon Steel has been experimenting with the replacement of some metallurgical coal in blast furnaces with hydrogen for 16 years. Introducing hydrogen, whether derived from top gas recycling or fresh hydrogen injection, can partially substitute for PCI and coking coal. However, its utilisation is constrained by the endothermic reaction in the blast furnace, necessitating an additional energy source to counteract temperature reduction. Furthermore, this approach may pose technical challenges, such as reducing CO_2 concentration, thereby complicating the CO_2 capture process.[141]

In Nippon Steel's COURSE 50 process, hydrogen generated by the steelworks itself is injected into the blast furnace. A further development known as Super COURSE 50 injects external hydrogen. While hydrogen injection into the blast furnace helps mitigate emissions to some extent, the continued use of metallurgical coal results in carbon emissions, requiring that CCUS is used in these processes to capture it.

Nippon Steel has announced that, in a small test furnace (with an inner volume of 12 cubic metres), a 33% reduction in CO_2 emissions from the blast furnace was achieved using Super COURSE 50. The company claims that, once ready, the Super COURSE 50 technology could reduce 50% or more of the emissions from large-scale blast furnaces.[142] Once implemented at commercial scale, Nippon Steel intends to use the technology until at least 2050, locking in coal-based steelmaking at and beyond the point that the company is targeting net zero emissions.

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[138] IEEFA. Is Japan's biggest steelmaker really considering more metallurgical coal investments? 18 July 2022.
[139] Nippon Steel. Nippon Steel to indirectly acquire a 20% interest in the steelmaking coal business of Teck Resources Limited. 14 November 2023.
[140] Nippon Steel. Acquisition of interest in the steelmaking coal business in Canada. 14 November 2023.
[141] WoodMackenzie. What's next for green steel technologies? 11 December 2023.
[142] Nippon Steel. Verified the World's Highest Level of CO2 Emissions Reduction at 33% by Heated Hydrogen Injection in the Super COURSE50 Test Furnace. 6 February 2024.

For Super COURSE 50 to have any chance of realising Nippon's expectations, it must lean heavily on unproven CCUS technology. The company has been involved in various aspects of the CCUS value chain, from capturing CO_2 to collaborating with oil and gas companies to sequester it underground.

Nippon Steel Engineering has developed a carbon capture technology named ESCAP. Short for Energy Saving CO_2 Absorption Process, ESCAP has been installed on a small scale to capture 143 tonnes of CO_2 per day from a coal-fired power plant, and 120 tonnes of CO_2 per day from steelworks. The capturing capacity is dwarfed by the actual carbon emissions from coal-based steel mills. The company is collaborating with various universities and corporations to advance carbon utilisation in chemicals and fuels. However, none of these initiatives currently has the capability to effectively remove a significant portion of CO_2 emitted from steel production.[143]

JOGMEC, the state-owned Japan Organization for Metals and Energy Security, has chosen seven potential CCS initiatives for financial support. The initiatives are situated in various locations in Japan and the wider Asia Pacific region. Japan has set a goal to attain a CO_2 storage capacity of between 6Mtpa and 12Mtpa by 2030, and between 120Mtpa and 240Mtpa of CO_2 by 2050.[144] Nippon Steel is a consortium member in three of these seven projects, including the Tokyo metropolitan initiative, with a storage capacity of 1Mt, and the Tohoku Region West Coast CCS initiative, with a capacity of 2Mt.[145] Additionally, the company is collaborating with Mitsubishi Corporation and ExxonMobil to jointly study capturing CO_2 emissions from Nippon Steel's domestic steelworks, with the aim of establishing CCS value chains in the Asia-Pacific region. The collaboration will evaluate potential storage options in Malaysia, Indonesia and Australia. Its press release announcing the project stated: "Nippon Steel set forth the 'Nippon Steel Carbon Neutral Vision 2050' in its medium-to-long-term management plan announced in March 2021 and positioned CCS as one of the key technologies to realize this vision."[146]

Nippon Steel is attempting to acquire U.S. Steel for USD15 billion. This acquisition would align with Nippon Steel's ambition to achieve a global steel production capacity of 100Mtpa. If the acquisition goes ahead, the combined crude steel production is projected to increase from Nippon's current 66Mtpa to 86Mtpa. If the acquisition succeeds Nippon Steel will become an even larger operator of blast furnace-based steelmaking, gaining ownership of eight blast furnaces in the US, as well as three additional blast furnaces in Slovakia. In a presentation outlining the rationale for the acquisition, Nippon Steel notes U.S. Steel's "Development of cutting-edge technologies" for decarbonisation. Number one on the accompanying list is CCUS.[147]

Nippon has pursued a strategy of global expansion in its steelmaking operations, with investments spanning 15 different countries. However, this approach raises concerns regarding the

[143] Nippon Steel. Nippon Steel Carbon Neutral Vision 2050. 30 March 2021. Pages 41-42.
[144] Argus. Japan to fund seven projects to advance CCS strategy. 13 June 2023.
[145] Nippon Steel. The JOGMEC Commission Entrusted with a Joint Study on Japanese Advanced CCS Project in FY2023. 2 August 2023.
[146] Nippon Steel. Nippon Steel, Mitsubishi Corporation and ExxonMobil to Evaluate and Establish CCS Value Chains in the Asia Pacific Region. 26 January 2023.
[147] Nippon Steel. Acquisition of U.S.Steel. 18 December 2023.

decarbonisation of steelmaking facilities worldwide. By acquiring coal mines and blast furnaces, the company is extending its significant dependency on coal, raising the risk that its domestic decarbonisation efforts in Japan will be more than offset by the construction of carbon-intensive, blast furnace-based steelmaking overseas, particular in developing nations.

POSCO

POSCO, the seventh-largest global steelmaker, is targeting net zero emissions by 2050 but only a 10% reduction by 2030. Although the steelmaker has added a 30% emissions reduction by 2035 target last year, the bulk of the company's emissions reductions are planned to occur after 2040. Relying heavily on HyREX, its under-development hydrogen-based technology for its shift to green steel, POSCO plans to continue using coal-based blast furnaces until at least 2050.

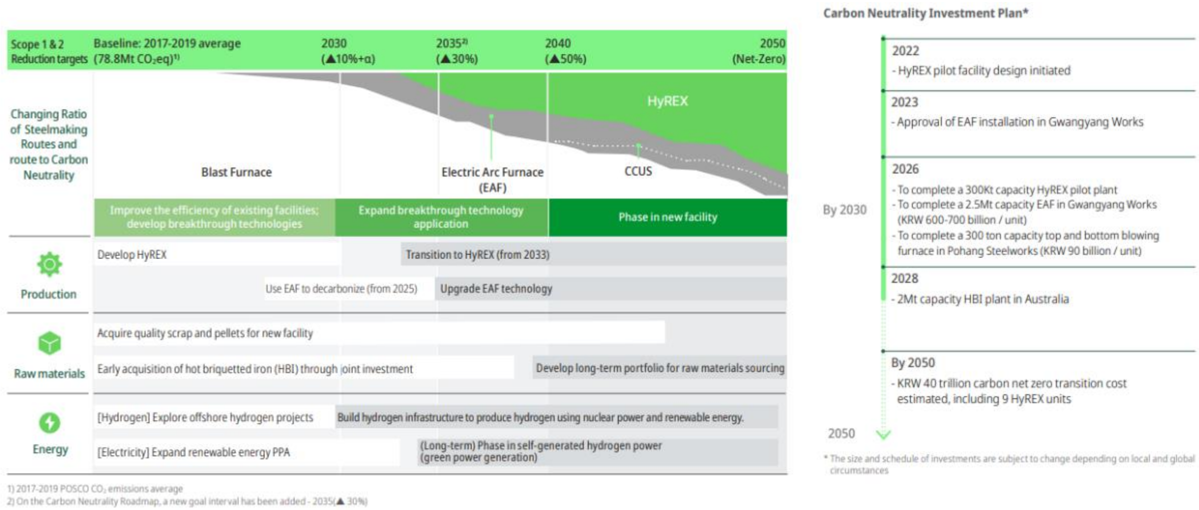
HyREX is POSCO's proprietary, fluidised bed-based steelmaking technology, which it is developing from its existing FINEX technology. Unlike standard, mature DRI shaft furnaces that use iron ore pellets, HyREX will use iron ore fines as well as hydrogen instead of coking coal to produce low-carbon steel. POSCO plans to build a 300,000 tonne per annum pilot HyREX plant at its Pohang steelworks by 2026. Once proven, the company intends to gradually replace its blast furnaces with full-scale HyREX plants to achieve net zero emissions by 2050.

In March 2023, South Korea's Ministry of Trade, Industry and Economy (MOTIE) released a national Low Carbon Steel Production Strategy with KRW200 billion (USD148 million) of funding, acknowledging the need for steel decarbonisation to ensure industrial competitiveness and allocating funds for the transition toward low carbon steel production. Although a promising first step, a relatively small portion of funding is directed towards green hydrogen-direct reduced iron commercialization projects and secondary steel production as the bulk of the funds have been allocated to facilities improvement, while transition to new facilities, such as POSCO's HyREX technology is only allocated KRW26.9 billion.

For HyREX to produce close-to-zero carbon steel, green hydrogen will be required. Given the uncertainties over domestic production costs and the structurally high cost of hydrogen imports, POSCO is among a number of steelmakers considering iron production overseas where renewable energy resources are higher.[148] POSCO is considering a major investment in Australia, where it would produce DRI before shipping it to its South Korea steelworks as HBI. It is also considering the Middle East as an HBI production base. It already has a green hydrogen project in Oman.[149]

[148] Bloomberg. Green Steel Challenges Could Trigger Overseas Push for Posco. 25 September 2023.
[149] ABC. Multi-billion-dollar South Korean investment could make Port Hedland a green iron centre. 16 December 2023.

Figure 18: POSCO's Carbon Neutrality Roadmap



Source: POSCO Holding Sustainability Report 2022.[150]

While it continues to develop its HyREX technology, POSCO intends to rely on several "bridge technologies" to start its decarbonisation process. These include the injection of hydrogen into blast furnaces to reduce coal use, increased production via EAF, increasing scrap input in basic oxygen furnaces, and increasing DRI/HBI input in blast furnaces. POSCO has also announced a CCU project focused on converting CO_2 gas to coke oven gas. The South Korean steelmaker maintains that this technology has the potential to enhance the heating value of the coke oven gas by 7% and reduce POSCO's annual emissions by 320,000 tonnes when applied to its giant Pohang and Gwangyang steelworks. With the baseline total CO_2 emissions (Scopes 1 and 2) from the steel sector averaging around 78.8Mt in 2017-2019, an annual reduction of 320,000 tonnes represents just 0.4% of POSCO's total emissions.[151]

As well as this CCU plan, POSCO also maintains in its most recent Sustainability Report that CCUS will play a role in its decarbonisation journey. CCUS is one of the medium-term plans in its Carbon Neutrality Roadmap, with implementation indicated after 2040 (Figure 18). However, the role of CCUS beyond 2040 remains unclear, and the company has not provided clarity in its roadmap.

POSCO is collaborating with global partners to set up CCS facilities, as demonstrated by the MoU signed in 2023 with Malaysian oil and gas company PETROS. The companies will examine a plan to capture CO_2 discharged in the production of steel and blue hydrogen, and transport it for storage in depleted oil and gas fields off the coast of the Malaysian state of Sarawak.[152] Other POSCO

[150] POSCO Holdings. Sustainability Report 2022. Page 34.
[151] POSCO HOLDINGS. Sustainability Report 2022. Page 36.
[152] POSCO. POSCO Group implements CCS business in Sarawak, Malaysia. 3 January 2023.

subsidiaries are also eying CCUS. Trading and energy company POSCO International is a member of a consortium working to establish offshore carbon storage in Texas with a capacity of 600Mt.[153]

Despite a long-term aim to transition to hydrogen-based steelmaking, POSCO's CCUS plans highlight that it remains committed to coal-based steelmaking. The company initiated the relining Blast Furnace No.4 in its Pohang steelworks, with a capacity of 5.3Mtpa, and has recently allocated funds for the relining of Blast Furnace No.2 in Gwangyang, with a capacity of 3.15Mtpa.[154]

In addition, POSCO plans to build new blast furnaces in developing nations. The company has entered into an MoU with Krakatau Steel to collaboratively invest USD3.5 billion in constructing a second blast furnace and cold rolling mill in Indonesia. The Krakatau POSCO joint venture already operates a 3Mtpa blast furnace, and the new investment aims to double the capacity. There are also plans to capture the plant's emissions and store them 50km to 200km away.[155]

With POSCO relining blast furnaces in South Korea while building and planning new blast furnaces in Asia, it is relying on unproven CCUS technology to meet its 2050 net zero target.

JFE Steel

JFE Steel, the second-largest steelmaker in Japan, aims to achieve a 30% reduction in emissions by the end of this decade, against a 2013 baseline, and attain carbon neutrality by 2050. Key technologies that JFE has identified to achieve its 2050 target include carbon recycling in blast furnaces, and a switch to EAF and DRI-based steelmaking using hydrogen. The company sees much of the emissions reductions coming post-2040, and it maintains that CCUS will play a key role at this time (Figure 19).

In its plan for carbon-recycling blast furnaces, CO_2 from the top gas will be transformed into methane. The methanation process involves combining captured CO_2 with hydrogen, with the resulting methane serving as an alternative reducing gas source instead of coke produced from coking coal. Currently, JFE is experimenting with the technology at pilot scale. It intends to conduct a mid-scale demonstration test by 2030 before completing full implementation by 2040. However, JFE notes this technology is only capable of reducing blast furnace emissions by 50% or more, meaning CCUS will be needed to allow it to continue to operate blast furnaces in 2050 and beyond.[156]

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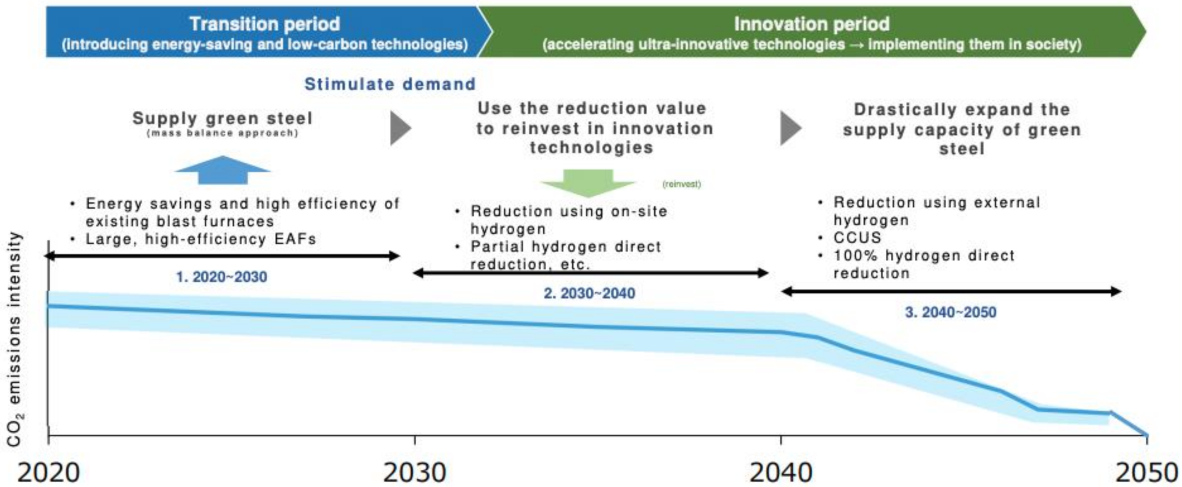
153 The Korea Times. POSCO International to capture, store carbon off Texas coastline. 7 September 2023.
154 Solutions for Our Climate. POSCO Profile No. 1 - Coal Tomorrow with POSCO: Doubts Rising on Korean Steelmaker's Net-Zero Future. 6 October 2023.
155 Korea JoongAng Daily. Posco's Indonesian steel mill runs red-hot after testing start. 24 September 2023.
156 JFE Steel Corp. Carbon Neutrality Strategy Briefing 2023. 8 November 2023. Page 6.

Figure 19: JFE's plan to reduce the emissions intensity of steel products



Source: JFE Steel.[157]

As a result, JFE has numerous CCUS development projects underway. In collaboration with JAPEX, JGC HD, and "K" LINE, JFE has agreed to conduct an evaluation of the possibility of capturing CO_2 in Japan before transportation to possible storage sites in Malaysia.[158] The target of this initiative is to store 1Mt of CO_2 by 2029, and 4Mt by 2034, with an assumed project budget of 500 billion yen (USD3.3 billion).[159] Front-end engineering design for the proposal is set to commence in 2024, and Chugoku Electric Power and Nippon Gas Line have joined the project.[160]

In a separate MoU, Kansai Electric Power Company (KEPCO) and JFE have embarked on a study to explore potential opportunities for CCS projects. This entails capturing CO_2 emissions from KEPCO's thermal power plants and JFE's steelworks, followed by transporting the CO_2 via ship to depleted oil and gas fields, aquifers and other locations both in Japan and internationally for underground storage. JFE's press release revealingly notes that the project is aimed at "sorting out various issues related to the technologies and costs required for CCS projects".[161]

In December 2023, JFE signed another MoU with Sumitomo Corporation, Sumitomo Osaka Cement, "K" LINE and Woodside Energy to conduct a feasibility study on a plan to aggregate captured Japanese CO_2 emissions before transporting them to Australia for storage. The proposal involves the

[157] JFE Steel Corp. Carbon Neutrality Strategy Briefing 2023. 8 November 2023. Page 21.
[158] JFE Steel Corp. Agreed on Joint Evaluation with JFE Steel Corporation to Establish CCS Value Chain Originated from Japan Aligned with CCS Study in Malaysia. 19 June 2023.
[159] JFE Steel Corp. Carbon Neutrality Strategy Briefing 2023. 8 November 2023. Page 18.
[160] JFE Steel Corp. The Chugoku Electric Power and Nippon Gas Line Participate in the Joint Evaluation to Establish CCS Value Chain Originated from Japan for the CCS Project in Malaysia. 26 February 2024.
[161] JFE Steel Corp. KEPCO and JFE Steel sign Memorandum of Understanding to jointly study possible projects for Carbon Dioxide Capture and Storage Projects. 19 October 2023.

collection of CO_2 by small vessels from emitters “scattered in multiple areas in Setouchi and Shikoku regions” and storing them temporarily at a port hub in Japan before transportation.[162]

The concept of capturing CO_2 – including at small scale from “scattered” emitters – and transporting it over thousands of kilometres for storage in depleted oil and gas reserves or other geological storage facilities appears highly likely to be a costly endeavour that will never be put into practice.

JFE Steel is also targeting DRI-based iron and steel production and even appears to be embracing the potential for a geographically restructured global steel ecosystem involving the import of DRI in the form of HBI from places with cheaper renewable energy resources than Japan. JFE has formed a collaborative partnership with Emirates Steel Arkan and ITOCHU Corporation. They aim to establish an ironmaking facility in the UAE focused on producing low-emissions iron materials like HBI for international export. This collaboration will adopt gas-based DRI technology, though a later switch to hydrogen is being considered. Additionally, there are plans to use CCS, with the captured CO_2 being used in EOR processes.[163]

Given EOR does little or nothing for overall emissions abatement, JFE cannot credibly claim that such a proposal is part of its net zero emissions plan. The UAE DRI project needs to focus on an early switch from gas to green hydrogen if effective emissions reduction is a priority.

[162] JFE Steel Corp. MOU for Feasibility Study to Realize "Setouchi / Shikoku CO_2 Hub Concept". 18 December 2023.
[163] JFE Steel Corporation. JFE Steel, Emirates Steel and Itochu to Study Building Supply Chain of Ferrous Raw Material for Green Ironmaking with Low-carbon Emission. 1 September 2022.

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