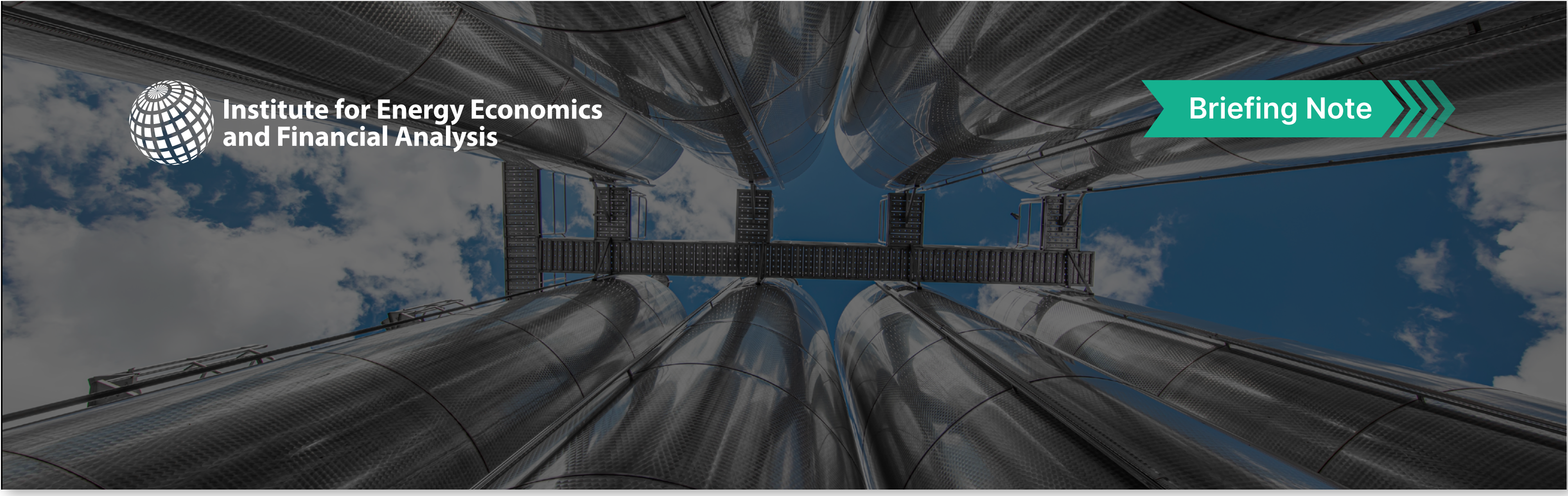

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Steel CCUS update: Carbon capture technology looks ever less convincing

- *Six commercial-scale carbon capture, utilisation and storage (CCUS) projects for iron and steelmaking are in the development pipeline, up from three in 2023. However, the lack of available detail casts doubts over their development status and timelines.*

- *The Al Reyadah project in the United Arab Emirates (UAE) is still the world's only operational commercial-scale CCUS project for steelmaking. It captured only 26.6% of the gas-based steel plant's emissions in 2023. There are still no commercial-scale CCUS plants for blast furnace-based steelmaking in operation anywhere in the world.*

- *Since IEEFA's April 2024 report on steel CCUS, carbon capture projects have continued to fail and underperform in other sectors. Equinor recently admitted over-reporting the performance of its flagship Sleipner CCUS project for years due to faulty monitoring equipment.*

- *Despite mounting evidence to the contrary, major steelmakers and miners such as Nippon Steel, ArcelorMittal and BHP continue to insist to their investors that CCUS will play an important role in meeting their decarbonisation targets.*

In October 2024, the Global CCS Institute (GCCSI) published its latest Global Status of CCS Report. The report lists all commercial-scale CCUS plants in operation and in the project pipeline. The GCCSI is tracking more than 500 commercial-scale projects globally, of which only 50 are operational, with the vast majority yet to reach construction. Just seven operate in the iron and steel sector (Table 1).

Given CCUS's poor track record across all sectors, the technology looks increasingly unlikely to play a significant role in decarbonising steel, as IEEFA highlighted in its April 2024 report. Since this report was published, CCUS's poor track record has continued. In Canada, the Boundary Dam CCUS project has continued to significantly underperform. In May 2024, a C$2.4 billion CCUS proposal for power generation near Edmonton was cancelled on the grounds it was not financially viable.

Perhaps most damningly, oil and gas producer Equinor recently admitted significantly over-reporting the performance of its flagship Sleipner CCUS project for years due to faulty monitoring equipment. Sleipner is often held up by advocates as proof of CCUS's technical feasibility. Instead, the project further highlights the risks of attempting to implement CCUS at scale around the world.

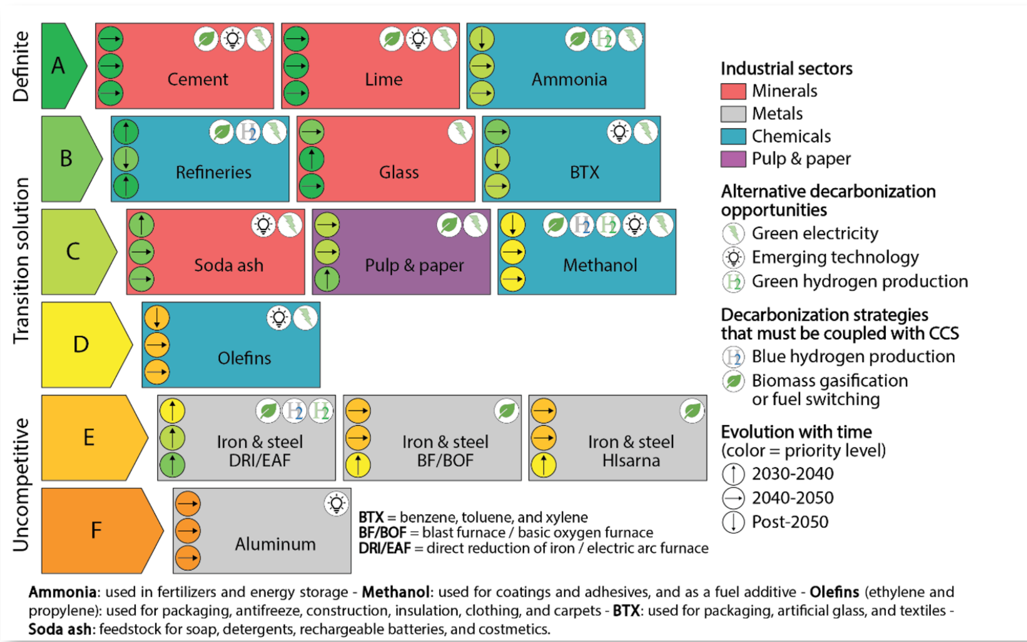
Major role for CCUS in steel decarbonisation increasingly unlikely

As highlighted in our April 2024 report, CCUS for the steel industry faces major drawbacks: some specific to the steel sector; some that affect CCUS across all sectors.

CCUS is predisposed to major financial, technological and environmental risks. Low capture rates is a key ongoing issue that is often underappreciated. The amount of carbon targeted for capture at a project tends to be significantly below its overall emissions. The world's only operational CCUS plant for steelmaking is an example. The Al Reyadah CCUS project in the United Arab Emirates (UAE) captured only 26.6% of the gas-based steel plant's emissions in 2023. Furthermore, CCUS projects consistently struggle to meet even these low capture targets.

In addition, there is the high cost of transporting captured carbon, and uncertainty over the long-term effectiveness of geological CO_2 storage. Each carbon storage project is unique, facing different geological conditions and issues. As a result, it is difficult to implement any learnings from one project to the next, which results in limited cost reductions. Despite decades of attempted implementation, the cost of CCUS remains high. The cost of green hydrogen – a key enabler of truly low-carbon iron and steel production – is also high but has a much better chance of declining through economies of scale and renewables cost reduction.

Figure 1: US CCS ladder for industrial decarbonisation



Source: Kleinman Center for Energy Policy

There are still no commercial-scale CCUS plants for blast furnace-based steelmaking in operation anywhere in the world. Coal-consuming, blast furnace-based steel plants have multiple sources of carbon emissions that would need multiple points of carbon capture to allow production of low-carbon steel. The cost involved means capturing sufficient carbon at coal-based steelmaking sites will likely never be financially viable.

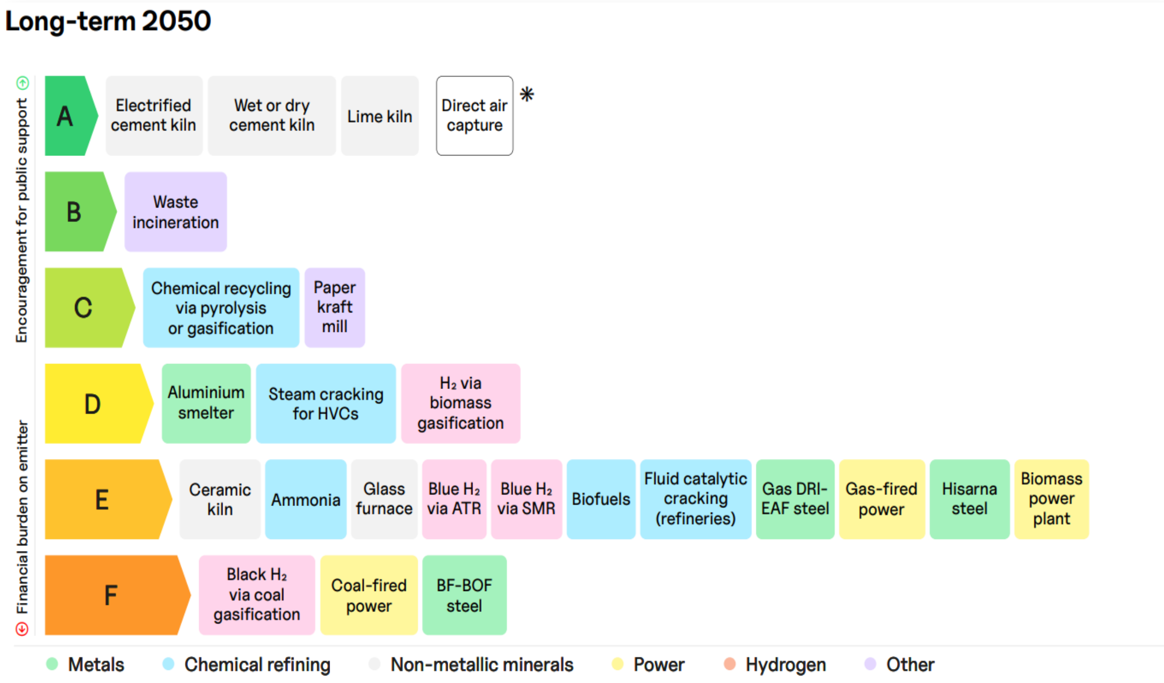
IEEFA is far from the only sceptic when it comes to CCUS for steelmaking. In October 2024, the Kleinman Center for Energy Policy at the University of Pennsylvania published a US CCS ladder for industrial decarbonisation. It highlights that, although CCUS may play a key role in decarbonising some industrial processes, its application for iron and steelmaking is "uncompetitive" (Figure 1).

The ladder used five criteria to rank the suitability of CCUS applications:

- Feasibility
- Mitigation potential
- Availability of alternative decarbonising technology
- Potential to lock in emissions-intensive technology or fossil fuel use
- Geospatial dispersion

The methodology was similar to that used by E3G and Bellona on their Europe CCS ladder, which also cast significant doubt on the future of CCUS in the steel sector (Figure 2).

Figure 2: E3G and Bellona Europe CCS Ladder 2050



Sources: E3G, Bellona

In July 2024, Sandbag found that retrofitting blast furnace-based plants with CCUS was "unlikely to be cost-competitive", particularly where hydrogen could be produced competitively for direct reduced iron-electric arc furnace (DRI-EAF) steelmaking, highlighting cost and feasibility challenges with CO_2 transportation and storage. Sandbag stated that, although there may be some opportunity for CCUS in gas-based DRI-EAF steelmaking, "given the slow pace of technological and market development we anticipate that capturing carbon will play a limited role in the steel industry, with its applications primarily confined to standalone cases".

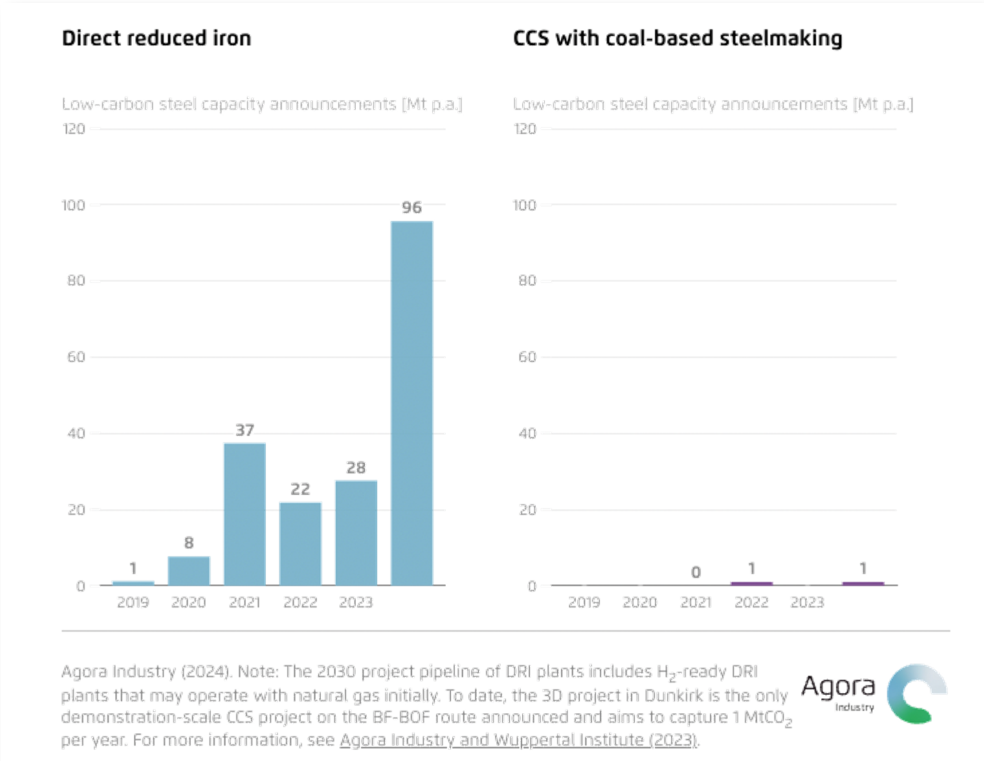
The International Energy Agency (IEA) is often referenced by CCUS supporters but it appears to be shifting its view of the role CCUS will play in decarbonising steel. In its milestone 2021 report, Net Zero by 2050: A Roadmap for the Global Energy Sector, the IEA saw 670 million tonnes of CO_2 ($MtCO_2$) a year being captured in the steel industry by 2050. However, just two years later in its 2023 update to the NZE Scenario, this had been reduced to 399$MtCO_2$ – a drop of 40%.

IEEFA expects the IEA to further reduce its projected contribution of CCUS in future updates.

Wood Mackenzie is also reducing its expectations of steel CCUS. In its 2024 net zero emissions scenario, it sees steel CCUS capturing 320MtCO_2 a year in 2050, down from 470MtCO_2 in its previous scenario.

While CCUS for steel continues to stall, some steelmakers are progressing their shift away from coal-based steelmaking to DRI, a perfectly mature technology that can run on green hydrogen as the cost of this alternative reductant comes down. Virtually all steelmakers planning or constructing commercial-scale low-carbon steelmaking capacity have turned to hydrogen-based or hydrogen-ready DRI plants, not CCUS. The 2030 project pipeline capacity of DRI plants has reached 96 million tonnes per annum (Mtpa), while the pipeline for commercial-scale CCUS for blast furnace-based operations remains stuck on just 1Mtpa (Figure 3). CCUS for blast furnace-based steelmaking is being left behind by a better alternative that can outcompete it on both cost and emissions reductions.

Figure 3: 2030 pipeline of low-carbon steel announcements



Source: Agora Industry (2024)

Steel and iron ore companies continue to back CCUS

Despite the poor outlook for CCUS in the iron and steel sector, some steelmakers and iron ore miners are still insisting to their investors that the technology will play a role in meeting their decarbonisation targets.

In Japan, Nippon Steel continues to maintain that CCUS will be a key part of its efforts to reduce emissions and it is still expanding its investments in metallurgical coal mines. The company's 2024 Integrated Report highlighted its approach to CCUS, stating, "Nippon Steel Group is aggressively engaged in developing these technologies to help realise the social implementation of CCUS."

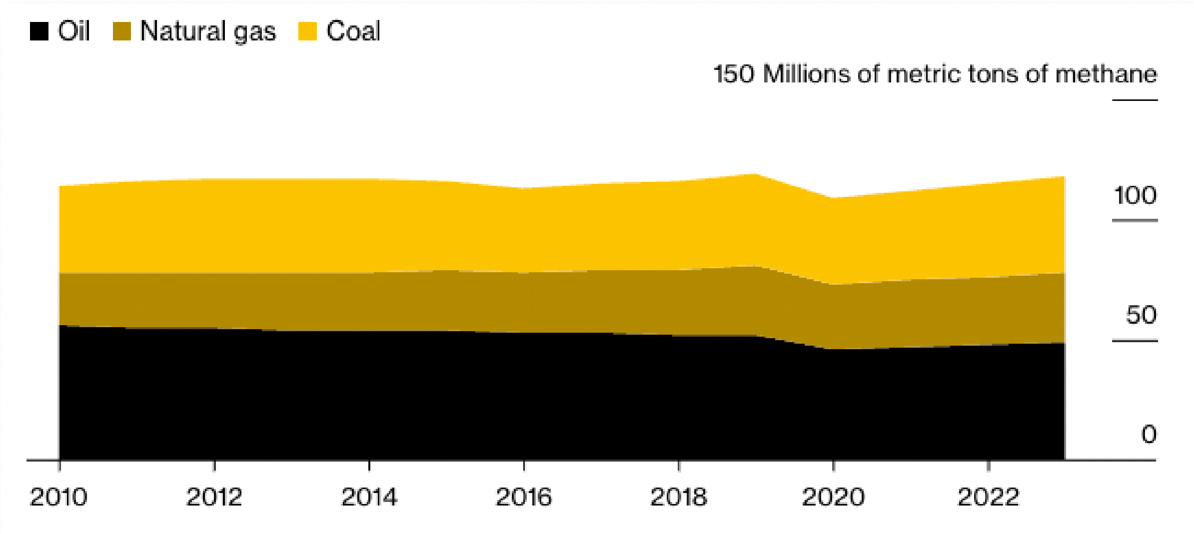
ArcelorMittal, along with project partners BHP, Mitsubishi Heavy Industries and Mitsubishi Development, continue to experiment with CCUS at pilot scale in Europe. This is just one of the CCUS pilot projects involving BHP. Since our April 2024 report, BHP has announced another CCUS collaboration, this time with India's JSW Steel, and continued to defend the technology – which would prolong the use of its metallurgical coal and blast furnace-grade iron ore – at its 2024 AGM.

Coalmine methane

Corporate backing for steel CCUS comes despite growing understanding of a key issue the technology does nothing to address. Installing CCUS at steel plants cannot tackle methane emissions from metallurgical coal mines that supply blast furnace-based steel plants or gas production supplying DRI-based steel plants. Along with low capture rates, this is another reason why steel production relying on CCUS will never be able to supply truly green steel.

Since our April 2024 report, the scale of the methane emissions issue has become more apparent. Methane emissions from oil, gas and coal production remain close to record highs, according to the IEA (Figure 4). Furthermore, there is growing evidence methane emissions from fossil fuel production are greater than previously estimated. In Australia – by far the largest exporter of metallurgical coal – a new online methane emissions tool (Open Methane) using satellite monitoring technology was released in October 2024 by the Superpower Institute. Initial results from the Open Methane Tool suggest Australia's methane emissions may be double the reported amount.

Figure 4: Methane emissions from fossil fuel production remain close to record high



Source: International Energy Agency

Status of commercial-scale steel CCUS project

The GCCSI's Global Status of CCS 2024 report lists six commercial-scale CCUS projects for iron and steelmaking in the development pipeline, in addition to the one operational project (Table 1). This is up from three projects under development in 2023. However, the lack of available detail for some of these projects casts doubt over their development status and timelines.

The total carbon capture capacity for these projects (where disclosed) amounts to a tiny fraction (0.13%) of global steel emissions (Table 1).

For all six projects under development, including the one under construction, the GCCSI is unable to confirm all aspects of the projects. In each case, at least one category of "operational year", "capture capacity" and "storage type" is listed as "under evaluation" by GCCSI. Two of the three projects supposedly in "advanced development" don't have a known operational year. The CO_2 capture capacity is unknown in half of the projects under development, and no information about carbon storage or usage is disclosed for any of them.

Table 1: Status of global commercial-scale CCUS projects for iron and steelmaking

Country	Facility Name	Project Status	Operational Year	Annual Capture Capacity ($MtCO_2$)	Storage Code
United Arab Emirates	ADNOC Al Reyadah	Operational	2016	0.8	Enhanced Oil Recovery
China	Baotou Steel	In Construction	2024	0.5	Under Evaluation
United States	Indiana Burns Habor Capture	Advanced Development	Under Evaluation	2.8	N/A
United States	ArcelorMittal Texas	Advanced Development	Under Evaluation	Under Evaluation	N/A
United States	Nucor Steel DRI	Advanced Development	2026	0.8	Under Evaluation
Japan, Malaysia	Japan Malaysia Steel CCS	Early Development	Under Evaluation	Under Evaluation	N/A
Spain	ArcelorMittal Sestao CCS	Early Development	2025	Under Evaluation	Under Evaluation

Total disclosed CO_2 annual capture capacity ($MtCO_2$)
4.9

Annual global steelmaking emissions ($MtCO_2$) (IEA)
3,700

Percentage of global steel emissions to be captured
0.13%

Sources: IEEFA Calculations, Global CCS Institute, Global Status of CCS 2024, IEA

ADNOC Al Reyadah

The Al Reyadah CCUS facility in Abu Dhabi remains the first and only commercial-scale carbon capture facility linked to a steel mill. With a nominal capacity of $0.8MtCO_2$ a year, this facility captures wet CO_2 from Emsteel's direct reduction (DR) units. After preparation, the CO_2 is injected into ADNOC's oil wells for enhanced oil recovery (EOR), ultimately enabling more carbon emissions. Eight years after coming online, Al Reyadah is still the only operating CCUS plant for steelmaking anywhere in the world.

The capturing technology, integrated into Emsteel's Energiron DR plants, captures approximately 45% of direct emissions from the iron ore reduction process. Public data on the actual CO_2 captured at Al Reyadah is unavailable. However, the overall capture rate as a percentage of the steel plant's total emissions is significantly lower than 45%.

Table 2 presents the annual CO_2 capture rate as a percentage of total steel plant emissions for 2020-2023. Assuming the plant operated at its nominal capacity in previous years, it only captured 19.3% to 26.6% of the steel plant's total carbon emissions. This limitation arises because the technology can only partially reduce emissions, and cannot address all sources of carbon emissions. Emsteel has pursued more effective strategies, including purchasing low-emission electricity, and is considering a longer-term shift from gas to green hydrogen.

Table 2: Emsteel CCUS capture rates and low-emissions electricity purchase

Description	Index	Unit	2020	2021	2022	2023
Disclosed maximum CO2 capture	A	tonne	800,000	800,000	800,000	800,000
Disclosed Scope 1	B	tCO2e	1,904,805	2,094,888	2,193,637	2,105,053
Disclosed Scope 1 + 0.8Mt CO2 as captured by CCUS plant	A+B	tCO2e	2,704,805	2,894,888	2,993,637	2,905,053
Disclosed Scope 2 (market-based)	C	tCO2e	1,434,462	1,120,521	411,159	100,455
Scope 1 and 2 + 0.8Mt CO2 from the CCUS plant	A+B+C	tCO2e	4,139,267	4,015,409	3,404,796	3,005,508
Rate of capture of total emissions	(A/(A+B+C))	%	19.3%	19.9%	23.5%	26.6%

Sources: Emsteel sustainability report 2023, IEEFA

In 2023, Emsteel consumed 2 million megawatt hours (MWh) of low-emissions electricity, significantly reducing its Scope 2 (indirect) emissions. This reduction has increased the CCS share in total carbon reduction, although it reflects the impact of low-emissions electricity use rather than enhancements to the CCS facility itself.

Emsteel, in collaboration with renewable energy company Masdar, has successfully launched a green hydrogen pilot plant. This new facility produces green hydrogen that can replace gas in the iron ore reduction process, thereby reducing total emissions associated with steel production. Although the project is at the pilot scale, green hydrogen has the potential to fully replace gas in the process. This will facilitate the production of truly green steel, which will be demonstrated by Stegra's under-construction plant in Sweden, where truly green iron and steel will be produced at commercial scale from 2026.

Baotou Steel

In June 2022, Baotou Steel (Baogang Group), based in the Inner Mongolia Autonomous Region, launched the construction of China's first steel sector CCUS project with a targeted, eventual capacity of $2MtCO_2$ a year. The initial phase aims to capture 500,000 tonnes of CO_2 from steel mill emissions.

GCCSI does not classify the storage type of this project, listing it as "under evaluation" despite disclosing that the project is due to become operational in 2024. It seems this project utilises Columbia University's advanced iron and steel slag treatment technology, which transforms solid waste into products such as high-purity calcium carbonate and ferrous materials using captured CO_2. Some of the captured CO_2 will be utilised in this way, with the rest used for enhanced oil recovery (EOR), enabling the emission of more CO_2. Specific data on the technology, transportation and storage remain limited.

Although this project is on GCCSI list of commercial-scale projects, numerous sources, including the Leadership Group for Industry Transition (LeadIT), classify it as a demonstration project. LeadIT also lists 2025 as its operational year, not 2024.

Indiana Burns Harbor Capture

Burns Harbor, Cleveland-Cliffs' second-largest US facility, is an integrated steelmaking plant in north-west Indiana, operating two blast furnaces with an annual crude steel capacity of 5Mt. In December 2022, Cleveland-Cliffs submitted a funding application for research into front-end engineering design (FEED) for large-scale carbon capture at the Burns Harbor facility. The first phase of this study was funded by the US Department of Energy's (DOE) Office of Clean

Energy Demonstrations (OCED). The second (FEED) phase is planned for completion within two years, with half of the financial support provided by the DOE. The Burns Harbor project aims to capture up to 2.8MtCO_2 a year from blast furnace gas.

In its Global Status of CCS 2024 report, GCCSI classifies this project as being in “advanced development” despite the fact its expected operational year is “under evaluation”. IEEFA suggests that this project may not be as advanced as GCCSI makes out.

Since the project was announced in 2022, there have been no further updates on it from Cleveland-Cliffs. It was not mentioned in the company’s most recent sustainability report or annual report, with the 2023 Sustainability Report simply stating, “Cliffs continued to engage with developers of carbon capture, utilization and sequestration (CCUS) … While additional research and development is needed, we believe that CCUS will be an important long-term decarbonization solution for the iron and steel sector.”

Cleveland-Cliffs plans to reline a blast furnace at Burns Harbor. Achieving net-zero carbon emissions with coal-based blast furnaces remains unrealistic, even with CCUS or hydrogen injection.

However, in contrast to CCUS, the company is also prioritising far more promising solutions to decarbonise its steel operations, with a primary focus on hydrogen initiatives. Key projects include research into using hydrogen at the Toledo hot briquetted iron (HBI) plant, deploying a hydrogen-fired reheating furnace and the installation of a hydrogen pipeline at Indiana Harbor in preparation for the anticipated DOE hydrogen hub in Indiana. In March 2024, Cleveland-Cliffs announced it had been selected for award negotiation for up to US$500 million to replace its Middletown Works blast furnace with a hydrogen-ready DRI plant and electric melting furnaces.

ArcelorMittal Texas

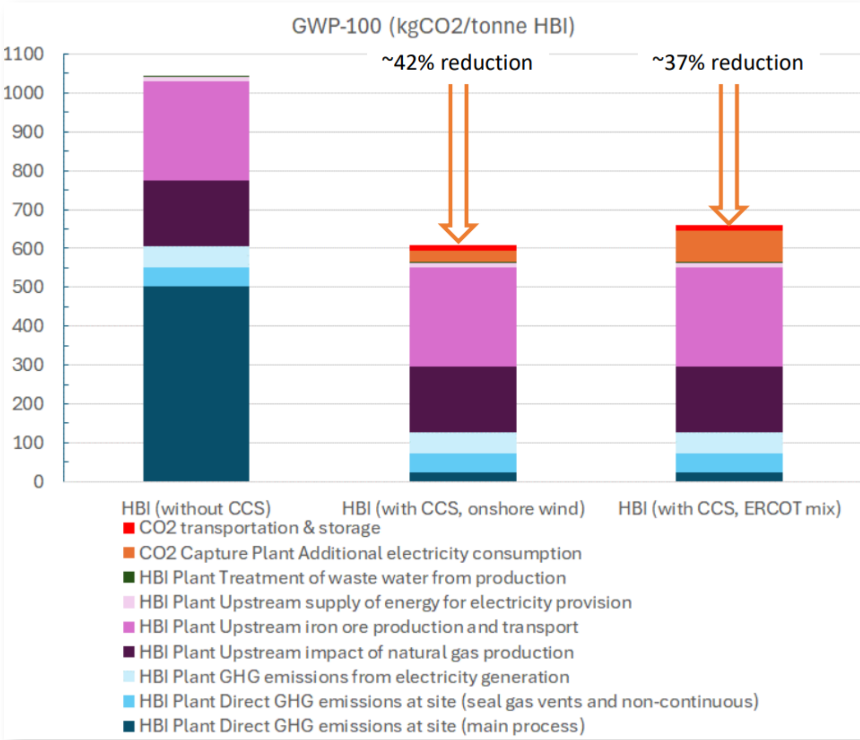
This project is another that GCCSI considers to be in “advanced development” despite not being able to disclose a date when it is expected to be operational nor its capture capacity.

The ArcelorMittal Texas HBI plant, with an annual capacity of 2Mt, is equipped with the latest technology from Midrex, and emits approximately 1MtCO_2 a year.

The facility is undergoing development studies by a coalition of partners, including the University of Illinois, Hatch, Midrex and ArcelorMittal. There are plans to retrofit the plant with Air Liquide’s Cryocap carbon capture technology to capture 95% of direct emissions from the DR shaft. The capture system utilises pressure swing adsorption (PSA)-assisted Cryocap technology. Information regarding transport and storage aspects of this project have not yet been disclosed.

Preliminary life cycle analysis shows that the technology fails to get close to the 95% emissions reduction level when taking account of upstream emissions from iron ore supply, methane emissions from gas production and the additional energy required for CO_2 capture and transportation. As a result, emissions reduction from the project would only be 37%-42% according to an August 2024 research project review meeting (Figure 5).

Figure 5: ArcelorMittal Texas CCS preliminary life cycle analysis



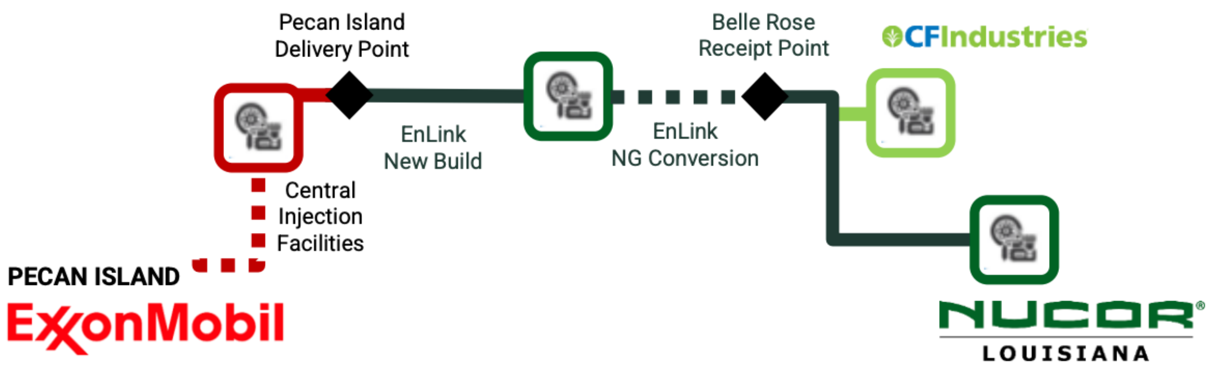
Source: US DOE Office of Fossil Energy / National Energy Technology Laboratory

Nucor Steel DRI

Nucor Steel, the largest steelmaker in North America, has operated an Energiron ZR DRI plant in Louisiana with a capacity of 2.5Mt since 2013.

In June 2023, Nucor Steel signed an agreement with ExxonMobil to capture up to 0.8MtCO_2 a year from the DRI plant, which will be stored at ExxonMobil's Pecan Island facility in Louisiana. In November 2023, Nucor stated that the capture capacity would be 0.6-0.88MtCO_2 a year. The project is scheduled to begin operations in 2026. ExxonMobil will utilise the same transportation and storage infrastructure as its CF Industries capture project, which is planned to start by 2025. These two projects will use EnLink Midstream's regional pipeline network for transportation.

Figure 6: Nucor carbon capture and storage project



Source: Nucor Net Zero by 2050 Strategy

However, Exxon has since withdrawn its application to drill two appraisal wells at Pecan Island. In February 2024, Exxon and EnLink announced that they were exploring additional carbon transportation opportunities in the Gulf Coast region, stating, "EnLink and ExxonMobil have agreed to reassess the Pecan Island Area project's near-term role, with the expectation that other joint opportunities may be prioritized ahead of the Pecan Island project".

Then in November 2024, it was reported there was further doubt over the storage sites for Exxon's proposed carbon capture projects in the region. As of October 2024, Exxon had not received permits to inject CO_2 at its two proposed storage sites in Louisiana or its three sites in Texas. Despite these doubts, GCCSI classifies this project as being in "advanced development".

Despite claiming to be the global leader in CCS with decades of experience with the technology, ExxonMobil has yet to achieve consistent success in CO_2 sequestration. Notably, the Shute Creek project in Wyoming – the largest and one of the oldest CCUS facilities in the world – has underperformed significantly. About half of the captured CO_2 has been vented into the atmosphere over the project's lifetime. Of the remainder, 47% has been used for EOR, enabling the release of more CO_2 emissions.

Japan Malaysia Steel CCS

GCCSI has a project entitled "Japan Malaysia Steel CCS" in its commercial-scale development list but no operational year, capture capacity or storage type is disclosed.

The Japan Oil, Gas and Metals National Corporation (JOGMEC) has designated nine carbon capture initiatives for development in fiscal year 2024. These projects collectively aim to store about 20MtCO_2 annually, with five intending to store CO_2 in or offshore Japan and four in the Asia-Pacific region. Among them, three projects intend to capture CO_2 from various companies and industries in Japan and transport it to sites offshore of Malaysia for storage. Two of these involve Japanese steelmaker JFE Steel, in addition to emissions from other sources. It is not clear which of these two projects is the one GCCSI refers to as "Japan Malaysia Steel CCS".

Another project involving Nippon Steel, among others, plans to store captured CO_2 off the coast of Japan.

All of these projects are in the early stages, and JOGMEC, which aims for these projects to start operations by 2030, is accepting applications for design work for the entire CCS value chain. Neither of these two projects are dedicated to the steel industry alone, as the total capacity will be distributed among participants in other sectors.

Table 3: Steel-related CCS collaboration between Japan and Malaysia

Project Title	Partners	Storage Area	Storage volume	Emissions Source	Transportation method
Malaysia Northern Peninsula	Mitsubishi, ENEOS, JX Nippon Oil & Gas Exploration, **JFE Steel**, Cosmo Oil Co, Nippon Shokubai, Petronas CCS Solutions	North-east offshore Malay Peninsula (depleted oil and gas fields)	≈ 3Mtpa	Multiple industries including **steel**, chemicals and oil refining in the Tokyo Bay coastal industrial complex	Ships and pipelines
Malaysia Sarawak Offshore	Japan Petroleum Exploration, JGC Holdings, Kawasaki Kisen Kaisha, Petronas CCS Ventures, **JFE Steel**, Mitsubishi Gas Chemical Co., Mitsubishi Chemical Co., Chugoku Electric Power Co., Japan Gas Line Co.	Offshore Sarawak, Malaysia (Depleted offshore gas field)	≈ 1.9-2.9 Mtpa	Multiple industries in the Setouchi region, including **steel mills**, power plants and chemical plants	Ships and Pipelines

Source: Carbon Herald

A key and obvious headwind to both the steel-related CCUS projects planning storage off the Malaysian coast is the likely high cost of transporting captured CO_2 from Japan to Malaysia. As a result, IEEFA suggests there is little chance such a project will ever becoming operational.

ArcelorMittal Sestao CCS

ArcelorMittal's Sestao facility in Spain is a scrap-based steel plant with two electric arc furnaces (EAFs). The company announced in 2021 that Sestao would become "the world's first full-scale zero carbon-emissions steel plant" by adopting a hydrogen-based decarbonisation pathway, using H2-DRI from the nearby Gijon plant by 2025. Although ArcelorMittal is pursuing several pilot-scale carbon capture projects under its Smart Carbon initiative, and a commercial-scale project for DRI-based ironmaking in the US, there is no mention of a CCUS project planned for Sestao in its most recent climate action report. The GCCSI's 2024 report gives no further details as to which project is being referenced here.

About IEEFA

The Institute for Energy Economics and Financial Analysis (IEEFA) examines issues related to energy markets, trends and policies. The Institute's mission is to accelerate the transition to a diverse, sustainable and profitable energy economy. www.ieefa.org

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