Steel and CCS/U

Decarbonisation potential, costs, and bottlenecks

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Executive Summary

The European iron and steel industry is a significant emitter of greenhouse gases and is therefore facing mounting pressure to decarbonise in order to align with EU climate objectives. Carbon capture, storage and/or utilisation (CCS/U) technologies are often touted as a 'catch all' solution for the decarbonisation of heavy industry, but their effectiveness and relevance vary widely across applications. This report offers a comprehensive assessment of CCS/U technologies in the context of iron and steel manufacturing in Europe.

We explored carbon capture options for various steel production routes, including the blast furnace- basic oxygen furnace (BF-BOF) and direct reduced iron-electric arc furnace (DRI-EAF) routes. We found that retrofitting existing BF-BOF plants with carbon capture is unlikely to be cost-competitive, especially in locations where hydrogen (H2) can be produced at a competitive cost which would make H2-DRI-EAF based steelmaking favourable. In the short term, the most favourable option for carbon capture would be when using natural gas (NG) as feedstock in this route (NG-DRI-EAF), considering its commercial availability. However, 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.

Captured CO_2 can be repurposed into valuable products (CCU). However, while some projects have explored utilising captured CO_2 from steel production for fuels, chemicals, and materials (e.g. ThyssenKrupp's conversion of steel mill gases into fuels and chemicals and ArcelorMittal's initiatives like Steelanol for bioethanol production), these technologies remain largely in the pilot phase. Overall, CCU is likely to offer limited emission reductions relative to the industry's overall emissions, is dependent on efficient carbon capture processes and, ultimately, falls short of more sustainable alternatives like DRI-EAF and EAFs with recycled scrap. Other concerns include "delayed emissions" embedded in products, indirect emissions from energy use, and the significant energy requirements of processes like CO_2 conversion to methanol.

The transport and storage (CCS) of captured CO_2 emissions should thus be prioritised over CCU. However, challenges persist in this part of the CO_2 value chain, too. The costs and feasibility of transport and storage remain an issue, as do the geological limitations that exist in Europe, with most natural reservoirs concentrated in the North Sea. The EU has yet to adopt common norms and standards to regulate its CO_2 transport and storage network, adding another layer of uncertainty for investors and project developers. From a climate perspective, the biggest concerns around CO_2 transport and storage remain the considerable risks of CO_2 leakage, both during transport and from storage reservoirs.

In conclusion, while CCS/U technologies will play a role in decarbonising heavy industry, their deployment in the iron and steel industry must be limited to DRI plants that do not operate with green hydrogen. With that being said, prioritising alternative steel production routes, such as Green-H2-DRI-EAF or EAFs using recycled post-consumer scrap, over the use of CCS/U, aligns more strongly with climate goals. Reevaluating EU policies and funding to focus on emission reductions rather than CCS/U deployment for economic opportunities is essential.

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Definitions

Carbon capture	The process of capturing carbon dioxide (CO_2) from industrial emissions that would otherwise be emitted into the atmosphere.
Carbon Capture and Storage (CCS)	The process of capturing carbon dioxide (CO_2) from industrial emissions, which is then transported and injected into a reservoir such as a geological formation where it is to be permanently stored.
Carbon Capture and Utilisation (CCU)	The process of capturing carbon dioxide (CO_2) from industrial emissions and using it to produce products such as fuels (for e.g. bioethanol), chemicals (for e.g. ammonia), and building materials.
Carbon Capture, Storage, and Utilisation (CCS/U)	Term and acronym that encompasses both CCS and CCU technologies. Whilst the CO_2 flows follow different routes after their capture, the two categories of carbon capture projects are often subject to the same policy and funding instruments.
Carbon dioxide removals (CDR)	Activities that capture carbon dioxide (CO_2) from the atmosphere and from biogenic emission sources before storing it in reservoirs or in long-lasting products. CDR may refer to a wide range of nature-based and technological solutions, including direct air carbon capture and storage (DACCS), bio-energy carbon capture and storage (BECCS), and carbon farming (activities that enhance carbon sequestration and storage in soils and forests such as forest restoration and wetland management).
Emission reductions	Reduction of the amount of CO_2 emitted into the atmosphere by a type of economic activity. This can be achieved through a variety of approaches, such as switching to renewable energy sources, improving energy efficiency, and using less carbon-intensive transportation fuels.
Zero vs. Net zero emissions	Zero emissions means that no greenhouse gases (GHG) are emitted into the atmosphere, while net zero emissions means that the amount of greenhouse gases (GHG) emitted into the atmosphere is balanced by the amount that is captured or removed.
Negative emissions	The action of removing CO_2 from the atmosphere, through activities such as carbon dioxide removals (CDR). They are described as 'net negative' when more CO_2 is removed from the atmosphere than is emitted and its storage is permanent.
Residual emissions	Residual emissions refer to emissions that are difficult to avoid or fully eliminate due to technological, financial, or other limitations, despite abatement efforts.

1. A growing faith in CCS/U

1.1 The role of carbon capture in the global transition to net zero emissions

In its latest report, *AR6 Synthesis Report: Climate Change 2023*, the Intergovernmental Panel on Climate Change (IPCC) insisted that the various pathways limiting global warming to 1.5°C and 2°C may differ in approach but all rely on rapid and deep emission reductions. Achieving these reductions generally involves a combination of measures aiming to reduce demand for carbon-intensive materials and processes as well as to increase recycling and reusing rates, improve energy efficiency, and switch to renewable energy sources. However, **reducing emissions can be technologically and/or financially difficult, particularly in some sectors, which has led to them being labelled as "hard-to-abate"**. These sectors include heavy industry (e.g. cement, steel, chemicals, mining) and some transport modes (e.g. aviation, shipping, heavy-duty vehicles). **Carbon capture and storage (CCS) and carbon capture and utilisation (CCU), collectively known as CCS/U technologies, have long been touted as possible solutions to capture these so-called hard-to-abate carbon dioxide (CO_2) emissions**.

The IPCC acknowledged the high economic costs involved with their deployment but confirmed that CCS/U technologies had been *"identified as playing key roles in the transition of industry to net zero"* (IPCC, 2022: 1211). They are present in most of the IPCC's mitigation pathways, although IPCC reports also specify that the potential contribution of carbon capture technologies to achieve net emission reductions in the industrial sectors in the short to medium term is relatively limited and particularly expensive compared to other mitigation options (IPCC, 2022: 1167; IPCC, 2023: 103-104). **At a global level, carbon capture technologies thus appear necessary to meet climate objectives, but only in limited and targeted applications.**

The European Commission has included CCS/U technologies in their climate-neutral scenarios and recently reiterated that achieving 2040 emissions reduction targets "*will require deployment of carbon capture and storage technologies, as well as the use of captured carbon in industry*".[1] As such, a number of policies supporting CCS/U technologies have been implemented in the EU.

1.2 EU policy instruments supporting CCS/U technologies

The EU has been supporting the development and deployment of CCS/U technologies for many years with legislative and regulatory actions. Early policy initiatives include the 2009 Carbon Capture and Storage Directive (2009/31/EC) (the so-called "CCS Directive"), which established a legal framework for the *"environmentally safe geological storage of carbon dioxide"* – described as the *"permanent containment of CO_2 in such a way as to prevent and, where this is not possible, eliminate as far as possible negative effects and any risk to the environment and human health"*, with the primary objective of *"contributing to the fight against climate change"*. In the past couple of years, however, these efforts have been accelerated – with the European Commission initiating a number of new legislative proposals and adopting others that had been in the works for some time. This growing momentum is highlighted in the timeline below.

[1] European Commission (2024), Recommendation for 2040 emissions reduction target

July 2021	Publication of the Connecting Europe Facility (CEF) for Energy programme for 2021-2027. The new guidelines mentioned the fact the Commission would *"aim to increase the number of […] CO_2 transport projects to be supported under the CEF"*.
October 2021	Launch of the Carbon Capture, Utilisation and Storage Forum (CCUS Forum). Organised in thematic working groups, it brings together a wide range of stakeholders and aims to facilitate the deployment of CCS/U technologies.
December 2021	Communication on Sustainable Carbon Cycles, setting out an action plan on how to develop sustainable solutions to increase carbon dioxide removals (CDR) in the EU, including direct air carbon capture and storage (DACCS) and bio-energy carbon capture and storage (BECCS).
January 2022	The European Commission adopted new guidelines on state aid for climate, environmental protection and energy (CCEAG). They integrate the new objectives of the European Green Deal and soften the conditions under which EU Member States can support sectors that promote decarbonisation, including CCS/U projects.
May 2022	Adoption of the revised Trans-European Networks for Energy (TEN-E) Regulation. It identified the development of a cross-border carbon dioxide network as one of three priority thematic areas, and thus expanded the eligibility for projects of common and mutual interest (PCIs and PMIs) to CO_2 transport and storage infrastructure projects between EU Member States and neighbouring third countries.
July 2022	Formation of an Expert Group on Carbon Removals to assist the Commission in the preparation and implementation of policy initiatives related to carbon removals, including carbon farming and industrial carbon removal initiatives. The CREG first met in March 2023.
December 2022	The European Commission published a notice to provide guidance to EU Member States on the process and scope of the update of the 2021-2030 National Energy and Climate Plans (NECPs). The Commission encouraged Member States to include clear references to their plans that aim to enable CCS/U in hard-to-abate sectors and to integrate long-term CO_2 geological storage.
February 2023	Publication of two Delegated Acts outlining the rules for producing "renewable fuels of non-biological origin" (RFNBOs) – which count towards EU Member States' shares of renewable energy, as described in the revised Renewable Energy Directive (2018/2001/EC) (also known as "RED II"). RED II provided a regulatory framework for CCU technologies, since RFNBOs include synthetic fuels produced from captured CO_2. The Renewable Energy Directive was revised again in October 2023 (cf. "RED III"). It raised the EU's binding renewable energy target for 2030 to at least 42.5% (but aiming for 45%) and set higher quotas for RFNBOs.
March 2023	The Commission adopted a "Temporary Crisis and Transition Framework" (TCTF), replacing the "Temporary Crisis Framework" that was first adopted in 23 March 2022 to support the European economy following Russia's invasion of Ukraine. The TCTF aimed at boosting and retaining clean tech investments in Europe. It introduced provisions enabling Member States to

use the flexibility foreseen under EU state aid rules to support investments in strategic sectors for the green transition and to provide incentives for their fast deployment. This includes financial support for the production of CCS/U equipment as well as any key component used as direct input for the production of these technologies. These measures will remain in place until 31 December 2025.

April 2023 — The European Parliament adopted its own Resolution on Sustainable Carbon Cycles, asking that verified emissions and removal data from farms be collected from 2026, and insisting on risks linked to double counting and liability issues in case of carbon removals reversals.

May 2023 — Adoption of the revised EU Emissions Trading System (EU ETS) Directive. The ETS Directive provides a system that incentivises CCS, as it allows and accounts the subtracting of emissions that are captured safely and permanently stored. It also provides specific guidelines on the accounting of emissions during transportation between the capturing installation and the CO_2 transport network. The revised text extended the scope of covered activities to all means of CO_2 transport (instead of only CO_2 pipelines). It also mandated the Commission to submit a report to the Parliament and the Council by 31 July 2026 – "accompanied, where appropriate, by a legislative proposal and impact assessment" – on whether and how permanent carbon removals could be accounted for and integrated into the EU ETS.

May 2023 — Publication of EnTEC's study analysing different options for a regulatory framework to support the infrastructure for CO_2 transport and storage and business models in Europe. The study was commissioned by the European Commission together with another study that will seek to better understand where, when and how CO_2 transport networks will grow in Europe as well as to assess the investment requirements of such a trans-European CO_2 network. This second study is conducted by the Commission's Joint Research Centre (JRC), which presented their preliminary findings in November 2023 at the latest CCUS Forum in Aalborg, Denmark. The final text has not yet been published but will be an update of the original version (dated 2010).

February 2024 — On 20 February, the Council and European Parliament reached an agreement on the proposal for an EU certification framework for carbon removals (CRCF). The CRCF's focus is on CDR, however it also covers CCS/U technologies such as DACCS and BECCS.

February 2024 — Ongoing political trilogues on the proposal for a Net-Zero Industry Act (NZIA). Proposed by the Commission on 16 March 2023, as part of the EU Green Deal Industrial Plan. The Parliament and the Council adopted their negotiating mandates on 21 November and 7 December 2023, respectively. The NZIA should significantly accelerate the deployment of CO_2 capture and storage in Europe. It introduces an EU-level injection target of at least 50 million tonnes of CO_2 per year by 2030. It also lays down obligations for oil and gas producers in the EU to contribute to this goal by investing collectively in CO_2 storage capacities. To reach the new EU target for CO_2 injection capacity, the NZIA calls on Member States to make geological data on areas where CO_2 storage sites can be permitted

		on their territory publicly available and to report regularly on their progress in developing these sites. Finally, to "support the creation of a European Net-Zero CO_2 transport and storage value chain that industries can use to decarbonise their operations", the NZIA also introduces the concept of "Net-Zero Strategic Projects" for CO_2 storage and transport – which means these projects would be given "priority status" to ensure faster permitting processes and predictable timelines.
February 2024	○	The Commission published its Communication on an Industrial Carbon Management Strategy (ICMS). The ICMS sets out what role CCS/U technologies can play in decarbonising the EU economy by 2030, 2040, and 2050, respectively. It also considers different measures to optimise their potential, including in the deployment of EU-wide CO_2 transport and storage infrastructures. The ICMS draws on the work of the CCUS Forum working groups and the results of a public consultation concluded in August 2023. The Commission published a report providing an analysis of the response received to the public consultation in November 2023.
30 June 2024	○	EU Member States were due to submit their final updated National Energy and Climate Plan (NECPs), detailing how they intend to achieve their 2030 climate targets and taking account of the Commission's recommendations. Only four Member States met the deadline and as of 8 July 2024, 22 Member States still had to submit their final updated NECPs. Prior to that, all Member States had to submit a draft updated NECP by June 2023. In December 2023, the Commission published its assessment and insisted on the fact CCS would contribute to reach climate neutrality. Based on the draft NECPs, the Commission concluded that Member States planned to capture 34.1 $MtCO_2$ annually by 2030 – of which 5.1 $MtCO_2$ from biogenic sources – compared to an estimated overall injection capacity of 39.3 $MtCO_2$ per year in 2030.

The EU plans on further accelerating the deployment of CCS/U technologies and the development and deployment of transport and storage hubs. In the remainder of 2024, several other key EU initiatives are expected to bring about important changes for CCS and CCU technologies.

Q3 2024	○	The Commission has commissioned DNV to revise the four Guidance Documents (originally published in 2011) accompanying the CCS Directive – to reflect technological progress and remove ambiguities identified during the development of the first CCS projects in the European Economic Area. DNV published draft zero versions of the updated Guidance Documents that were discussed in a public stakeholder workshop in July 2023. They submitted the revised Guidance Documents to DG CLIMA in September 2023. Capacity-building workshops have been organised for competent authorities and potential storage site operators in Q2 2024. DNV are now set to provide a final report with recommendations for additional guidance in Q3 2024.
Q4 2024	○	A concept note for a new delegated act pursuant to Article 12(3b) of the ETS Directive was first shared with participants to the Climate Change Policy Expert Group on 24 November 2023. The delegated act determines the rules and criteria for the inclusion of "permanent CCU" in the ETS. The

European Commission published the draft legal act on 18 June 2024 and opened a public consultation until 16 July 2024. Unless the Parliament or the Council makes any objection, the delegated act should be adopted around October 2024.

1.3 Increasing EU funding for carbon capture and storage/utilisation

Growing support for CCS/U technologies in the EU is also visible in the amount of funding available to CCS/U developers. At national level, the revised state aid guidelines (cf. CCEAG in 2022 and TCTF in 2023) enabled EU Member States to channel more money towards CCS/U projects – with notable support in Denmark and the Netherlands (as well as in Norway and in the United Kingdom). At the EU level, important funding programmes such as the EU Innovation Fund, Connecting Europe Facility for Energy, and Horizon Europe showed growing support for CCS/U projects, as detailed below. As the price of EU emission allowances (EUAs) traded on the EU ETS reached new highs (cf. €100 per tonne of CO_2 in February 2023), this also contributed to improving the business case for CCS projects in some sectors.[2]

The most visible increase in EU funding for CCS/U technologies can be seen in the allocation of grants under the **EU Innovation Fund grants for large-scale projects** (cf. Figure 1):

- 1st call for large-scale projects (open in July 2020; results in November 2021): 5 out of the 7 selected projects featured CCS/U technology and received €884.9 million (out of €1.146 billion).
- 2nd call for large-scale projects (open in October 2021; results in July 2022): 9 out of the 17 selected projects featured CCS/U technology and received €1.177 billion (out of €1.906 billion).
- 3rd call for large-scale projects (open in November 2022; results in July 2023): 13 out of the 39 selected projects featured CCS/U technology and received €1.720 billion (out of €3.447 billion).

A handful of CCS/U projects also benefitted from the **EU Innovation Fund grants for small-scale projects** (cf. Figure 1):

- 1st call for small-scale projects (open in December 2020; results in July 2021): 3 out of the 30 selected projects featured CCS/U technology and received €11.53 million (out of €109.16 million)
- 2nd call for small-scale projects (open in March 2022; results in December 2022): 1 out of the 16 selected projects featured CCS/U technology and received €4.27 million (out of €59.38 million)
- 3rd call for small-scale projects (open in March 2023; results in December 2023): 1 out of the 17 selected projects featured CCS/U technology and is expected to receive €4.15 million (out of €55.13 million).

The EU Innovation Fund's fourth call for net-zero technologies was launched on 23 November 2023 and closed on 9 April 2024. The European Commission received a total of 337 applications, including

2 Global CCS Institute (2023), Global Status of CCS Report 2023

204 from energy-intensive industries (of which some applied to finance CCS/U-related projects). The call results will be published in Q4 2024, and the grants awarded in Q1 2025.

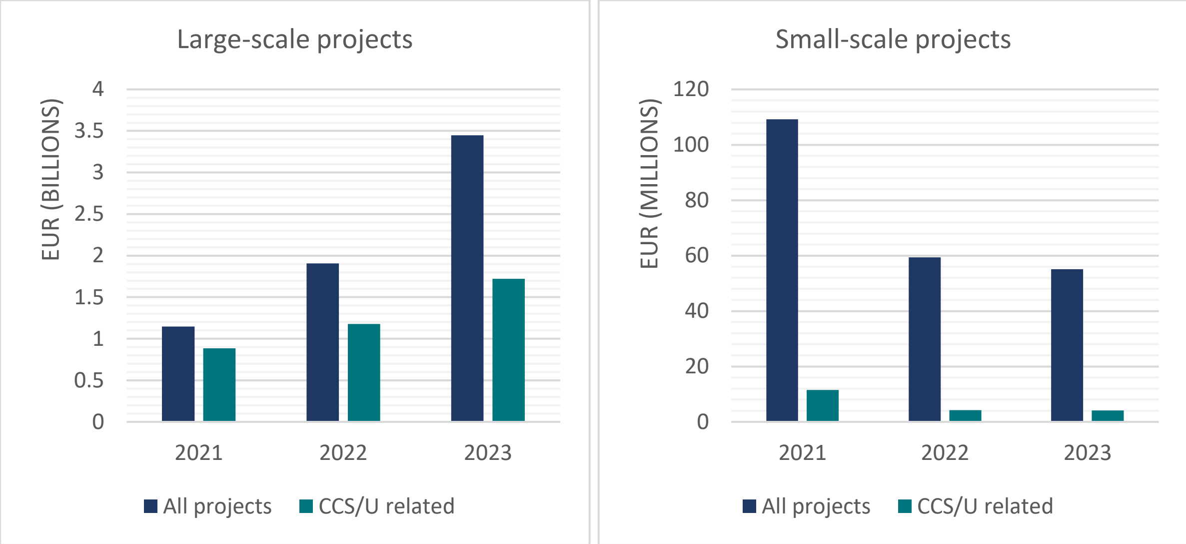

Figure 1. *Funding allocated to CCS/U projects under the EU Innovation Fund since 2021. Source: Sandbag calculations (2024), based on data provided by the European Agency for European Climate, Infrastructure and Environment Executive Agency (CINEA).*[3]

In addition to the EU Innovation Fund, **several CCS/U projects have also been funded under the Connecting Europe Facility (CEF) for Energy programme**. More specifically, CO_2 infrastructure projects that have a "significant impact" on at least one EU Member State and another neighbouring country fall under the scope of the Trans-European Networks for Energy (TEN-E) and can thus apply to become projects of common or mutual interest (PCIs and PMIs). The list of PCIs and PMIs is adopted every two years. CO_2 infrastructure projects that obtain the PCI or PMI status are then eligible to apply for a CEF Energy grant for studies or for works.

Over the period 2014-2020, the CEF Energy programme had a total budget of €4.7 billion, from which €143.9 million were allocated to CO_2 network projects. For the 2021-2027 period, the CEF Energy budget has been increased to €5.84 billion. Grants worth a total of €1.66 billion have already been awarded, including €638.9 million to CO_2 network projects – i.e. already more than 4 times than the total budget for CO_2 projects under the previous CEF Energy programme (cf. Figure 2). The 5th list of selected PCIs (published in November 2021) included 6 CO_2 infrastructure projects. In November 2023, the 6th list of selected PCIs (and first list of PCIs and PMIs established under the revised TEN-E Regulation) included 14 CO_2 infrastructure projects.

[3] CINEA (2024). Innovation Fund Project Portfolio dashboard.

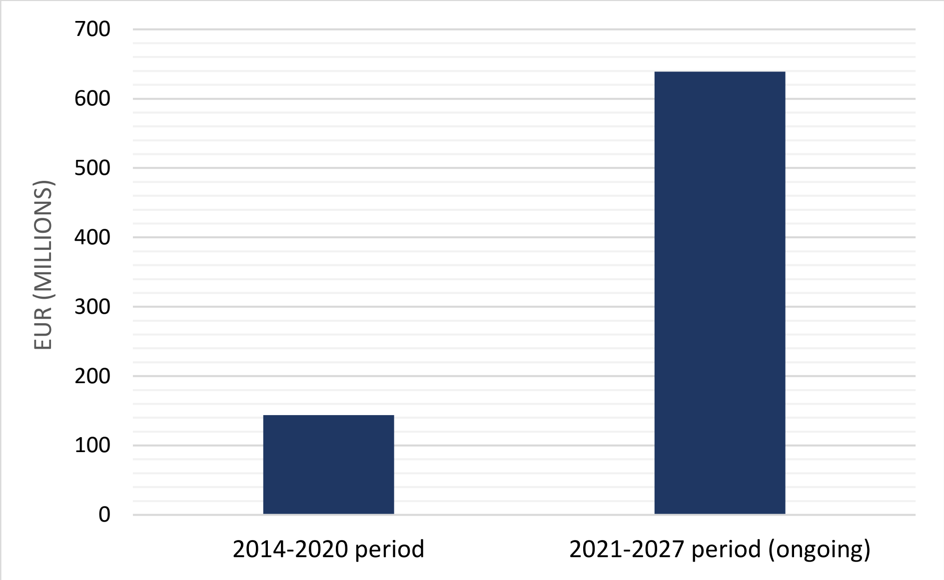

Figure 2. *Funding allocated to CCS/U projects under Connecting Europe Facility (CEF) for Energy – as of December 2023. Source: Sandbag calculations (2024), based on data provided by the European Commission.*

The European Commission has also been actively supporting research, development and innovation for CCS/U technologies through stakeholder engagement (see for instance the Zero Emissions Platform and the Working Group on CCUS established under the Strategic Energy Technology Plan) and EU funding under the Horizon Europe programme. More than €13 billion have been allocated to CCS and CCU projects since 2014, including nearly €7 billion between 2020 and 2023 (cf. Figure 3). The Commission has earmarked a budget of €95.5 billion for Horizon Europe for the 2021-2027 period and it is likely that more CCS/U projects will receive support from the funding programme in the years to come.

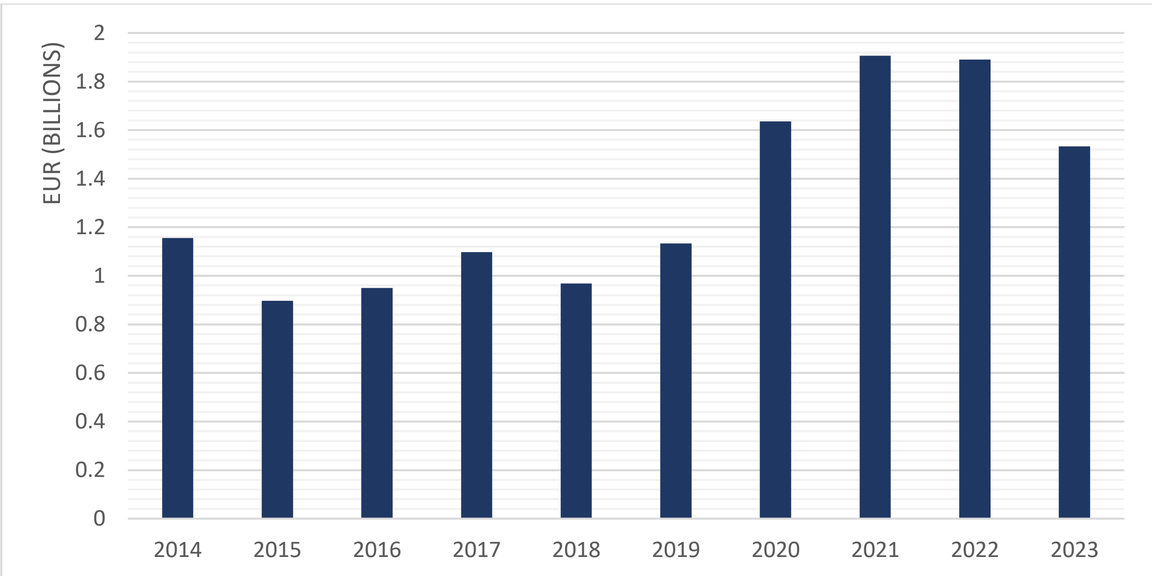

Figure 3. *Funding allocated to CCS/U projects under Horizon Europe (per call year) between 2014 and 2023. Source: Sandbag calculations (2024), based on data provided by CINEA.*

Thanks to increasing legislative and financial support, the number of CCS projects in the EU has thus rapidly increased. The Global CCS Institute, for instance, observed a 61% increase between September 2022 and October 2023 in the number of CCS projects across Europe (from 73 projects to 119 projects) – although at various stages of development, construction or operation.[4]

1.4 Investing in CCS/U: a costly distraction for the steel sector?

All of the European Union's efforts mentioned above support the idea that CCS/U technologies will be taking a central role during the next phase of the European Green Deal's implementation. Yet carbon capture technologies still come with a certain degree of risk. While the European Commission foresees a significant role for CCS/U technologies and CO_2 storage to decarbonise European industrial sectors and achieve substantial emission reductions between 2030 and 2050, it also acknowledges that "*despite the policies supporting industrial carbon management and the projects planned, operational large-scale projects are limited in Europe*".[5] Important investment decisions have been announced in Europe in the last few years, but **many capture and utilisation technologies remain non-operational to this day and are still in development or at a pilot phase**.

Some analysts point out that the decarbonisation potential of CCS/U technologies varies significantly across industrial sectors (see, for instance, E3G and Bellona's "CCS ladder"[6]). In the impact assessment (Part II, p. 78) preceding the publication of the "Fit for 55" package,[7] the European Commission stated that: *"The industrial sector is composed by many diverse subsectors with different energy and material needs resulting in different types, mixture, volumes and concentration of industrial effluents containing greenhouse gases"*. **CCS/U technologies are thus unlikely to act as a silver bullet and are not necessarily relevant as a policy option to decarbonise all hard-to-abate industrial processes**. This is also why, in cases where existing and more sustainable alternatives exist, CCS/U has sometimes been portrayed as a "costly distraction".[8]

The IPCC (2023: 104) too noted that there were "*several options to reduce industrial emissions that differ by type of industry".* For instance, while it acknowledges the role CCS/U technologies can play to reduce carbon emissions from the production of cement and, to some extent, chemicals, the IPCC specifies (with high confidence) that "*light industry and manufacturing can be largely decarbonised through available abatement technologies (e.g., material efficiency, circularity), electrification (e.g., electrothermal heating, heat pumps), and switching to low- and zero-GHG emitting fuels (e.g., hydrogen, ammonia, and bio-based and other synthetic fuels)".* In a European context, the European Scientific Advisory Board on Climate Change (ESABCC) recently also asserted that ***"EU policies support CCU/CCS, including CO2 infrastructure, but do not currently target their deployment to applications with no, or limited, other mitigation options"***.[9]

In a previous report we explored economic barriers related to the decarbonisation of steel production in the EU.[10] **This report will specifically seek to assess the potential and cost of carbon capture**

[4] Global CCS Institute (2023), Global Status of CCS Report 2023
[5] European Commission (2024), Towards an ambitious Industrial Carbon Management for the EU
[6] E3G, Bellona (2023). Carbon capture and storage ladder
[7] European Commission (2020). Impact Assessment accompanying the document Stepping up Europe's 2030 climate ambition: Investing in a climate-neutral future for the benefit of our people
[8] Zero Waste Europe (2021), CCS for incinerators? An expensive distraction to a circular economy
[9] European Scientific Advisory Board on Climate Change (2024), Towards EU climate neutrality Progress, policy gaps and opportunities
[10] Sandbag (2024), From Niche to Mainstream: Shaping Demand for Green Steel

technologies to decarbonise the iron and steel industry, with a particular focus on European steel plants. While CCS/U technologies are not expected to bring about most of the emission reductions needed in this sector (compared to switching from the use of "hot metal" to ferrous scrap or green hydrogen-based direct-reduced iron, for instance), carbon capture continues to be considered as an option by major steel companies around the world, including in the EU.

While the aim of this report is not to contest the role CCS/U can play in contributing to achieving EU climate objectives, it will endeavour to assess its relevance for the iron and steel value chain. Given that the use and effectiveness of carbon capture technologies varies not only across industrial sectors, but also from one application to another within the same sector, **this report will look into the potential of carbon capture technologies for each manufacturing process involved in steelmaking and will strive to show the costs involved**. Of course, the economic motivation for capturing CO_2 also depends on the possibility to utilise the CO_2 by repurposing into valuable products (CCU) or the feasibility of transporting and storing the captured CO_2 (CCS). The report therefore also includes sections exploring these elements in the context of the European steel industry before we summarise the extent to which we believe CCS/U should play a role in decarbonising European steel production.

2. Evaluating the potential of carbon capture for iron and steel manufacturing

2.1 Iron and steel industry's growing interest for carbon capture technologies

Carbon capture technologies seem to have gained traction as a potential solution to mitigate carbon emissions in the iron and steel manufacturing industry in recent years. Steel giants such as ArcelorMittal, ThyssenKrupp and Tata Steel all have both ongoing and planned carbon capture and storage/use (CCS/U) projects. However, their **projects differ according to the specificities of each steel plant, the type of CCS/U technology used, and the various point sources of the manufacturing process that they target** – each with varying costs, energy requirements, and effectiveness. Some steel manufacturers are fully investing in CCS/U technologies while others plan on using them in combination with other decarbonisation technologies. Part of the reason for this growing interest lies in the possibilities that CCS/U technologies offer in helping to achieve emission reductions without having to significantly alter the existing infrastructure and business model of a steel plant.

However, while interest for carbon capture is growing, the uptake remains slow and **most CCS/U projects in the iron and steel sector are still in their early stages, with only a few pilot or demonstration projects in operation**.[11] Despite the many funding opportunities, the costs of these projects still constitute an obstacle. In addition, while retrofitting existing assets is seen as desirable as it would require only small modifications to the existing processes, CCS/U technologies have not yet been tested on the scale of a large steel plant and therefore their cost effectiveness remains somewhat unproven, which poses a number of risks for project developers. Furthermore, retrofitting existing assets to preserve the traditional (and heavily polluting) blast-furnace – basic oxygen furnace (BF-BOF) steelmaking route would prolong the use of fossil fuels in the steel industry, which may attract backlash.[12]

While the International Energy Agency (IEA, 2020) does foresee an increase in the overall share of CO_2 emissions captured from industrial processes as part of its IEA Sustainable Development Scenario, only a small portion is attributed to the iron and steel sector, with most of the captured emissions expected to take place only after 2050 (left panel of Figure 4). **Estimates for future CCS/U applications in iron and steelmaking from the IEA show that these applications are not expected to contribute to any significant emission reductions before at least 2040** (right panel of Figure 4). In addition, the IEA (2020) argues that capturing 75% of total emissions from the iron and steel sector by 2070 would require building around 10 CCS-equipped steel plants every year until 2070, which contrasts sharply with current market developments and raises questions in terms of the costs and electricity needs involved to achieve such a scenario.

[11] IEA (2023), CCUS Projects Explorer, IEA, Paris

[12] Agora Industry and Wuppertal Institute (2023), 15 insights on the global steel transformation.

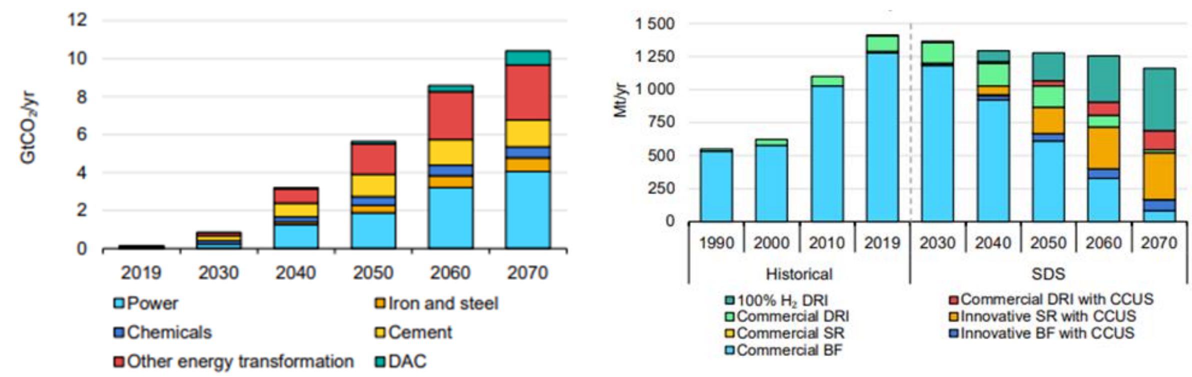

Figure 4. *Projections for global CO_2 capture by sector (left) & iron production by technology (right). Source: International Energy Agency (IEA), 2020.*

At first sight, therefore, it seems like the iron and steel industry's ambition to deploy and incorporate CCS/U technologies in their value chain does not satisfy the need to achieve deep emission reductions in the sector to meet EU and global climate targets. **This chapter will examine this question in further detail and review the cost-effectiveness of specific carbon capture methods applied to integrated steel mills**.

2.2 Capturing CO_2 emitted during the manufacturing processes of iron and steel

Carbon capture methods typically fall into the following categories: chemical absorption (utilizing a solvent to absorb CO_2 from exhaust gases), adsorption (employing porous materials to trap CO_2), membranes (using thin layers to selectively remove carbon), and SEWGS (Sorption Enhanced Water Gas Shift – a combination of chemical absorption and adsorption). These methods are applied at various stages of industrial processes, which can be divided between:

(i) **pre-combustion** stage (where carbon is captured before the fuel is burned, typically by chemical reaction of the fuel with water or oxygen to produce hydrogen and carbon dioxide);

(ii) **post-combustion** stage (where carbon is captured after the fuel is burned using solvents or adsorbents to remove the CO_2 from exhaust gases);

(iii) and **oxy-combustion** stage (where oxygen is used instead of air to burn the fuel that allows for more efficient carbon capture).

In the iron and steel industry, however, most carbon capture projects tend to focus primarily on the post-combustion stage. This is because the largest share of carbon emissions generated in the manufacturing of iron and steel products takes place in blast furnaces. Blast furnaces are extensively utilised in the "conventional" steelmaking route in the EU, particularly for the production of nearly all flat steel products (Global CCS Institute, 2010).

In this section, we explore carbon capture options for the BF-BOF, TGR-OBF, smelting reduction, and NG-DRI-EAF routes. Table 1 provides a list of carbon capture technologies that we analyse in the following sub-sections.

Production route	Description
BF-BOF (section 2.2.1)	Chemical absorption is well-suited for handling CO_2 streams with low concentrations and considered most suitable for capturing CO_2 from blast furnace gas in the conventional iron and steelmaking route (Keys et al. 2019).
	Amine-based solvents, like mono-ethanolamine (MEA), are commonly employed for CO_2 removal due to their good capture rates.
	The STEPWISE project investigated the use of SEWGS technology (Sorption Enhanced Water Gas Shift) for carbon capture from the BF-BOF route.
TGR-OBF (section 2.2.2)	For gas streams with higher CO_2 concentrations, commercially available adsorption methods in the steel industry, such as pressure swing adsorption (PSA) or vacuum pressure swing adsorption (VPSA), are more suitable.
	The Ultra-Low CO_2 steelmaking (ULCOS) program has explored the application of various CCS technologies in iron and steelmaking, with the main ones being PSA, VPSA, and cryogenics.
	For alternative ironmaking options such as TGR-OBF, the ULCOS programme explored the use of adsorption technologies as the most effective in capturing carbon; therefore, we consider VPSA carbon capture for TGR-OBF route.
Smelting reduction (HIsarna) (section 2.2.2)	Smelting reduction produces a gas stream with high CO_2 concentrations, and cryogenics is considered the most effective method for carbon capture, given its suitability is limited to gas streams with CO_2 concentrations above 90% vol (Leung, Caramanna, & Maroto-Valer Mercedes, 2014).
NG-DRI-EAF (section 2.2.2)	In the case of the NG-DRI-EAF route, we examine the technical parameters of ENERGIRON ZR, a process developed by Tenova and Danieli. The Energiron ZR technology incorporates an in-built selective carbon removal system. [13]

Table 1. *List of carbon capture technologies used in the iron and steel industry that are analysed in this report.*

2.2.1 Retrofitting to BF-BOF Route

Carbon Capture from BF-BOF route using chemical absorption

In the conventional BF-BOF route, blast furnace gas is the largest source of CO_2. The majority of studies evaluating carbon capture applications for integrated steelworks primarily concentrate on removing CO_2 from blast furnace gas. As a result, **our focus is on retrofitting a conventional integrated steel mill with post-combustion capture from blast furnace gas**, employing chemical absorption with monoethanolamine (MEA) solvent. Chemical absorption, particularly using MEA, stands out as the most mature capture technology in terms of capture performance.[14] In our analysis, we assume a 90% capture rate based on M.T. Ho et al. (2013).[15] Depending on the specific designs of the process, there

[13] Energiron (2012). Energy Saving and CO_2 Reduction in Energiron DRI Production. 6th International Congress on the Science and Technology of Ironmaking – ICST.
[14] Wang, N., Wang, D., Krook-Riekkola, A., & Ji, X. (2023). MEA-based CO2 capture: A study focuses on MEA concentrations and process parameters. doi.org/10.3389/fenrg.2023.1230743.
[15] Ho, M. T., Bustamante A., and Wiley, D.E. (2013) Comparison of CO2 capture economics for iron and steel mills, International Journal of Greenhouse Gas Control 19: 145-159.

may also be a loss of revenue from power generation, as the process gas is used for the capture process and solvent regeneration rather than electricity production.

Carbon Capture from BF-BOF route using SEWGS (Sorption Enhanced Water Gas Shift)

An alternative method for carbon capture involves utilising SEWGS (Sorption Enhanced Water Gas Shift) to capture carbon from the blast furnace flue gas. The SEWGS process combines the high-temperature water gas shift reaction with the adsorption of CO_2, a process where CO_2 is captured by certain materials (solid sorbents). The sorbent material is integrated into the gasification process, where carbon monoxide (CO) is produced from carbon-containing feedstocks. This CO is then converted into CO_2 and H_2. During the water gas shift reaction, the sorbent selectively captures CO_2. The SEWGS method is claimed to achieve a 90% carbon capture rate, but it comes with a high energy requirement for the capture and compression process, reported at 2.24 GJ/tCO_2 (Gazzani, 2015), which is 0.22 MWh/t steel higher than the MEA method. The potential of the SEWGS process was demonstrated under the STEPWISE initiative at a pilot plant, capturing 14 tCO_2 per day.

	Emission intensity	Electricity use (MWh/t CS)	CO_2 avoided (%)	Cost of carbon capture (€/tCO_2)
BF-BOF	1.71	0.28	-	-
BF-BOF + MEA	0.51	0.81	70 %	71.0
BF-BOF + SEWGS	0.51	1.03	70 %	81.3

Table 2. *Retrofitting BF-BOF route with carbon capture. Sources: Keys et. al. (2019), IEAGHG (2013), H2FUTURE (2021). Sandbag's own calculations.*

2.2.2 Alternative production technologies equipped with carbon capture

The steel industry has been actively investing in exploring innovative alternatives to replace the conventional BF-BOF route with low emission intensity technologies, especially those that allow for the integration of carbon capture units. We will focus on three such alternatives: the NG-DRI-EAF route, the Top Gas Recycling Oxygen Blast Furnace (TGR-OBF) developed by the ULCOS programme, and the HIsarna smelting reduction technology. These alternatives are of particular interest due to their ability to incorporate carbon capture technologies with high capture rates.

Carbon Capture from Top Gas Recycling Oxygen Blast Furnace (TGR-OBF) using VPSA

The top gas recycling oxygen blast furnace (TGR-OBF) was developed by the ULCOS programme. **In the TGR-OBF configuration, the blast furnace is modified to enable the combustion of coal with the injection of pure oxygen**. This process results in increased CO_2 and reduced nitrogen content in the top gas. The CO_2 is subsequently removed from the top gas for storage or utilisation. The remaining gas which is rich in CO and H_2 is injected back into the process. Some advantages of the TGR-OBF includes recycling the top gas back into the furnace to reduce coke consumption and lower the energy requirement for the capture process, because of the high CO_2 content in the flue gas. Within the ULCOS program, pilot studies for the TGR-OBF were conducted with a 40 tCO_2/day capacity in Luleå, Sweden. A VPSA carbon separation plant was constructed near the OBF, leading to 76% CO_2 emission reductions and 88% CO_2 recovery (Air Liquide, 2010). We assume a 94% capture rate for the VPSA capture method (Birat, JP., 2010). According to literature, electricity required for VPSA carbon capture and compression ranges between 0.38 – 0.94 GJ/tCO_2. In our calculations, we consider an electricity consumption of 0.73 GJ/tCO_2 (approximately 0.3 MWh/tCO_2).[16]

Carbon Capture from Smelting reduction (HIsarna) using Cryogenics

The HIsarna process is a smelting reduction technology where iron ore is fed at the top of the smelter where it reacts with coal and oxygen to produce hot metal. The process generates a gas stream with highly concentrated CO_2, which is suitable for further processing. Cryogenic separation is typically considered appropriate for gas streams with CO_2 concentrations above 90%, as seen in the HIsarna smelting reduction process (IEACCC, 2012). One advantage of cryogenic separation is its ability to produce liquid CO_2 suitable for storage. The HIsarna process without carbon capture produces around 1.26 tCO_2/t steel. According to our calculations, incorporating a cryogenic CCS component with a 100% capture rate (Leung et. al. 2014) could potentially reduce total process carbon emissions to 0.15 tCO_2/t steel (refer to Figure 7).

Carbon capture from NG-DRI-EAF route using PSA

For the natural gas-direct reduced iron (NG-DRI)-electric arc furnace (EAF) route, we consider the Energiron ZR technology, a **commercially available DRI plant developed by Tenova and Danieli, as it offers a simple integration of a carbon removal system into the process scheme**. As in our previous report[17], we chose this process over other DRI alternatives due to its lower GHG emissions and its adoption in new plants across Europe, including the HYBRIT and SALCOS projects. It incorporates a selective CO_2 removal system that, according to the manufacturer, can reduce carbon emissions down to 0.16 tCO_2 per tonne of DRI – a figure slightly lower than our new calculation of 0.22 tCO_2 per tonne of steel (refer to Figure 7). Our estimation suggests that the cost of PSA-based carbon capture on an NG-DRI-EAF route would be around 90 €/tCO_2.

2.3 Comparing the performance of different CCS options for iron and steelmaking (costs, effectiveness, electricity consumption)

Figure 5 below highlights the cost of carbon capture for each production route in terms of EUR per tonne of carbon captured. **The highest emissions reduction is achieved in the smelting reduction (HIsarna) + CCS route**, where the technology is designed to operate with carbon capture to increase its emissions reduction potential. Nevertheless, the development of the technology is unclear since the cancellation of the demonstration project, and its readiness for commercial scale remains uncertain. We find that it costs less to capture carbon from the BF-BOF route, but the application has not been proven at a commercial scale, it poses the risk of perpetuating the use of fossil fuels, and it

[16] Birat, J. P. (2010). Global Technology Roadmap for CCS in Industry. Steel Sectoral Report.
[17] Sandbag (2022). Starting from scrap. The key role of circular steel in meeting climate goal.

does not address emissions from coking and sintering. While above 90% CO_2 capture rates have been shown theoretically to be economically feasible for concentrated gas streams, in practice the average capture efficiencies over the long term are likely to be lower.[18] As we also argued in our previous report,[19] **the most viable option for carbon capture in the steel industry is the NG-DRI-CCS route**. The relatively low capture rate can be attributed to its focus on emissions from the reduction system rather than the flue gases produced during the preheating process.[20] In addition, the NG-DRI-EAF process emits less carbon (0.56 tCO_2 /t steel) which translates into a lower percentage of CO_2 avoided compared to other production routes considered.

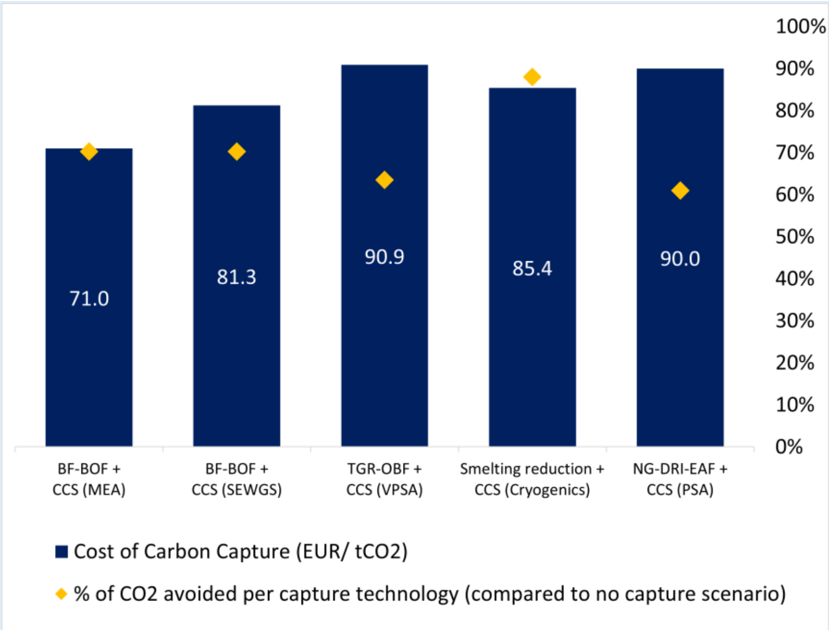

Figure 5. *Cost of Carbon Capture (€/tCO_2) and % of CO_2 avoided per production route. Sources: Keys et. al. (2019), IEAGHG (2013), Tata Steel, Energiron (2019), Eclareon (2021), H2FUTURE (2021). Sandbag's own calculations for the entire production route. Cost of transport and storage not included.*

Simply comparing carbon capture costs is insufficient, as the steelmaking technologies to which they are applied also have varying costs. Figure 6 illustrates the total production cost of each production route both with and without carbon capture. Depending on the production route, **capturing the CO_2 emissions increases the total production costs by approximately 30 to 97 € per tonne of steel, excluding the costs of transport and storage**. Capital expenditures for BF-BOF and TGR-OBF routes are specified for retrofitting and only include the cost of relining. In contrast, smelting reduction (HIsarna) and NG-DRI-EAF routes involve the greenfield construction of plants, resulting in a higher initial capital expenditure. Operational costs include both fixed and variable costs, including process inputs. Cost estimates for the CCS-equipped routes focus only on the costs related to capture and compression, excluding the expenses associated with transport and storage.

[18] Brandl, P., Bui, M., Hallett, J. P., & Mac Dowell, N. (2021). Beyond 90% capture: Possible, but at what cost? International Journal of Greenhouse Gas Control, 105, 103239. https://doi.org/10.1016/j.ijggc.2020.103239.
[19] Sandbag (2022), Starting from scrap: The key role of circular steel in meeting climate goals.
[20] Duarte, P. E., Tavano, A., & Zendejas, E. (2010). Achieving carbon-free emissions via the ENERGIRON DR process. In AISTech 2010 Conference Proceedings. Pittsburgh: American Iron and Steel Society (p. 165e73).

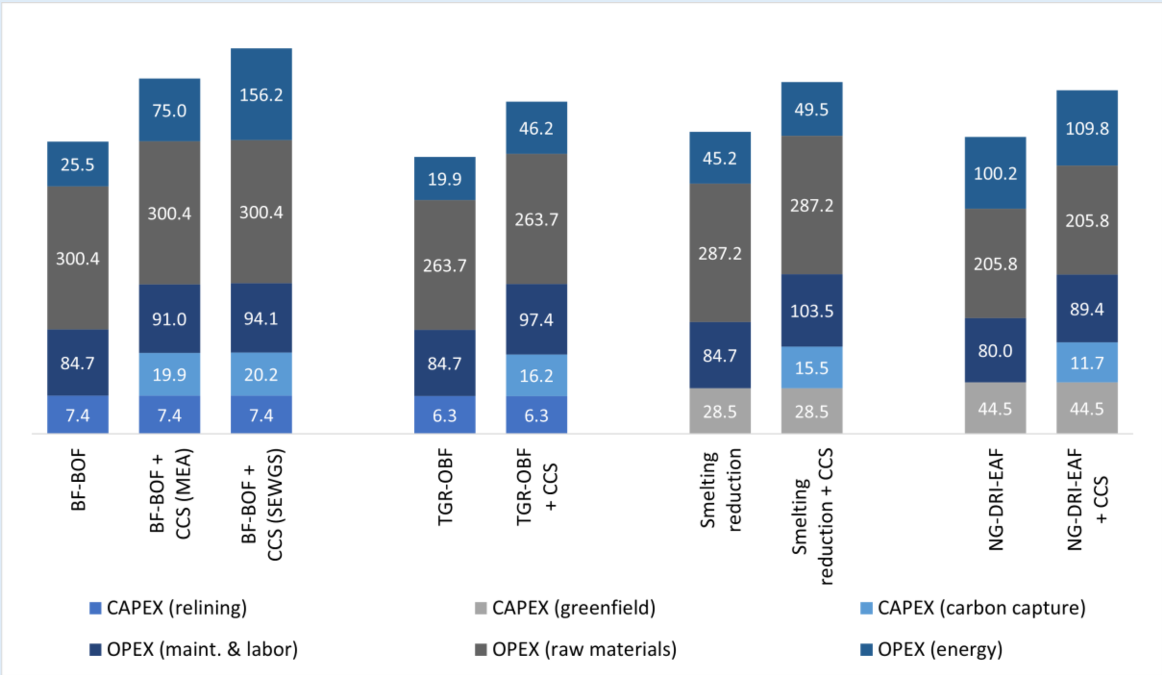

Figure 6. *Total production cost by production route (€/per t steel). Sources: Keys et. al. (2019), IEAGHG (2013), Energiron (2019), Eclareon (2021), H2FUTURE (2021). Sandbag's own calculations. 20 years plant lifetime and 6% discount rate assumed. Techno-economic assumptions used in the cost estimations can be found in the Appendix. Cost of transport and storage not included.*

Quantity of material required per tonne of crude steel	BF-BOF	TGR-OBF	Smelting reduction (Hisarna)	NG-DRI-EAF
Iron ore (t)	1.51	1.31	1.42	1.40
Coal (t)	0.43	0.16	0.45	0.0
Natural Gas (MWh)	0.0	0.0	0.0	2.37
Electricity (MWh)	0.11	0.10	0.11	0.24

Table 3. *Key resource use assumptions for steel production technologies*

Figure 7.1 below illustrates the greenhouse gas (GHG) emissions for each relevant process, both with and without carbon capture. Our analysis indicates that **BF-BOF + CCS is not highly effective in mitigating carbon emissions in the manufacturing of iron and steel**. The total emissions from the BF-BOF route include emissions from coking and sintering (0.38 tCO_2/t steel), which are not addressed by carbon capture. Moreover, the uncaptured CO_2 from carbon capture processes will lead to residual emissions, in addition to the upstream emissions mentioned. The NG-DRI-EAF route appears to be the most effective, with an emission intensity of 0.56 tCO_2/t steel, and this can be further reduced to 0.22 tCO_2/t steel when carbon capture is employed.

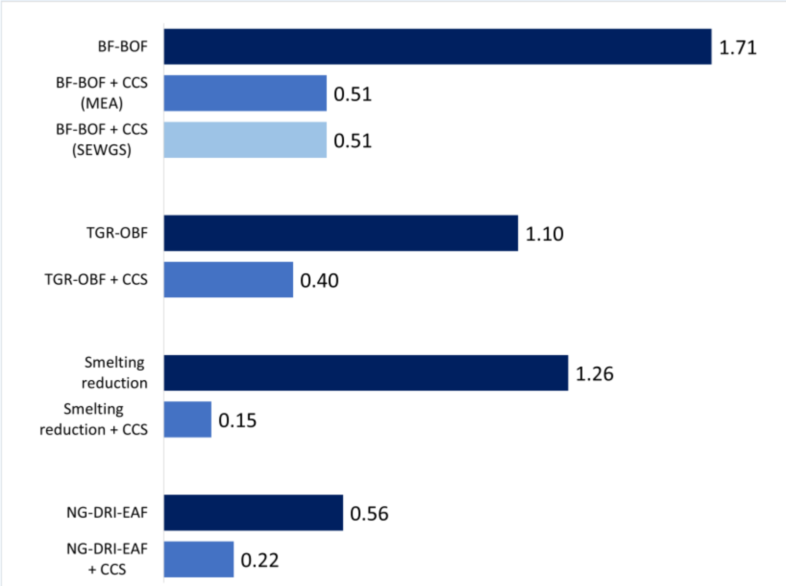

Figure 7.1 *Total process GHG emissions (tCO_2/t steel). Source: Sandbag's own calculations.*

Furthermore, Figure 7.2 displays the electricity consumption (MWh/t steel) of each production route without carbon capture and the additional electricity that would be needed for the addition of carbon capture. Among the production routes, NG-DRI-EAF + CCS exhibits the lowest electricity consumption, standing at 0.45 MWh/t steel. This occurs because electricity consumption rises proportionally with the capture of larger amounts of CO_2. Therefore, **the lower initial emissions intensity of the NG-DRI-EAF route results in a correspondingly lower amount of electricity required for carbon capture**. The highest additional electricity would be needed in BF-BOF and smelting reduction routes since higher initial emission intensity translates into larger need for energy use for capture process. It should be noted that only CCS production routes are being compared and the emission intensity of production involving use of scrap for example is not considered.

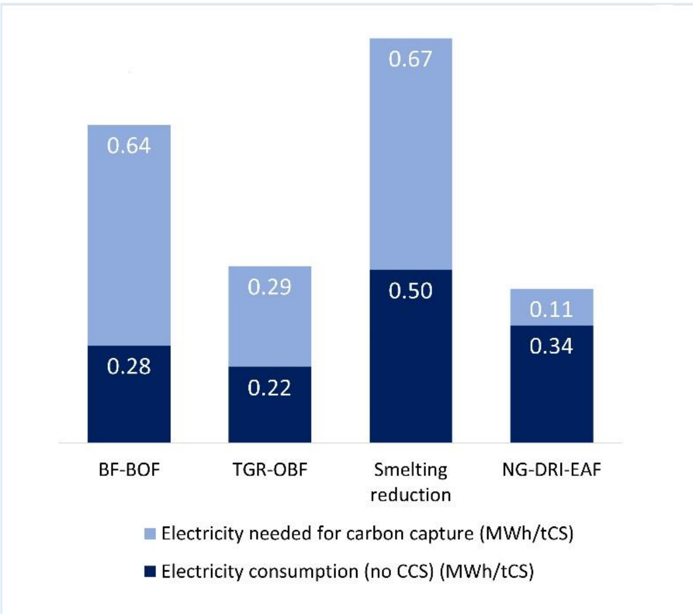

Figure 7.2 *Electricity consumption of each production route (MWh/t steel). Source: Sandbag's own calculations*

Figure 8 below clearly illustrates the disparity between the project developments in the steel industry for DRI and blast furnace-basic oxygen furnace (BF-BOF)-CCS routes in Europe. By 2030, the DRI route is expected to have 71.8 Mt capacity, while the BF-BOF-CCS route is expected to have a capacity of just 1 Mt. This clearly highlights the lack of appetite for investment in the BF-BOF-CCS technology. Additionally, according to the Global Carbon Capture and Storage Institute (GCCSI) report,[21] **there are only four commercial-scale CCS projects in the steel industry, and three of these are based on DRI production routes which supports our argument that the most viable carbon capture option in the steel industry is the NG-DRI-EAF route**. Currently, the only fully commercialised CCS project in the steel industry is the Al Reyadah CCS Project in Abu Dhabi where CO_2 is captured from a DRI plant. The project has been in operation since 2016 and it captures 0.8 $MtCO_2$/year.

There are other projects focusing on the development of novel carbon capture methods from conventional steelmaking routes, such as the 3D Project (DMX™ Demonstration in Dunkirk), supported by Horizon 2020. The project aims to develop and demonstrate the DMX™ capture method (a chemical solvent) at ArcelorMittal's steel facility in Dunkirk, France. The DMX™ process demonstration pilot, with a nominal capacity of 0.5 tCO_2 per hour, has been in operation since April 2023.[22] The first industrial unit is slated to begin operation in 2025, capturing more than 1 $MtCO_2$ per year. However, thiswould only account for around 8% of estimated total emissions of Dunkirk site (12 $MtCO_2$ in 2019).

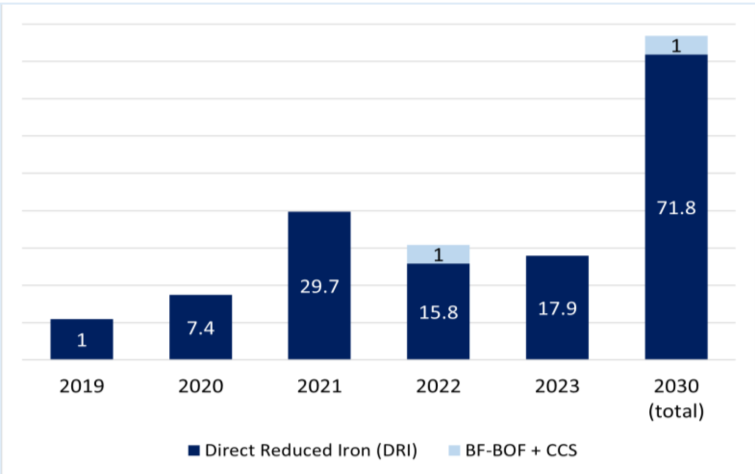

Figure 8. *2030 low-carbon steel capacity announcements in Europe (Mtpa). Author's own interpretation based on data from Agora Industry (2023) Global Steel Transformation Tracker.*

Retrofitting existing BF-BOF plants with carbon capture may not be competitive in the long term, especially in locations where hydrogen can be produced at a competitive cost which would make H2-DRI-EAF based steelmaking favourable with an emission intensity of 0.01 tCO_2/t steel (Table 4). It falls short in addressing upstream emissions from coal mine methane leakages associated with the BF-BOF route, which is around 12% - 14% of end use emissions CCS aims to capture (Agora Industry, 2023). Furthermore, the low carbon dioxide concentrations in iron and steelmaking gas streams make carbon capture less cost-effective and efficient.

[21] Global Carbon Capture and Storage Institute (2023). Global Status of CCS Report 2023
[22] Axens (2023), Successful demonstration in Dunkirk of the CO_2 capture DMX™ process

Technology	Emission intensity (tCO_2 / t steel)	Emissions reduction potential	TRL	Expected market entry date
BF-BOF + CCS	0.4 - 0.6	60-70%	4	2030
Smelting reduction + CCS	0.1 - 0.2	Up to 88%	5-6	Unknown
TGR-OBF + CCS	0.40	63%	3-4	Unknown
NG-DRI-EAF + CCS (10% scrap)	0.22	61%	9	Ready
100% scrap-EAF	0.05	Up to 100%	9	Ready
Green H2-DRI-EAF (50% scrap)	0.05	Up to 100%	8-9	2030
Blue H2-DRI-EAF (50% scrap)	0.08	Up to 100%	8-9	2030
Electrowinning-EAF (100% scrap)	0.01 – 0.06	Up to 100%	4-5	2040
Green H2-DRI-Smelter-BOF	0.02	Up to 100%	7-8	2030
Molten Oxide Electrolysis	0	Up to 100%	5	2040

Table 4. *Comparison of various steel production routes. Sources: Sandbag (2022), Sandbag (2024), JMK Research (2023), Green Steel for Europe (2021).*

In the short term, the most favourable option for carbon capture application would be the NG-DRI-EAF route considering its commercial availability. Yet, given the slow pace of technological and market development we anticipate that carbon capture will play a limited role in the steel industry, with its applications primarily confined to standalone cases. Consequently, **we advocate for a shift in focus within the steel industry towards investing in alternative production technologies with lower carbon intensities and greater emission reduction potential** (Table 4). Carbon capture should not divert investment away from these alternative production technologies.

3. Carbon Capture and Utilisation (CCU) applications in the iron and steel industry

Carbon Capture and Utilisation (CCU) involves repurposing captured CO_2 from industrial processes into valuable products such as chemicals or fuels. In contrast to carbon capture and storage (CCS), which focuses on the permanent storage of CO_2, CCU seeks to harness the potential of captured carbon for productive purposes.

In the steel industry, **CCU is being explored through pilot projects that aim to repurpose captured CO_2 from steel manufacturing facilities for the production of chemicals, fuels, or other materials**. ThyssenKrupp is investigating the production of fuels and chemicals, including ammonia, methanol, fertilisers, and plastics, by converting steel mill gases. ArcelorMittal also explored the production of chemicals by utilizing steel mill gases under the Carbon4PUR project, which was completed in 2021 at the pilot stage. The company is also involved in other ongoing CCU projects, namely Steelanol and INITIATE. The Steelanol project, funded by Horizon 2020, is a demonstration plant that converts blast furnace process gases from ArcelorMittal's Ghent plant into bioethanol. In May 2023, the initial ethanol samples were produced after introducing the first blast furnace gases from the Ghent site to LanzaTech's biocatalyst. Meanwhile the Ghent plant is also hosting the first industrial trial of a technology, developed by climate tech company D-CRBN, that uses plasma to convert captured CO_2 into carbon monoxide (CO). The CO can be used as a reductant in the steelmaking process – replacing part of the coke or metallurgical coal used in the blast furnace – or as a basic ingredient in the Steelanol plant.

The EU-funded C2FUEL project focused on developing **CO_2 conversion technologies for the production of energy carriers**. The demonstrations took place at Dunkirk in DK6 (natural gas-fired combined cycle power plant) and ArcelorMittal's steel factory. Certain steel manufacturers, like Tata Steel, are also exploring partnerships with the chemical industry. Tata Steel has partnered with Dow Benelux to build a pilot plant in Ghent that would utilise CO from blast furnace waste gases to produce syngas, which would be further used to produce naphtha. This approach would reduce emissions from the steel mill, as the waste gases would not be used for in-site electricity generation and would instead be transferred to the production of naphtha.[23] The table below provides further details on major CCU projects in the steel industry.

[23] De Ingenieur (2018). Tata Steel and Dow to Invest in Green Chemicals.

Steelanol	
Location	Ghent, Belgium
Company	ArcelorMittal, LanzaTech
Description	Production of bio-ethanol using industrial waste gases from the steel industry.
Product	Fuels, Bio-ethanol
Timeline	2015 – Start 2021 – Demonstration 2025 – Operation
Status	Ongoing
TRL	8 (Commercial demonstration)
Capacity ($MtCO_2$ / year)	0.125

Carbon2Chem	
Location	Duisburg, Germany
Company	Thyssenkrupp
Description	Converting steel mill gases (CO/CO_2) from the steel industry into fuels and chemicals such as ammonia, methanol, or fertilisers and plastics.
Product	Fuels, Chemicals - fertiliser, methanol
Timeline	2016: Start Not before 2030: Industrial scale – depending on research consortium's decision
Status	Ongoing
TRL	6 (Pilot)
Capacity ($MtCO_2$ / year)	0.86 tCO_2/t steel reduction in BF-BOF route emission intensity

INITIATE (formerly FRESME and Stepwise)	
Location	Lulea, Sweden
Company	Multiple (ArcelorMittal, SSAB as partners)
Description	Converting residual carbon-rich gas from the steel sector into feedstock for the chemical sector, such as urea generation.
Product	Chemicals, Ammonia/urea
Timeline	Stepwise: 2015-2019 Fresme: 2016 - 2020 INITIATE: 2020 – 2025 (Demonstration)
Status	Ongoing
TRL	7 (Demonstration)
Capacity ($MtCO_2$ / year)	95% reduction in C02 intensity of residual steel gas

CARBON4PUR	
Location	Marseille, France
Company	Multiple (ArcelorMittal as partner)
Description	Conversion of waste gases from steel industry into intermediates for polyurethane production.
Product	Chemicals (Polyols, Polyurethane)
Timeline	2017-2021
Status	Completed
TRL	6 (Pilot)
Capacity ($MtCO_2$ / year)	0.09

C2FUEL	
Location	Dunkirk, France
Company	Multiple (ArcelorMittal as partner)
Description	Develop and test two innovative routes for conversion of CO_2 into chemical energy carriers to be used for mobility applications.
Product	Fuels, Chemicals
Timeline	2019-2023
Status	Completed
TRL	6 (Pilot)
Capacity ($MtCO_2$ / year)	2.4 (combined potential reduction from all project partners)

Table 5. *Overview of CCU projects in the steel industry. Source: Project websites, CO_2 Value Europe, IEA CCUS Project Database (2023), Somers, J. (2021).*

3.1 Limitations of CCU applications for the iron and steel industry

While CCU may hold some promise for achieving emissions reductions in certain sectors, it seems greatly limited in the steel industry. **Currently, only a few projects are in progress, primarily in early research or pilot phases, and their viability at a commercial scale remains uncertain**. These projects offer only a limited potential for reducing total industry emissions. As an illustration, the Steelanol project anticipates an annual reduction of carbon emissions from ArcelorMittal's Ghent plant by only 0.125 $MtCO_2$, a relatively minor contribution considering the plant's total emissions, as it utilizes approximately 15% of blast furnace off-gas (Somers, J. 2021). Another crucial aspect to consider in CCU is the concept of delayed emissions, where emissions are not completely avoided but are rather embedded into the products. These embedded emissions are subsequently released back into the atmosphere throughout the product's lifecycle, for example fuel produced through CCU would return the carbon back into the atmosphere.

The effectiveness of CCU processes also heavily depends on the efficiency of the preceding carbon capture process. To fully unlock CCU's potential in mitigating emissions, higher rates of energy-efficient carbon capture at lower costs would be needed. Another critical factor is the indirect emissions linked to the production of energy required for CCU processes. Using energy from fossil fuels could compromise the overall emissions reduction achieved through CCU. Losses during the gas purification and conditioning process, along with incomplete conversion of some emissions during chemical synthesis, reduce the emissions reduction potential of the CCU process.[24] Furthermore, emissions result from the energy used to power the CCU process, whether from electrical energy, natural gas, or heating.

In comparing the energy demand between the conventional steel manufacturing process and the same process with additional chemical production from CCU, Wich et al. (2020) demonstrate that **the energy demand of the process with CCU (MJ per ton of crude steel) is approximately twice as high**. This difference is primarily due to the energy needed for gas conditioning and chemical processing. In the case of the conversion of CO_2 to methanol, the captured carbon needs to be reacted with hydrogen to produce methanol. Bazzanella and Ausfelder (2017) report an 11.02 MWh energy demand per ton of methanol. If green hydrogen is used, the overall process could contribute to mitigating carbon emissions compared to conventional methanol production that uses fossil fuels as process inputs. Producing methanol using solar PV or wind-sourced electricity could enable emission reduction of 90 percent and above compared to fossil-based methanol. However, if the grid electricity is used, then the emissions from feedstock production will increase, and the life cycle carbon footprint of methanol can even be above the fossil-based methanol (Hamelinck and Bunse, 2022). ThyssenKrupp's Carbon2Chem project aims to produce the H_2 required for methanol production through water electrolysis, which requires large amounts of renewable electricity.

In summary, only a handful of CCU projects have been carried out in the steelmaking industry, most of which are still at the pilot stage. **The total emission reduction potential is a very small fraction of total industry emissions**. Crucially, utilisation of CO_2 first requires it to be captured. However, as we

[24] Wich T, Lueke W, Deerberg G and Oles M (2020). Carbon2Chem®-CCU as a Step Toward a Circular Economy. Frontiers in Energy Research, 7. doi:10.3389/fenrg.2019.00162.

have already demonstrated, carbon capture is only relevant in very limited scenarios in the steelmaking process. We therefore consider the potential for CCU in the steel sector to be limited.

4. CO2 Transport and Storage

4.1 CO2 storage limited by the availability of suitable geological formations in Europe

As we have explored in Section 3, options to utilise the captured carbon (CCU) tend to be limited and/or controversial, and this is not exclusive to the iron and steel industry.[25] Most European heavy industries that invest in carbon capture technologies to decarbonise their activities thus rely on CO_2 storage solutions which involves transporting the captured carbon from their facilities to CO_2 storage sites that meet the criteria set out in the 2009 CCS Directive. The growing hype around carbon capture technologies has prompted a series of new investments in CO_2 infrastructure projects across Europe. However, these also faced regulatory and financial barriers, and hopes to see a well-functioning European CO_2 transport and storage network have not yet materialised. The European Commission commissioned the Joint Research Centre to update a 2010 study[26] on the evolution of the extent and the investment requirements of a trans-European CO_2 transport network. In the report, published in February 2024, the JRC asserted that the EU faced a lack of CO_2 storage capacity.[27] The JRC confirmed that **the number of announced or ongoing carbon capture projects far outweigh those for CO_2 storage**. As a result, they concluded that early CCS adopters would probably have a significant impact on the evolution and extent of the future European CO_2 transport network, as they expect the CO_2 network to develop around their locations.

For now, **CO_2 storage projects are mostly located in the North Sea**. In the Netherlands and in Belgium, several projects plan on using depleted offshore natural gas fields. For instance, the "Porthos" project aims to collect CO_2 from industry in the Port of Rotterdam, transport it via pipelines to an offshore platform, then store it in empty gas fields under the seabed.[28] The project aims to store approximately 2.5 $MtCO_2$ per year for 15 years (i.e. for a total of 37 $MtCO_2$). Construction works should start in 2024, with the start of operations expected from 2026. According to a study commissioned by the Dutch Ministry of Economic Affairs and Climate Policy, the average transport and storage cost of the Porthos project is around 45-60 €/tCO_2 (without subsidies).[29] In Norway, 13 exploration licenses for CO_2 storage in the North Sea have been issued since 2018.[30] And in Denmark and in the UK, both governments recently (2023) issued their first tenders to convert saline formations and depleted oil and gas fields located in the North Sea into CO_2 storage sites.

One of the largest CO_2 storage projects that emerged in the North Sea is the "Northern Lights" project.[31] Described as *"the world's first open-source* CO_2 *transport and storage infrastructure"*, "Northern Lights" consists of a cross-border CO_2 network project stretching over 110 km that will link at least nine European capture initiatives (in the United Kingdom, Ireland, Belgium, the Netherlands, France, and Sweden) – including four cement factories and one steel plant – to a storage site on the

[25] de Kleijne, K., Hanssen, S. V., van Dinteren, L., Huijbregts, M. A., van Zelm, R., & de Coninck, H. (2022). Limits to Paris compatibility of CO2 capture and utilization. *One Earth*, 5(2), 168-185.
[26] JRC (2010), The Evolution of the Extent and the Investment Requirements of a Trans-European CO2 Transport Network
[27] Tumara, D., Uihlein, A. and Hidalgo Gonzalez, I., Shaping the future CO2 transport network for Europe, European Commission, Petten, 2024, JRC136833.
[28] Porthos (2023). https://www.porthosco2.nl/en/project/
[29] Xodus Advisory (2020). Porthos CCS – Transport and Storage (T&S) Tariff Review. Submitted to The Dutch Ministry of Economic Affairs and Climate Policy.
[30] Norwegian Offshore Directorate (2023), Announcement 2023, round 1
[31] European Commission (2023), Project of common interest: 12.4 PCI fiche

Norwegian continental shelf. The captured CO_2 will be transported both by ship and by pipeline. The project is expected to be online by 2025, with capacity to transport, inject and store up to 1.5 Mtpa by mid-2024, and the ambition to later expand storage capacity to 5 Mtpa. According to estimates by DNV GL (2020), the net cost of CO_2 transport and storage will range between 44.2-115.5 €/tCO_2.[32] "Northern Lights" has been listed as a Project of Common Interest (PCI) since 2020 and received more than €660 million in EU funding from the Connecting Europe Facility (CEF) for Energy programme.

Even though most CO_2 storage projects are concentrated in the North Sea, other projects have been emerging in the last few years. In Italy, for instance, the Ravenna CCS Hub project was awarded a pilot storage license in the Adriatic and aims to store 4 MtCO_2 per year by 2027 in a depleted offshore gas field. In Bulgaria, the ANRAV project – which secured €190 million from the Innovation Fund in 2022 – is planned to enter operations in 2028 and aims to store 0.8 MtCO_2 per year in a depleted gas field in the Black Sea, using an onshore and offshore pipeline system. Some countries, like Denmark and Poland, are also looking into onshore CO_2 storage sites (Global CCS Institute, 2023).

To boost the development of CO_2 storage sites and address the lack of CO_2 storage capacity, the European Commission introduced an EU-level injection capacity target of at least 50 million tonnes of CO_2 per year by 2030 in its proposal for a Net Zero Industry Act. However, **the EU's storage capacity will also be limited by geological factors**. As the IPCC (2023: 86) observed, *"CCS is an option to reduce emissions from large-scale fossil-based energy and industry sources provided geological storage is available. […] The technical geological storage capacity is estimated to be on the order of 1000 Gt*CO_2*, which is more than the* CO_2 *storage requirements through 2100 to limit global warming to 1.5°C, although the regional availability of geological storage could be a limiting factor."*[33] While the IPCC estimates the global CO_2 storage capacity to be in the range of 1000 GtCO_2, the European Scientific Climate Advisory Board (2023: 78-79)[34] estimates the EU's geological storage capacity to be limited to 57.2 GtCO_2. Considering that their scenarios assume between 127 and 425 MtCO_2 captured per year by 2050, but taking also into account social, political, financial, and technical uncertainties, the ESCAB's estimate concurs with the JRC study's preliminary results pointing to a lack of storage capacity in Europe.

The limited availability of CO_2 storage options in Europe also raises questions about the distance that separates potential CO_2 storage sites from industrial facilities from which captured CO_2 emissions will be transported. Several think tanks[35,36] have already pointed out the fact that the concentration of CO_2 storage sites in the North Sea will create logistical and financial challenges for industrial facilities that are located far from these storage sites. Figure 9 maps the distribution of BF-BOF plants over potential geological CO_2 storage sites in Europe. It shows that 65% of the European BF-BOF steel production capacity is located less than 65 km away from a suitable geological formation. However, very few of these storage sites are being explored. In addition, four steel mills (representing 12% of the European primary steel capacity) are located more than 100 km away from a potential CO_2 storage site.

[32] DNV-GL (2020). The Norwegian Full-Scale CCS Demonstration Project. Gassnova SF. Report No. 2019-1092, Rev. 2. Reported amounts converted from Norwegian kroner to EUR.

[33] IPCC (2023): Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change

[34] European Scientific Advisory Board on Climate Change (2023), Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050

[35] Clean Air Task Force (2019), Unlocking Europe's CO_2 Storage Potential

[36] E3G (2022), Making Carbon Capture Work: A Framework to Facilitate High-Value Uses in Europe

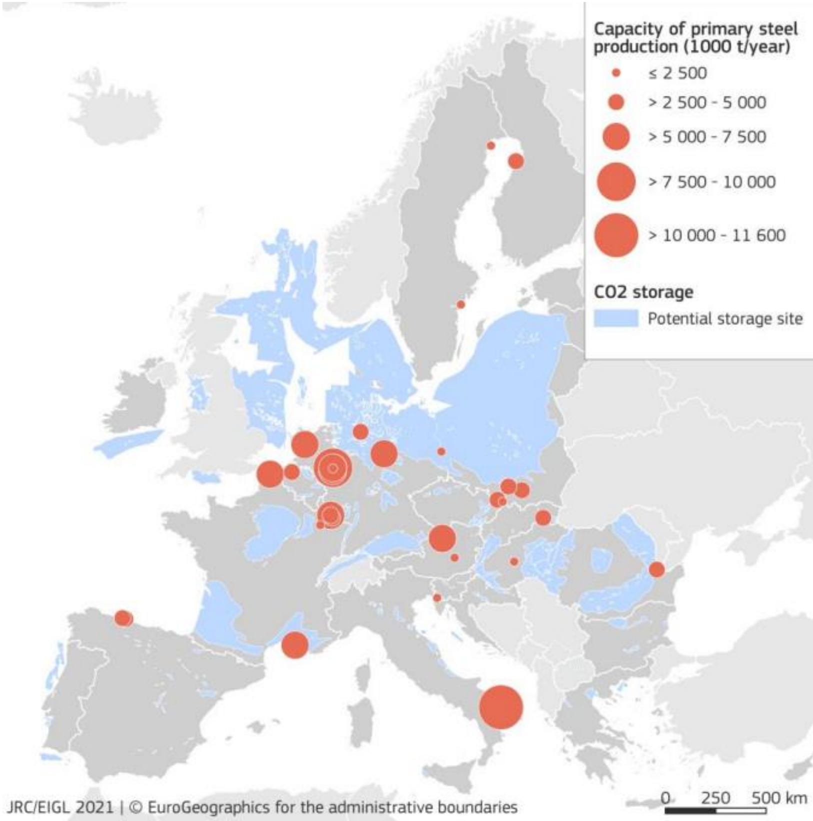

Figure 9. *Primary steel production and CO_2 storage sites in the EU. Source: JRC/Energy and Industry Geography Lab, based on (Steel Institute VDEh, 2019) and CO_2StoP, as per quoted by Somers, J. (2021).*

Every 4 years, EU Member States report to the European Commission on the CCS Directive implementation, after which the European Commission publishes a report. The latest report (published in October 2023)[37] confirmed this imbalance: *"The locations of initial geological CO2 storage opportunities and hard-to-abate energy intensive industries that could capture CO2 emissions are not evenly distributed among Member States and EEA countries. This requires cross-border cooperation as regards CO2 transport and/or storage sites."*

Transporting captured CO_2 over long distances therefore poses challenges in terms of costs and feasibility, but also requires high levels of coordination and cooperation between EEA countries. Several EU Member States have committed to capture CO_2 as part of their climate mitigation plans but have already announced they planned on storing it in other European Economic Area countries – either because of geological limitations or because of public opposition. Norway, which has positioned itself as a prime region for CO_2 storage, is already oversubscribed with demands from EU-based industries.[38] The United Kingdom, which recently announced plans to support a new domestic CCUS market by 2035,[39] should also have additional storage capacity. However, while the UK confirmed they would continue dialogues with the EU regarding potential cross-border CO_2 transport and storage, the

[37] European Commission (2023), Report from the Commission to the European Parliament and the Council on Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide

[38] Carbon Pulse (2021), Burial at sea: Europe's industry queues up for North Sea CO2 storage

[39] UK Department for Energy Security and Net Zero (2023), Carbon Capture, Usage and Storage: a vision to establish a competitive market

separation of their respective ETS following Brexit means that any CO_2 transferred to a UK-based CO_2 geological storage site by an EU ETS emitter would be regarded as "emitted" – and vice versa.[40]

4.2 CO2 transport challenges

In addition to risks related to the EU's limited geological storage capacity, **transporting the captured CO_2 from industrial facilities to CO_2 storage sites also pose a number of challenges**. Figure 10 compares cost estimates for CO_2 transport by onshore pipeline, offshore pipeline, and shipping. The costs vary according to the total travel distance and volume of CO_2 transported per year. Over very short distances (under 200 km), transport via pipelines tends to be cheaper, especially for high volumes of CO_2 (> 5 Mtpa). Shipping otherwise proves more competitive, especially when CO_2 is transported over long distances. These comparisons are particularly relevant for emitters located in Southern Europe, where storage options are scarce. For example, d'Amore et al. (2024) reviewed different options to transport 10 $MtCO_2$/year from Greece to the North Sea. They found that using larger vessels (>50 $ktCO_2$ capacity) instead of smaller vessels (10 $ktCO_2$ capacity) could reduce transport costs from €55/tCO_2 to €30/tCO_2. Transporting CO_2 by ship thus constitutes a very attractive option for CO_2 network developers. Several CCS projects across Europe include CO_2 shipping in their strategy, such as the "Northern Lights" CO_2 storage project in Norway, "Antwerp@C" and "Ghent Carbon Hub" in Belgium, and "D'Artagnan" and "Grand Ouest CO_2" in France. However, initial infrastructure costs are high, and the evolution of fuel costs remains uncertain.

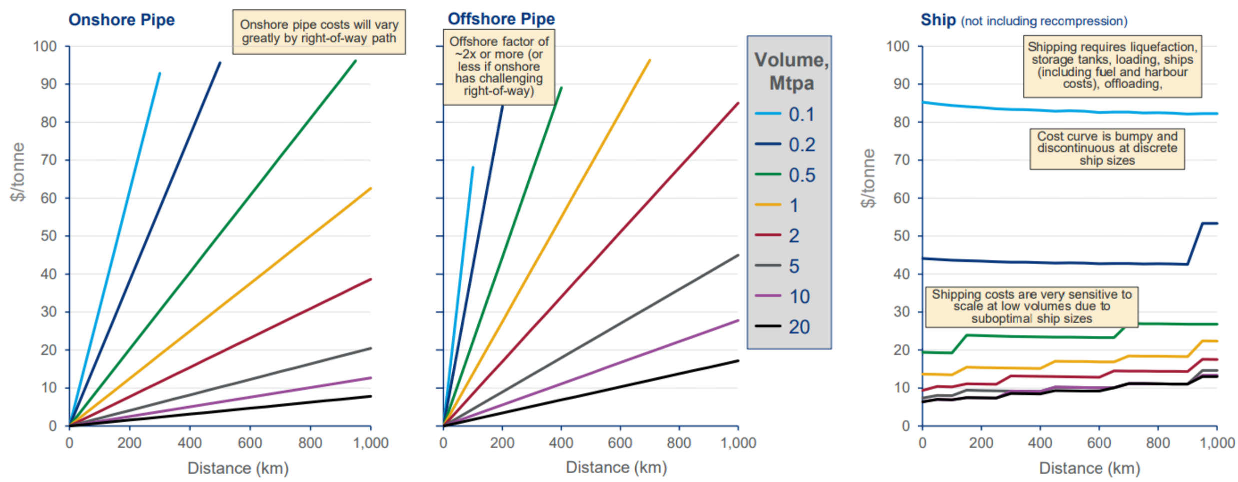

Figure 10. Cost of CO_2 transport (USD/tCO_2). CapEx and OpEx included. Source: Wood Mackenzie (2023).

Pipelines continue to be the preferred option to transport CO_2 from capture facilities to storage sites (Global CCS Institute, 2023). Projects currently in development in Europe include the "Aramis" project in the Netherlands, which is listed as PCI and received funding from the Connecting Europe Facility (CEF) for Energy programme. The project consists of an onshore CO_2 collection hub (known as "CO_2next") in the Port of Rotterdam and an offshore CO_2 pipeline to offshore platforms, where the CO_2 will be injected via wells into depleted gas fields. Many other pipeline projects are underway, most often seeking to link industrial facilities to the CO_2 storage sites in the North Sea. Yet **some fear that the construction of new CO_2 pipelines represents unnecessary investments** and that they will

[40] Carbon Pulse (2023), Analysis: How carbon capture could help bring Britain back closer to the EU

result in stranded assets,[41] echoing the IPCC's concerns (2022: 1211) about the potential lock-in of existing energy structures due to the growth of CCS. There are also debates about the feasibility of repurposing old fossil fuel pipelines for CO_2 transport as well as abandoned oil and gas wells for CO_2 storage.[42] Furthermore, as CO_2 storage already has decades of industrial exploitation behind it, there are very limited cost reductions to be expected from technological improvements.

4.3 The threat of CO2 leakage

The biggest criticism against CO_2 transport and storage stems from the considerable risks of CO_2 leakage, both during transport and from storage reservoirs. The IPCC (2022: 1211) too made explicit warnings against potential leaks from undersea or underground CO_2 storage reservoirs. In the EU, the CCS Directive provides a regulatory framework designed to prevent hazards such as CO_2 leakage, damage to health or the environment, and any adverse effects on the security of the CO_2 transport network or storage sites. However, CO_2 leakage is considered by some scientists not just as "likely", but rather as "inevitable" – leaving only options that reduce the risk of leakage without ever completely guaranteeing permanent storage.[43] The risks of CO_2 leakage and adverse environmental impacts seem to be even greater for offshore CCS infrastructure.[44] Many environmental organisations and civil society groups thus remain sceptical of the extent to which CO_2 storage can really be "safe" and "permanent" as promised by industrial stakeholders.[45]

In a report published in 2023, IEEFA pointed out that **there is a great deal of uncertainty surrounding the risks associated with underground carbon storage, even in the best-known cases**.[46] According to them, CCS proponents often cite the Norwegian offshore geological fields "Sleipner" and "Snøhvit" as proof of the technology's viability. The two CO_2 storage sites have been operating since 1996 and 2008, respectively, and have been the subject of more than 150 academic papers, ranking them among the most studied geological fields globally. Yet, despite their popularity, IEEFA showed that the two projects encountered alarming problems, and that both *"the security and stability of the two fields have proven difficult to predict".*

The IEEFA reported that:

- *"In 1999, three years into Sleipner's storage operations,* CO_2 *had already risen from its lower-level injection point to the top extent of the storage formation and into a previously unidentified shallow layer. Injected* CO_2 *began to accumulate in this top layer in unexpectedly large quantities. Had this unknown layer not been fortunate enough to be geologically bounded, stored* CO_2 *might have escaped."*
- *"At Snøhvit, problems surfaced merely 18 months into injection operations despite detailed pre-operational field assessment and engineering. The targeted storage site demonstrated acute signs*

[41] Clean Air Task Force (2024), Risk Allocation and Regulation for CO2 Infrastructure

[42] Lane, J., Greig, C. & Garnett, A. (2021) Uncertain storage prospects create a conundrum for carbon capture and storage ambitions. Nat. Clim. Chang. 11, 925–936.

[43] Li, D., Ren, S. and Rui, H. (2019), CO2 Leakage Behaviors in Typical Caprock–Aquifer System during Geological Storage Process. *ACS Omega* 4 (18), 17874-17879, DOI: 10.1021/acsomega.9b02738

[44] Centre for International Environmental Law (2023), Deep Trouble: The Risks of Offshore Carbon Capture and Storage

[45] Centre for International Environmental Law (2021), Over 500 Organizations Call on Policymakers to Reject Carbon Capture and Storage as a False Solution

[46] IEEFA (2023), Norway's Sleipner and Snøhvit CCS: Industry models or cautionary tales?

of rejecting the CO_2*. A geological structure thought to have 18 years' worth of* CO_2 *storage capacity was indicating less than six months of further usage potential. This unexpected turn of events baffled scientists and engineers while at the same time jeopardizing the viability of more than US$7 billion of investment in field development and natural gas liquefaction infrastructure. Emergency remedial actions and permanent long-term alternatives needed to be, and were, identified on short notice and at great cost."*

5. Conclusion: What role should CCS/U play in the iron and steel sector?

The rationale behind this report is simple. As a heavy industry, **the iron and steel sector generates vast quantities of emissions and must quickly find ways to decarbonise its activities to align with EU climate goals**. Carbon capture is often mentioned as a possibility to tackle so-called "hard-to-abate" industrial emissions, including in the iron and steel sector. Yet relying on the general idea that carbon capture is possible instead of delving into the potential of specific CCS/U applications perpetuates vague promises and does not allow for constructive debates.

To address this issue, **this report sought to provide clear and detailed information about the various CCS/U technologies used to decarbonise iron and steel manufacturing processes, and to evaluate their performance**. The aim of this report was not to reject the value of carbon capture technologies altogether, but rather to assess their relevance for the iron and steel industry – particularly in Europe. To do so, this report examined the costs, effectiveness, and electricity needs of specific CCS/U technologies used to cut down emissions from iron and steelmaking. It also reviewed the wider regulatory and economic context in which they are being developed and discussed the status quo of other segments of the CO_2 value chain on which they depend.

This report has shown that there are reasons to be concerned about the growing hype around CCS/U technologies in this sector. We found that **CCS/U applications were not equally relevant, but most importantly that they all performed worse in terms of achieving emissions reductions than other available solutions to decarbonise iron and steel manufacturing processes** – such as DRI-EAF, or EAFs using recycled post-consumer scrap. While coupling iron and steel production with carbon capture solutions obviously leads to reduced carbon emissions compared to simply keeping the old facilities running, reliance on CCS/U technologies in the iron and steel sector does not make sense economically, environmentally, and energy-speaking. Furthermore, while they can achieve significant emission reductions for specific production stages like post-combustion in blast furnaces, CCS/U technologies do not solve the emissions from coal mining, which can add up to 27% to the overall emissions currently produced in steel production[47] – let alone other upstream emissions from coking, sintering, lime production etc. CCS/U technologies must therefore not be seen as a silver bullet, nor serve as a license that allows to perpetuate the use of carbon-intensive iron and steel production methods.

The availability of CCS/U solutions allows steel companies to temporarily continue doing business as usual until these technologies are operational, thereby delaying decarbonisation efforts instead of **implementing alternative production methods that would result in faster and deeper carbon emission reductions**. In the iron and steel industry, the push for CCS/U solutions can be explained by the industry's reluctance to abandon old production methods and transition to more sustainable, more energy-efficient, already-proven carbon-free processes. For instance, the circular potential of steel continues to be underused in the EU, with nearly 20 million tonnes of ferrous scrap leaving the continent each year.[48]

Concerns about CCS/U expressed in this report also extend to the increasing number of EU policies and EU funding supporting the deployment of these technologies, irrespective of their sectoral

[47] Ember (2023), Coal mine methane adds 27% to steel's climate footprint

[48] Sandbag (2023), Flat Steel in the Free Allocation Regulation

relevance. Other climate mitigation technologies may be underfunded as a result. It is thus important that the EU's ambition to create a market for CO_2[49] does not come at the expense of the main objective of reducing carbon emissions. It is often said that carbon capture technologies should only be deployed to tackle residual, "unavoidable" industrial emissions.

In the iron and steel industry, most carbon emissions can be avoided without the help of carbon capture technologies, with material efficiency and technology performance improvement expected to play larger roles in achieving emissions reductions up to 2050 under the IEA's Sustainable Development Scenario.[50] **EU policymakers should therefore ensure that policies and funding reflects this, and support these proven and more cost-effective decarbonisation methods over CCS/U where it makes sense to do so**.

[49] European Commission (2024), Towards an ambitious Industrial Carbon Management for the EU
[50] IEA (2020). Energy Technology Perspectives 2020, IEA, Paris

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Appendix

Assumptions for the techno-economic analysis

Parameter	Unit	Value	Source
BF-BOF relining	€/t CS	85	Vogl, Åhman and Nilsson (2018)
TGR-OBF relining	€/t CS	45	IEAGHG (2013)
Smelting reduction CAPEX (Hisarna)	€/t CS	300	Tata Steel (2013)
DRI CAPEX (Energiron)	€/t CS	300	Danieli (2019)
EAF CAPEX	€/t CS	210	Eclareon (2021)
CO_2 Capture and compression unit	€/t CS	134	IEAGHG (2013)
Air Separation Unit	€/t CS	27	IEAGHG (2013)
MEA equipment CAPEX	€/t CS	17.5	Manzolini, G. (2020)
SEWGS equipment CAPEX	€/t CS	20.2	Manzolini, G. (2020)
VPSA equipment CAPEX	€/t CS	16.2	Subraveti et. Al. (2021)
Cryogenic equipment CAPEX	€/t CS	15.5	M.J. Tuinier et. Al. (2011)
MEA solvent price	€/kg	1.25	Manzolini, G. (2023)
Iron ores price	€/t	116	CME Group (2023)
Scrap price	€/t	366	Investing.com (2023)
Coal price	€/t	135	Trading Economics (2023)
Electricity price	€/MWh	91	EEX (2023)
Limestone / fluxes price	€/t	90	Vogl, Åhman and Nilsson (2018)
Natural gas price	€/MWh	25	IEA (2019)

Capture method	Capture rate (%)	Electricity (kWh/tCO_2)	Source
MEA + compression	90	417	M.T. Ho et al. (2013)
SEWGS + compression	90	623	Gazzani, M. (2015)
VPSA + compression + cryogenic flash	94	292	Birat, JP. (2010)
Cryogenic distillation + compression	100	691	Leung et. Al. (2014); Birat, JP. (2010)
PSA + compression + cryogenic flash	90	310	Riboldi et. Al. (2017); Birat, JP. (2010)