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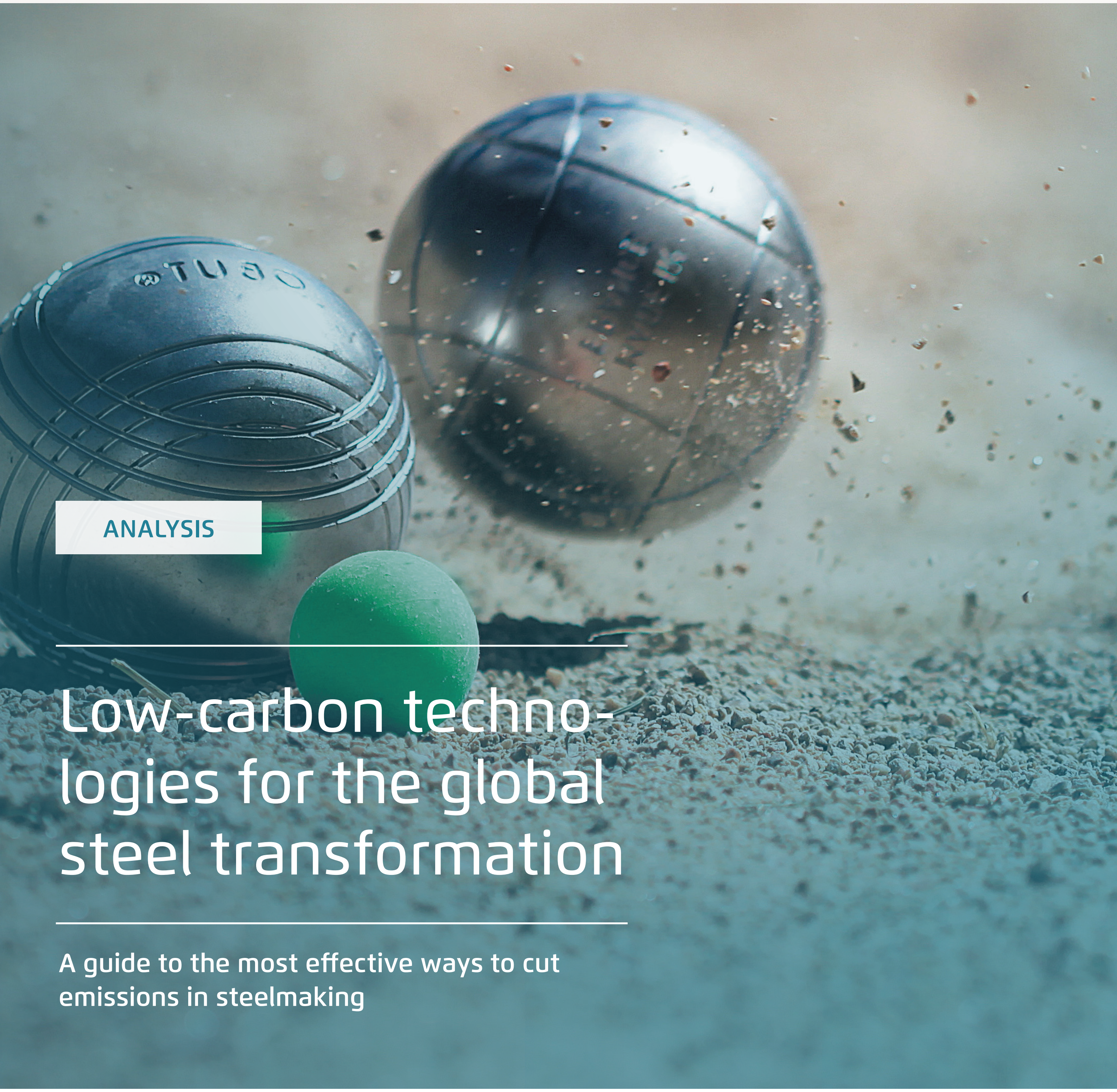

ANALYSIS

Low-carbon technologies for the global steel transformation

A guide to the most effective ways to cut emissions in steelmaking

Wuppertal Institut

Lund University

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Analysis
Low-carbon technologies for the global steel transformation.
A guide to the most effective ways to cut emissions in steelmaking.

Written by
Agora Industry
Anna-Louisa-Karsch-Straße 2
10178 Berlin | Germany
P +49 (0)30 700 14 35-000
www.agora-industry.org
info@agora-industrie.de

Project partners
Wuppertal Institute for Climate, Environment and Energy
Döppersberg 19 | 42103 Wuppertal
T +49 (0)202 2492-0
F +49 (0)202 2492-108
https://wupperinst.org/
info@wupperinst.org

Environmental and Energy Systems Studies at Lund University
John Ericssons väg 1 | 223 63 Lund | Sweden
T +46 46 222 72 00
https://miljo.lth.se/english/
info@lth.se

Project lead
Julian Somers
julian.somers@agora-industrie.de

Ole Zelt
ole.zelt@wupperinst.org

Authors
Wido K. Witecka, Julian Somers, Kathy Reimann, Niklas Wagner (all Agora Industry); Ole Zelt, Alexander Jülich (all Wuppertal Institute); Clemens Schneider (Universität Kassel); Prof. Max Åhman (Lund University)

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Preface

Dear reader,

The steel sector's transformation is speeding up: COP28 saw pledges to procure low-CO_2 steel, fresh steps to harmonise measuring the sector's greenhouse gas emissions and the launch of the Climate Club, aimed at fostering international cooperation to accelerate industrial decarbonisation.

These are encouraging signals for a sector that is responsible for 8 percent of global CO_2 emissions and has long been labelled as hard to abate. While the current primary steelmaking route is hugely CO_2 intensive and coal dependent, our study shows that near-zero CO_2 technologies, in particular those based on the direct reduction of iron, can be deployed this decade, offering flexible pathways and new business cases for economies at different stages of industrial transformation. However, these key low-carbon technologies are often more expensive than current production methods. This is especially the case in the early stages of the transition. Targeted support and increased international cooperation are needed to build on the current momentum and enable an accelerated transformation of the global steel sector.

In this study, we assess eight potential low-CO_2 steelmaking technologies, analysing key parameters such as their market readiness, cost and CO_2 emission reduction potential to determine the role they can play in the steel sector's transformation.

We hope you enjoy reading this report!

Frank Peter
Director, Agora Industry

Professor Manfred Fischedick
President, Wuppertal Institute

Key findings at a glance

1 **Key technologies for transforming the global steel industry will be commercially available this decade.** By 2030, over 70 percent of existing blast furnaces (BF) will require reinvestment, providing a window of opportunity to replace this CO_2-intensive process towards scrap- and hydrogen-based steelmaking. Improving scrap quality and using renewable electricity allows high-quality steel production with close to zero CO_2 emissions.

2 **The flexibility provided by direct reduced iron-based (DRI) steelmaking as well as future electrification technologies can address bottlenecks.** DRI technology can be deployed today and operate with a gradually increasing share of hydrogen; furthermore, it allows the iron and steelmaking stages to be decoupled. Pairing the DRI process with existing basic oxygen furnace (BOF) steelmaking will unlock the use of lower-quality iron ores, as may future iron ore electrolysis technologies.

3 **Carbon capture and storage (CCS) is unlikely to save the coal-based BF-BOF route.** Retrofitting BF-BOF plants with CCS is a risky strategy: it leaves high residual emissions, requires significant CO_2 transport and storage infrastructure, needs to take high upstream methane emissions from coal mines into account and will become less and less commercially attractive as hydrogen costs decline and CO_2 prices rise.

4 **The higher cost of low-CO_2 steelmaking requires targeted regulatory support and international cooperation to accelerate large-scale deployment of low-CO_2 steelmaking.** Measures need to address the entire steelmaking value chain, including support for technological options and the development of a global market for green products. International cooperation can enable the production of green iron in renewable hydrogen 'sweet spots' by rethinking global value chains.

Content

List of abbreviations

Term	Explanation
AEL	Alkaline iron electrolysis
BECCS	Bioenergy carbon capture and storage
BF	Blast furnace
BOF	Basic oxygen furnace
Capex	Capital expenditures
CCS	Carbon capture and storage
CO	Carbon monoxide
CO_2	Carbon dioxide
CS	Crude steel
DACCS	Direct air carbon capture and storage
DR	Direct reduction
DRI	Direct reduced iron
EAF	Electric arc furnace
EOR	Enhanced oil recovery
EU-ETS	EU emissions trading system
Fe	Iron
GHG	Greenhouse gases
GJ	Gigajoule
GWP	Global warming potential
H_2	Hydrogen
HBI	Hot briquetted iron
LNG	Liquefied natural gas
MOE	Molten oxide electrolysis
Mtpa	Megatonnes per annum
NG	Natural gas
NZE-scrap-EAF	Near-zero emissions scrap electric arc furnace
Opex	Operating expenditures
OSBF	Open slag bath furnace
PGH	Process gas heater
SAF	Submerged arc furnace
SMELT	Smelter
tCO_2eq	Tonne of carbon dioxide equivalent
TRL	Technology readiness level
USD	US dollar

Introduction

The steel sector has an important role to play in delivering on the world's climate targets. Steel is a crucial material for the global economy, including for the technologies and infrastructure that will be needed to achieve climate neutrality, yet the sector that produces it is a major greenhouse gas (GHG) emitter, responsible for around 8% of global GHG emissions. Using coal-based blast furnaces, the current primary steelmaking route has inherently high CO_2 emissions, and it is clear that the steel sector will require transformational change to be brought into line with climate neutrality. At the same time, ambitious steelmakers around the globe have made rapid progress with the necessary breakthrough technologies to decarbonise the sector, with the result that solutions are already available or near market readiness. The rapid introduction of key low-carbon breakthrough technologies this decade is vital in order to accelerate the global steel transformation and avoid the risk of stranded assets. Our previous work has shown that this decade marks a crossroads for the global steel sector: more than 70% of existing blast furnaces will require reinvestment by 2030. Reinvesting in existing CO_2-intensive processes with no pathway to decarbonisation will create path dependencies that lock in high emissions for several decades and carry a high risk of stranded assets. This means that investments must focus on the breakthrough technologies that are compatible with climate neutrality.

In this report, eight breakthrough technologies to decarbonise the steel sector are analysed and compared. The analysis focuses on a number of important parameters, including expected commercial readiness, energy requirements, CO_2 abatement potential and residual emissions, and the CO_2 abatement costs. While low-CO_2 steelmaking will be more expensive than current primary steel production, this gap is expected to narrow as low-CO_2 energy becomes more widely available and CO_2-intensive production becomes increasingly expensive. An appropriate regulatory framework that acknowledges the requirements of these breakthrough technologies can help bridge the gap from first-of-a-kind to mass-market deployment. A combination of market demand for green steel and an incentivising regulatory framework in various regions around the world has already resulted in a race to produce green steel, giving steelmakers at the front of the pack the opportunity to secure a competitive advantage.

Among the various technologies available, the pathway to low-CO_2 steel that most steelmakers are developing revolves around the direct reduction of iron ore. This overall process comprises a set of technological options, each with their respective strengths and weaknesses. A detailed comparison of the direct reduced iron-electric arc furnace (DRI-EAF) and the direct reduced iron-smelter-basic oxygen furnace (DRI-SMELT-BOF) routes highlights the important complementary roles that these technologies can play in the global steel transformation. At the same time, it seems that parts of the industry are still hoping that applying carbon capture and storage (CCS) to their existing coal-based steelmaking assets will allow them to reach climate neutrality, with the result that they will continue to invest in existing and new BF-BOF production. A deep dive into the potential role of post-combustion CCS on the BF-BOF route reveals the risks associated with continued reliance on this technological option.

Based on our analysis of decarbonisation technologies for the steel sector and their main techno-economic parameters, a global effort to accelerate the deployment of these technologies will need to consider the following important elements:

1. **The average CO_2 abatement costs of most breakthrough technologies are likely to be above USD 100/tCO_2 in 2030. A comprehensive policy framework is needed to create a viable business case for low-CO_2 steelmaking technologies.** Currently, few countries have a regulatory framework in place that enables final investment decisions to be made in favour of clean technologies, which

will initially be significantly more expensive than conventional steelmaking routes. This gap can be bridged by a comprehensive policy framework that encompasses the entire steelmaking value chain, addressing the supply of upstream raw materials and clean energy, supporting the development of low-CO_2 steelmaking technologies midstream and unlocking the potential of a green lead market downstream (Agora Industry and Wuppertal Institute 2023).

2. **Expanding scrap-based EAF production is a key strategy as this is the most energy-efficient route.** Of all the breakthrough technology options, the scrap-based EAF route is by far the most energy-efficient route, requiring five to seven times less energy than primary steelmaking. Maximising the share of scrap-based steel production is therefore a vital lever when it comes to reducing the sector's CO_2 emissions. The scope for significantly increasing the share of scrap-based steel at a global level is dictated by the quantity and quality of scrap. To ensure the full potential of scrap-based steelmaking is realised, measures that support the recycling and reuse of steel must be enhanced, from the design of products to the end-of-life treatment of scrap (Agora Industry and Systemiq 2023).
3. **Hydrogen-based DRI steelmaking technologies will be commercially available before 2030 and the key to decarbonising primary steelmaking. The flexibility to use any proportion of natural gas or low-carbon hydrogen is an important advantage for its roll-out.** The only breakthrough technologies for low-CO_2 primary steelmaking that will be commercially available before 2030 are DRI-based technologies such as the DRI-EAF and the DRI-SMELT-BOF route. Modern state-of-the art DRI plants can produce steel with close to zero CO_2 emissions when operating on 100% low-carbon H_2, though they can also be run on any ratio of natural gas and low-carbon hydrogen and combined with CCS. This has several important advantages: DRI plants can be rolled out now and run on natural gas initially until low-carbon H_2 becomes available, already entailing significant emission reductions of up to 70% compared to the BF-BOF route. With their flexibility to incorporate rising proportions of low-carbon H_2 over time, they are also an ideal anchor for ramping up the hydrogen supply and transport infrastructure. Finally, a DRI-based steelmaking process can take place in an integrated manner, combining iron and steel production, but also allows these two steps to be geographically decoupled. Green iron could thus be produced in locations with potential for low-cost renewable electricity and hydrogen, while still supplying the existing downstream steelmaking value chain. Through international cooperation and coordination efforts, this international green iron trade has the potential to both accelerate the global steel transformation and lower its costs.
4. **The insufficient availability of direct reduction (DR)-grade pellets could prove a serious bottleneck to the global steel transformation. The DRI-SMELT-BOF route could be a possible solution, opening up over 50% of the current iron ore market for use in DRI steelmaking.** The DRI-EAF route requires pellets made from high-grade iron ores, which represent only a small share of the current iron ore market and will likely remain in limited supply. The alternative DRI-SMELT-BOF route currently being developed will allow the use of a lower-grade range of iron ore qualities similar to those used by blast furnaces today. This technology could be one of the main solutions to alleviate the pressure from the DR-grade pellet bottleneck and accelerate the switch to H_2-based steelmaking (Agora Industry and Wuppertal Institute 2023).
5. **A combination of risk factors raises the question of whether post-combustion CCS on the BF-BOF route will play any significant role at all in the global steel transformation.** Our analysis has revealed a number of factors weighing against post-combustion CCS on the BF-BOF route by comparison with other breakthrough technologies. It will likely result in high residual CO_2 emissions and involve high upstream methane emissions from coal mining. Given the current low level of industrial development activity, it will probably not be available before 2030 and, once available, will entail similar costs as natural gas-based DRI routes, though the latter have the potential to be converted into climate-neutral assets once low-carbon H_2 is available. Given the high residual

emissions, a rising CO_2 price towards the middle of the decade will likely make BF-BOF-CCS uncompetitive compared to other breakthrough technologies. Finally, steel made via BF-BOF-CCS faces an offtake risk in green markets due to customers not wanting to be associated with coal-based technologies when other zero-emission alternatives exist.

6. **Molten oxide electrolysis (MOE) and alkaline electrolysis (AEL) are potential game-changer technologies – once they become available.** The costs of MOE and AEL and their CO_2 emissions depend largely on the costs and emission intensity of the electricity they use. If clean electricity is available, these direct electrification-based technologies combine comparatively low production costs and the potential to eliminate almost all emissions from the primary steelmaking process. Currently, however, there is considerable uncertainty about when and at what cost these technologies may become available. In the case of MOE, large-scale application by 2030 seems optimistic given its low current technology readiness level, even though the project developers are aiming for commercialisation before 2030.
7. **HIsarna-BOF-CCS looks like a game-changer technology from a cost perspective but faces a number of risks and uncertainties.** Solely from the cost perspective, HIsarna-BOF-CCS also has the potential to be a disruptive technology that could undercut the costs of various other breakthrough technologies. However, there are also a number of risks: the technology's technology readiness level (TRL) is currently uncertain, nor is it known whether it is being actively further developed. It is therefore unclear whether the technology will be available in the 2030s, which was the initial deployment target stated by its developers (Tata Steel 2020). Furthermore, it faces similar risks as CCS on the BF-BOF route as regards upstream methane emissions from coal mines, as well as a possible offtake risk with regard to steel-consuming companies not wanting to be associated with coal-based production technologies, not to mention the sector's general shift away from coal-based steelmaking technologies, especially since this is not a retrofit steelmaking route but would require entirely new production facilities.

This report aims to provide a better understanding of the various breakthrough technologies, their techno-economic parameters and their potential roles in the global steel transformation. The appropriate breakthrough technologies chosen by each steelmaker will have to be considered site by site, as the choices will largely depend on existing local conditions; specifically, the potential for low-carbon electricity and hydrogen, the availability of key raw materials, the existing industrial infrastructure and the specific structure of the local regulatory framework. Nevertheless, with more than 70% of global blast furnace capacity reaching the end of its campaign life by 2030, there is a clear window of opportunity for major investment decisions to accelerate the deployment of key low-carbon technologies and kickstart the transformation of the steel sector towards climate neutrality.

1 Overview of low-carbon technologies

To achieve its climate neutrality targets, the steel sector will need to switch from highly CO_2-intensive iron and steelmaking routes to new low-carbon technologies. Currently, more than 70% of global steel production is coal based via the integrated steelmaking route, relying on blast furnaces in which iron ore is reduced to hot metal through the use of coke and then further processed into steel in a basic oxygen furnace (known jointly as the BF-BOF process). This is a highly energy- and CO_2-intensive process, with CO_2 being produced at multiple points within an integrated steelmaking plant, including the BF, the coking ovens that produce coke, the sinter plants and the BOF. This route is also heavily coal-dependent, with coke playing a major role as an energy carrier, a reducing material and providing structural properties in the BF – a role that cannot be fully substituted by different fuels. The other main steelmaking route is via the electric arc furnace (EAF), which is mainly used to turn recycled steel scrap into new steel. This is a comparatively energy-efficient process that can run almost entirely on electricity. EAFs are also used to turn direct reduced iron (DRI) into steel. DRI is a primary ironmaking route that involves reducing iron ore pellets in a DRI plant by a syngas (CO and H_2), which currently comes mainly from natural gas. Though natural gas-based DRI is a mature, commercial process, it currently accounts for only around 5% of global steel production.

Given that the iron and steel sector is currently responsible for 7 to 8% of global GHG emissions and that global steel demand is set to continue to rise, decarbonising primary steel production by deploying new steelmaking routes is one of the most important challenges faced by the steel sector. This report analyses eight technologies which can play an important role in the transition to a climate-neutral steel sector. They can be grouped according to the following categories: 1) primary steel via hydrogen-based technologies; 2) primary steel via technologies based on direct electrification; 3) primary steel via CCS-based technologies; 4) secondary steel via scrap-based technologies. Section 5 of this report presents specific factsheets for each technology, which provide an overview of key information such as existing projects, production costs and CO_2 emission reduction potential.

1.1 Hydrogen-based primary steel production

Using coking coal to reduce iron ore to iron in the blast furnace and then turning it into crude steel in the basic oxygen furnace (the BF-BOF route) is highly CO_2-intensive because carbon is not only an energy input but also generates CO_2 emissions when it removes oxygen from the iron ore in the form of CO_2. When hydrogen (H_2) is used instead of coking coal to reduce iron ore, the by-product is H_2O rather than CO_2, meaning that these emissions can be almost entirely eliminated if hydrogen produced via renewable energy is used. Instead of the BF-BOF route, ironmaking with hydrogen uses direct reduced iron (DRI) technologies. The iron is subsequently made into steel in steelmaking furnaces.

The current commercial process combines the direct reduction furnace with an electric arc furnace (DRI-EAF route), where iron ore pellets are reduced in their solid state in the shaft furnace of the DRI plants and the resulting DRI is processed into crude steel in an EAF, where steel scrap can be used as an additional feed depending on the desired steel quality. While the DRI-EAF steelmaking process using natural gas is already mature and accounts for 5% of global steel production, DRI using hydrogen is currently being developed by several steelmakers. Modern DRI plants also allow the use of natural gas until sufficient volumes of renewable hydrogen become available.
A small amount of solid carbon is required to foam the slag in the EAF (a necessary step to remove impurities and to increase the efficiency of the process) as well as to add carbon as an alloying element to steel.

To produce high-quality steel grades via the DRI-EAF route, iron ore pellets with a high Fe content (DR-grade pellets) are needed.

In contrast to the DRI-EAF production route, the second hydrogen-based route included in this analysis, the direct reduced iron-smelter-basic oxygen furnace (DRI-SMELT-BOF) route, is based on the continued use of the basic oxygen furnace (BOF). Here, the solid DRI needs to be liquified so that it can be processed in the BOF. A submerged arc furnace (SAF) or an open slag bath furnace (OSBF) unit are therefore required as a smelting stage between the DRI production and the BOF. For the BOF to turn the hydrogen-based DRI into steel, the DRI needs not only to be melted but must also have its carbon content increased (carburisation) through the addition of carbon into the smelter (SMELT). The DRI-SMELT-BOF route thus requires a larger input of carbon than the DRI-EAF route. The main advantage of this route is that lower-grade BF-grade iron ore pellets can be used to produce high-quality steel. This is due to several reasons: as the DRI process does not fully reduce the iron oxides to iron, the metal can be further reduced in the smelter by the prevailing reducing atmosphere; and by melting the solid iron, impurities can be removed in both the smelter and the BOF via slag formation. Therefore, the DRI-SMELT-BOF route can tolerate higher levels of impurities and lower iron-content ores than DRI-EAF, which, by contrast, requires higher-grade DR pellets to ensure the highest possible metallisation level and to operate efficiently.

1.2 Direct electrification of primary steel production

In this report, we examine two primary iron and steelmaking processes that use electricity directly to reduce the iron ore. On the molten oxide electrolysis (MOE) route, the iron ore is directly converted into a liquid metal by electrolysis. In the electrolytic cell, the iron ore is dissolved in an electrolyte solution above the melting point of iron and electricity is passed through the solution to reduce the iron ore. The desired steel properties can be achieved by subsequently adding alloying elements. This route generates no direct CO_2 emissions since no carbon-based reducing agent is required.

In the alkaline electrolysis or electrowinning (AEL-EAF) process, ultra-finely ground iron ore grains in an alkaline solution are reduced at around 110 degrees Celsius by an electric current before being turned into steel in an EAF. In contrast to the MOE route, the electrolytic cell operates at much lower temperatures and the iron ore is reduced to a solid iron plate. Direct CO_2 emissions can also be almost entirely eliminated on this route since no carbon is used in the ironmaking process. Some small residual emissions occur in the grinding and leaching of the iron ore, as well as in the EAF steelmaking step. While the AEL route will likely be paired with an EAF to melt the iron and make steel, the MOE process produces liquid metal which can be directly fed into the downstream steelmaking processes.

1.3 CCS-based primary steel production

Conventional steel production via the BF-BOF route can be retrofitted with a chemical absorption amine-based CO_2 capture unit that is connected to major CO_2 point sources: the on-site power plant that runs on the steel plant's flue gases, the coking plants and the blast furnace hot stoves. These three CO_2 sources have the highest concentration of CO_2 in the flue gas. According to our analysis, capturing the additional flue streams at the steel site which have lower concentrations of CO_2 (for instance from the sinter plant) would be technically and economically difficult. As a result, our calculations show that the BF-BOF route with carbon capture and storage (BF-BOF-CCS) allows for a capture of around 70–75% of on-site CO_2 emissions.

The natural gas-based DRI process can also be combined with post-combustion CO_2 capture since the DRI furnace emits a stream of CO_2 of relatively high concentration and is the main CO_2 emitting process. If high capture rates are achieved, this could lead to CO_2 emissions of 89% below those of the current BF-BOF route. It must be noted that natural gas-DRI (NG-DRI) with CCS is already a commercially deployed technology, albeit one with currently relatively limited CO_2 capture rates and where the CO_2 is being used for enhanced oil recovery (EOR).

The HIsarna-BOF-CCS technology entirely replaces the blast furnace with a new type of smelting reactor, thereby also eliminating the need for the coking and sintering stages of the current BF-BOF route. In the HIsarna reactor, iron ore is reduced to pig iron in a single smelting process and further processed in a basic oxygen furnace, as in the current steelmaking process. Given that the HIsarna reactor produces only one relatively pure CO_2 off-gas stream, this technology can be combined with cryogenic separation as a capture process – a much less energy-intensive process than capture with amine-based absorption. In combination with CCS, CO_2 reductions of up to 93% are possible according to our estimates. Without CCS, HIsarna-BOF can reduce 38% of CO_2 emissions by comparison with the BF-BOF route. It should be noted that the status of the HIsarna-BOF-CCS technology is unclear, since it is not apparent whether Tata Steel, the steelmaker behind the technology, is planning to continue developing this route. The development of the technology in the Netherlands seems to have been put on hold in favour of the hydrogen-based DRI route. It remains to be seen whether Tata Steel will implement the technology in India instead (in current corporate announcements, HIsarna is still included as one potential long-term (2030–2050) decarbonisation option (Tata Steel 2023)).

1.4 Secondary steel production

The electric arc furnace (scrap-EAF) route is the predominant route for secondary steel production. It is operated mainly with electricity to melt the scrap. Around 20% of current global steel production takes place via the secondary route (IEA, 2020). Today, secondary steel is often characterised by lower quality – i.e. a higher level of tramp elements such as copper and nickel due to contaminated end-of-life scrap – than steel from primary production. This often limits the use of secondary steel to applications that can tolerate lower-quality steel, such as the long steel products used in construction. This represents a significant challenge in many developed countries that needs to be addressed. In these countries, the annual availability of scrap is projected to exceed the need for low-quality steel by 2030, since less new infrastructure build-up is required and there are high scrap recycling rates from the existing steel stock in the economy. Possible solutions to increase the use of scrap in steelmaking include better dismantling and sorting of scrap, new recycling technologies to remove tramp elements, or a product design that facilitates end-of-life recycling. In the United States, for example, high-quality steel products can also be produced via the EAF route thanks to the use of modern EAF mini-mills, the use of high-quality scrap and the addition of metallic inputs to dilute impurities.

At the same time, the demand for typical EAF steel products in developing countries is projected to exceed scrap availability by 2030, as a substantial amount of new infrastructure and steel-containing products will be added to the economy, yet the existing steel stock still has a relatively recent age profile and will only gradually reach its end-of-life. In China, this is already the case today: scrap flows are not sufficient to cover the need for long products such as reinforcing bars, these are mainly produced via the BF-BOF route. Therefore, a second key challenge is the lack of scrap availability. This may prompt developing countries with high demand for long steel to start investing in the BF-BOF route rather than in the scrap-EAF route to compensate for the lack of scrap imports.

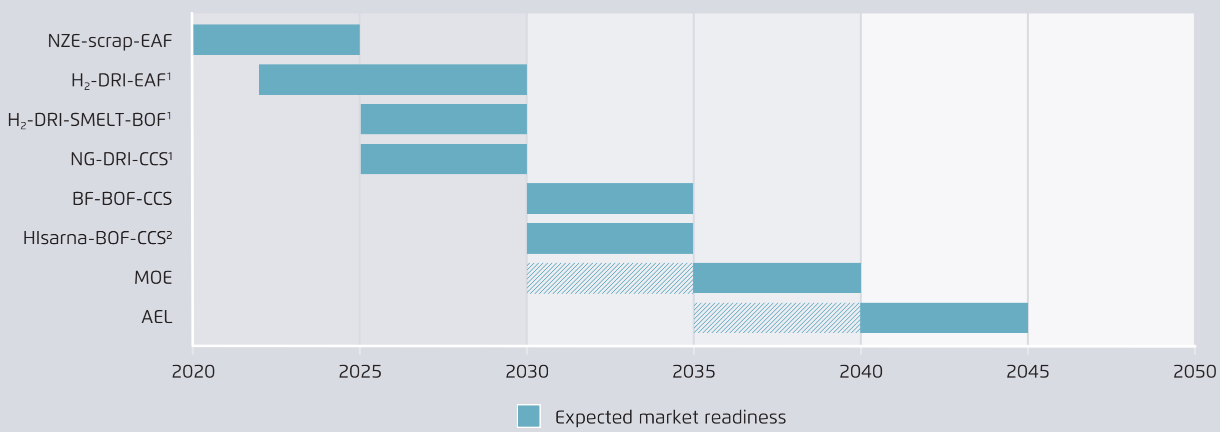
2 Comparison of low-carbon technologies

2.1 Expected commercial readiness

The transformation of steel production that will be necessary to achieve climate neutrality will require technologies to be developed both at speed and at scale. Given the urgent timelines – 2050 being less than three decades away – and the long lifetimes of industrial plants, a key factor when assessing breakthrough technologies for iron- and steelmaking is their expected commercial readiness. Typically, this is assessed by a technology readiness level (TRL) ranging from 1 to 9 – where 9 indicates that the process is proven on a commercial scale. Based on our assessment of the TRL of the analysed breakthrough technologies, their expected commercial availability can be grouped into three different phases: before 2030, between 2030 and 2040, and after 2040 (see Figure 1).

Before 2030, we expect only the already mature scrap-based EAF route, (as the the near-zero emissions (NZE)-scrap-EAF route when running completely on renewable electricity), and the DRI-based routes to be available (see Figure 1). The first industrial-scale hydrogen-ready DRI-EAF plant came online in China in 2023 (GMK Center 2023). Although the 0.6 million tonne DRI plant from Chinese steelmaker HBIS may not be operated with renewable hydrogen initially, it is 100% hydrogen-ready and could produce near-zero emissions steel once renewable hydrogen is used. By the mid-2020s, the first commercial-scale DRI plants running exclusively on 100% renewable hydrogen are scheduled to begin operation in Sestao (Spain), Luleå (Sweden) and Salzgitter (Germany). In addition, steelmakers have made dozens of announcements to build commercial-scale H_2-ready DRI plants (Agora Industry 2023b). These state-of-the-art DRI plants are 100% hydrogen-ready and thus compatible with climate neutrality, but can be operated with natural gas initially if sufficient amounts of hydrogen are not available. H_2-based commercial-size DRI plants are being built in China (DANIELI 2023; tenova 2022), and several final investment decisions for H_2-ready DRI plants around the world have been taken (Agora Industry 2023b). These announcements demonstrate

Expected market readiness of selected breakthrough technologies for steelmaking — Figure 1



Agora Industry and Wuppertal Institute (2024). Note: [1] DRI plants running on natural gas can already blend high shares of H_2. Commerical DRI plants running on 100% H_2 are expected by 2025. [2] It is currently not clear what the TRL of the technology is and whether it is actively being developed further.

that H_2-based or H_2-ready DRI-EAF processes are sufficiently mature for steel companies to take final investment decisions today.

The DRI-SMELT-BOF technology has not yet been demonstrated on a commercial scale. However, the German steelmaker Thyssenkrupp is planning to start operation of a 2.3 megatonne (Mt) commercial-scale DRI and smelter plant by 2026 (Thyssenkrupp 2022). The final investment decisions, backed by German government subsidies, were taken in 2023 (European Commission 2023d). In other words, the technology is on the verge of market readiness. The TRL is therefore already estimated at 7–8 for the DRI-SMELT-BOF route. Due to the expected limited supply of low-carbon hydrogen in 2025, Thyssenkrupp is planning to initially operate the plant with natural gas, blending in increasing proportions of low-carbon hydrogen over time, as it becomes available. While operating the plant with 100% hydrogen and carburising the carbon-free DRI in the smelter need to be further investigated, it is likely to be possible by 2030 at the latest to operate the DRI-SMELT-BOF route with close to 100% hydrogen once renewable hydrogen is available on a large scale (for a more technical analysis, please see Section 3).

The natural gas-based DRI process also lends itself to being combined with post-combustion CO_2 capture since the DRI furnace emits a stream of CO_2 of relatively high concentration. From a technology readiness perspective, this technology is already being deployed commercially, albeit with a limited CO_2 capture potential and for the purposes of enhanced oil recovery (EOR).

A further set of technologies could reach market readiness between 2030 and 2040: BF-BOF with CCS, HIsarna-BOF with CCS and MOE. As far as combining the BF-BOF route with CCS is concerned, limited efforts have been made to develop this technology in conjunction with an integrated steel mill despite the fact that certain post-combustion carbon capture technologies are already being used for specific industrial applications and are available on an industrial scale. For example, the 3D project in Dunkirk started operations in March 2022 and is aiming to capture 4 kilotonnes (kt) of CO_2 per year from BF-based production in the demonstration phase. The aim is to expand this to 1 Mt of CO_2 in 2025 and to explore a future Dunkirk-North Sea capture and storage cluster with 10 Mt of CO_2 in 2035 (ArcelorMittal 2023). However, recent announcements by ArcelorMittal on their transition plans for the Dunkirk steelmaking site raised doubts about whether the 10 Mt target by 2035 is still up to date given that ArcelorMittal have announced the construction of a DRI plant and two EAFs at the Dunkirk site to replace two of the three existing BFs, backed by government subsidies (European Commission 2023c). Another pilot project that is based on this technology option is a consortium of Tata Steel, Carbon Clean and Veolia in Jamshedpur, India (Tata Steel 2021). The capture rate of 5 t of CO_2 per day for onsite reuse (carbon capture and utilisation, CCU) corresponds to yearly captured emissions of around 1 800 t of CO_2. This is only a tiny fraction compared to the yearly CO_2 emissions of the Jamshedpur integrated BF-BOF steel mill, which emits around 20 Mt of CO_2 from its production of around 10 Mt of steel per year. Several rounds of upscaling would be required for this technology to reach commercial scale in the steel sector (see Section 4 for a detailed discussion of this technology).

Regarding the HIsarna-BOF-CCS technology, its further development was postponed after initial successes in the pilot phase and the planned CCS integration in Ijmuiden, Netherlands, did not take place. While it aimed to have a HIsarna plant ready at full scale by 2033, the company decided in 2021 to focus fully on the production of steel via the hydrogen DRI route and to replace one of two blast furnaces even before 2030 (Tata Steel Nederland 2023). It remains to be seen whether Tata Steel will actually implement their planned HIsarna demonstration plant in India with a capacity of 0.5 Mt of steel, however, given that HIsarna is still currently included as one potential long-term (2030–2050) decarbonisation option (Tata Steel 2023).

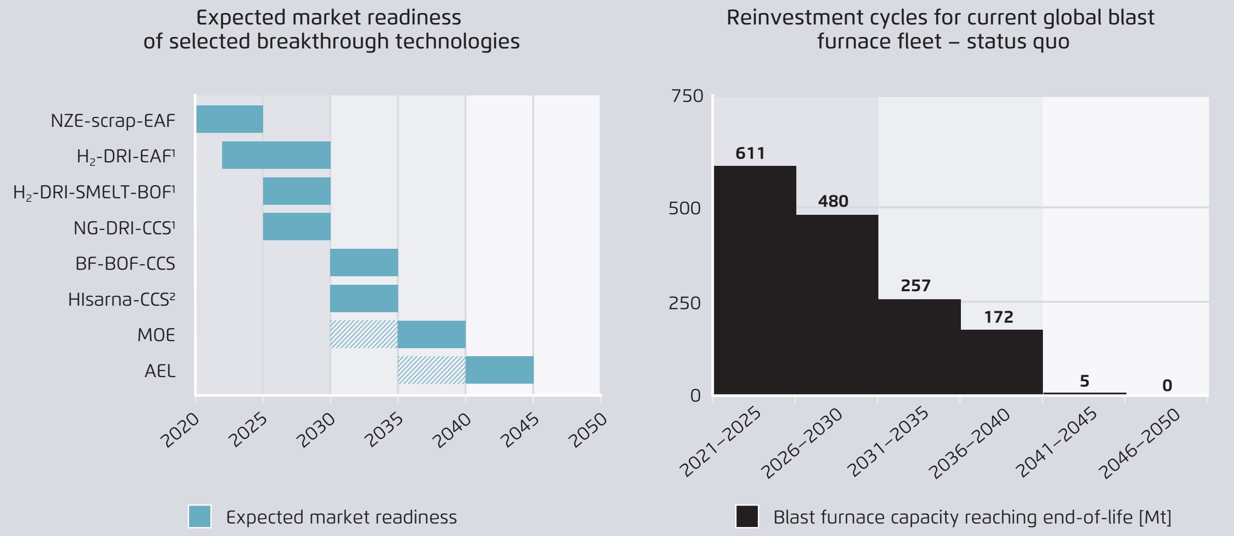
Both electrolysis routes (MOE and AEL) have a current TRL of 3–4. Interestingly, the companies developing these technologies have widely differing targets for their respective technologies to reach commercial readiness. Boston Metal has extremely ambitious plans and aims to have an MOE demonstration plant deployed by 2025 and a commercial plant built by 2026. However, due to the novelty of the process and its current low-TRL state at pilot scale, we only expect the technology to be ready for commercial use (TRL 9) between 2030 and 2040. This is because developing a novel technology from pilot to commercial million-tonne capacity involves significant time scales. If the construction and operation of the pilot plant with a 25 kt/year capacity planned for 2024/2025 is successful, several rounds of upscaling would still be required to reach a million-tonne commercial-scale facility.

The AEL technology developed in the EU funded Siderwin project developed a small scale pilot plant (Cassauwers 2023). In the next stage, ArcelorMittal and its technology partner aim to build a medium scale pilot plant by 2027 (40–80 kt), and increase its capacity to between 300 kt and 1 Mt by 2030 (TRL 7), aiming to to reach commercial readiness of the process (TRL 9) by 2040.

Commercial readiness in light of upcoming investment cycles

Another key aspect of the global steel transformation will be the need to reconcile the market readiness of breakthrough technologies with the reinvestment cycles of the global blast furnace fleet. By 2030, more than 70% of existing blast furnaces will reach the end of their campaign life and require relining reinvestments to extend their operating life, which would lock in high emissions for over a decade and risk creating stranded assets. However, this upcoming reinvestment cycle also represents a key window of opportunity to substitute blast furnaces with a low-carbon technology steelmaking process. This is an important consideration when analysing the potential of various breakthrough technologies for the global steel transformation. For example, although MOE and AEL combine potentially competitive production costs with very high CO_2 emission reductions (see Section 2.4), the technology is only expected to reach market readiness by the end of the next decade and into the 2040s. By that point, more than 90% of the current blast furnace fleet will have already

Comparing the TRL of breakthrough technologies and blast furnace reinvestment cycles — Figure 2



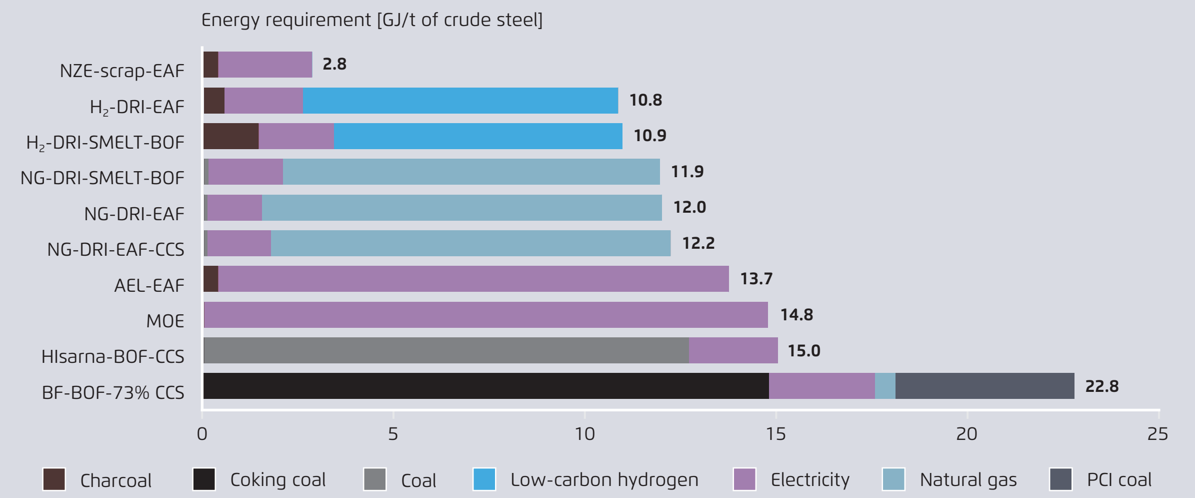
Agora Industry and Wuppertal Institute (2024). Note: [1] DRI plants running on natural gas can already blend high shares of H_2. Commerical DRI plants running on 100% H_2 are expected by 2025. [2] It is currently not clear what the TRL of the technology is and whether it is actively being developed further.

reached the end of their current campaign life (see Figure 2). In spite of their promising techno-economic parameters, this raises questions about the extent to which electrolysis technologies such as AEL and MOE will play a role in the rapid transformation of the steel sector. This is also true of the HIsarna-BOF with CCS technology, depending on when and if it will reach market readiness. Conversely, the opposite applies to DRI-based steelmaking routes: based on our analysis, this is the only suite of technologies capable of producing low-CO_2 primary steel that is expected to be available before 2030. DRI technologies will thus play a very important role in kickstarting the global steel transformation and replacing blast furnaces that reach the end of their campaign life from now on. Given the uncertainty over the exact timeframe when other breakthrough technologies will become available, this is a key argument in favour of DRI-based steel production routes. Our analysis of the deployment rate needed for low-carbon technologies to reliably replace blast furnaces reaching the end of their campaign life shows that even if they cannot realistically be scaled up fast enough to replace 1 000 Mt of blast furnace capacity by 2030, the fact that blast furnace relinings have shorter average lifetimes and blast furnace operators have several options for shorter retrofit measures, the vast majority of blast furnaces (90%) could technically be phased out by 2040 without a premature shutdown (Agora Industry and Wuppertal Institute, 2023).

2.2 Energy requirements

The energy requirements for the different steelmaking routes vary widely. Coal-based steel production routes such as the conventional BF-BOF process and the CCS routes have the highest final energy consumption: conventional steelmaking in the BF-BOF process requires approximately 20 gigajoule (GJ) per tonne (GJ/t) of crude steel, mainly coming from the use of coking coal. 15 GJ are needed to produce the coke which acts as a reducing agent in the blast furnace. Pulverised coal injected from the bottom of the blast furnace accounts for another 5 GJ as well as minor shares of natural gas to produce hot air account for another 5 GJ. The off-gases produced by the steel plant are recovered and used for on-site purposes. In addition, any excess off-gases are combusted in a dedicated power plant to generate on-site heat and electricity. Retrofitting the BF-BOF route with post-combustion CCS would increase the specific energy requirement to 22.8 GJ/t of crude steel, due to the additional energy (in the form of electricity) required for CO_2 capturing and

Final energy consumption of different steel production routes — Figure 3



Agora Industry and Wuppertal Institute (2024) compression. Assuming that the reference BF-BOF configuration generates exactly the same amount of electricity via the combustion of off-gases in the on-site powerplant as is consumed within the entire plant (see methodology section for more information), this means that additional electricity would have to be purchased when retrofitting with CCS.

With an energy demand of 15 GJ/t of crude steel, the HIsarna-BOF with CCS route ranks in the middle of the technologies. Since the agglomeration steps of sintering and coking are eliminated on this route, conversion losses are reduced and less energy is required than on the BF-BOF route. In addition, only a small amount of electricity is needed for CO_2 capturing, since the CO_2 is already highly concentrated in the exhaust gas of the HIsarna reactor and cryogenic separation can therefore be used instead of the more energy intensive amine-based CO_2 absorption.

The high- and low-temperature iron electrolysis routes require less energy than the coal-based steelmaking routes. In both cases, the energy demand is almost exclusively due to the electricity needed for the electrolysis of iron ore – up to 15 GJ/t of crude steel for the MOE route and 13 GJ/t of crude steel for the AEL-EAF route.

In terms of final energy consumption, the DRI routes are the most energy-efficient primary steelmaking options. The DRI-EAF and the DRI-SMELT-BOF route both require around 12 GJ/t of crude steel when the reduction process is based on 100% natural gas. We estimate that the total final energy consumption will decrease on both routes as the proportion of hydrogen in the reduction gas increases because the reaction kinetics achieved with H_2 are faster than with carbon monoxide (CO). When using a 100% hydrogen feed, the energy demand in the form of hydrogen is about 7.6 GJ/t of crude steel for the H_2-DRI-SMELT-BOF route and 8.3 GJ/t of crude steel for the H_2-DRI-EAF route. The steelmaking step in the EAF or SMELT-BOF requires some additional carbon as the DRI has a very low carbon content, close to 0% if the DRI reducing gas is pure hydrogen. Since steel is an alloy of iron and carbon, small amounts of carbon need to be added during the steelmaking process. Carbon also plays an important role as a slag foaming agent to remove impurities during the steelmaking process. This is particularly important in the smelter, since the BOF requires a carbon content of about 4% in the liquid hot metal to operate efficiently. By blowing oxygen into the BOF to remove impurities, the carbon content is then further reduced to below 0.5%, which is the level required

→ Comparing DRI routes with direct electrolysis of iron ore technologies

When run on 100% renewable hydrogen or electricity respectively, DRI-based routes and direct electrolysis technologies like MOE and AEL allow steel to be produced with close to zero CO_2 emissions. A major difference between hydrogen-DRI and direct electrolysis technologies is that electrolysis technologies are not expected to reach industrial-scale development before 2035 at the earliest. DRI routes can thus play a major role in decarbonising the global steel sector by taking advantage of the window of opportunity provided by blast furnace reinvestment requirements. The low TRL of direct electrification technologies means that it is still unclear what future role they could play – a number of key factors will determine whether iron ore electrolysis routes can become competitive options in the transformation of the steel sector.

Since both electrolysis technologies are still in the pilot phase, the energy demand of the overall steelmaking process on an industrial scale is uncertain. Early-stage analysis indicates that AEL and MOE routes will require between 3.7–4.1 MWh/tCS of electricity. Even though direct electrolysis routes do not suffer from the conversion losses inherent to the production of hydrogen, their energy demand is similar to that of hydrogen based DRI routes. Comparing the two electrolysis pathways that are currently being developed, the AEL electrowinning process is slightly more energy efficient than MOE, as it operates at much lower temperatures.

Flexibility and renewable energy system integration

Depending on how the H_2-DRI-EAF or H_2-DRI-SMELT-BOF routes are configured, both have the potential to provide significant demand-side flexibility in a future energy system that relies on renewable electricity. This is because both the energy feedstock, hydrogen, and the intermediary output, DRI/hot briquette iron (HBI), can be stored. Consequently, hydrogen production via electrolysers and usage in the DRI furnace could adapt to and take advantage of variable electricity prices. Additionally, the steelmaking process in the EAF does not run continuously but has a relatively short tap-to-tap time of less than 60 minutes (Toulouevski and Zinurov 2010), providing steelmakers with some additional flexibility in adapting production times to avoid windows of high energy demand. However, the use of hydrogen also increases the infrastructure and investment requirements of the hydrogen-based steelmaking routes. This includes the electrolysers themselves, as well as assets related to the transport, conversion and storage of hydrogen. Locating green iron production in regions with high renewable electricity potential significantly reduces the hydrogen infrastructure requirements, as described by Agora Industry and Wuppertal Institute (2023). This is in stark contrast to the MOE ironmaking process, which requires a large and constant electricity supply to maintain the high process temperature and avoid solidification of the molten oxide. Since liquid metal, the intermediary product, cannot be readily stored, this is also likely to reduce the flexibility of subsequent production steps. The electrowinning AEL process would probably offer more flexibility and demand-side response potential since it does not need to run continuously due to the lower temperature of the process (SIDERWIN 2023) and because the solid iron plates can be stored, allowing for potentially better timing of subsequent EAF usage.

Feedstock requirements

Both iron ore electrolysis technologies offer the potential to use low-grade iron ore feedstocks. This is a major advantage compared to the DRI-EAF route, which requires high-quality DR-grade pellets. Though there is a lack of detailed information and data regarding the real-life operation of the technology, its developers claim that MOE can process a wide range of ferrous materials, including low-grade iron ore fines (Boston Metal 2023). The AEL process is also expected to be more flexible regarding its feedstock. In general, AEL includes pre-treatment (leaching) of the fine-grinded iron ore to reduce the gangue. Furthermore, AEL might be able to process various ferrous materials, including waste materials such as "red mud", a bauxite residue from aluminium production with an iron content of approximately 50%, or secondary ferrous material for recycling (Koutsoupa et al. 2021; SIDERWIN 2023).

Process modularity

Though it is not yet clear what the entire MOE iron and steelmaking process will comprise, it is expected to offer a simplified process chain compared to competing technologies because it would not require any prior treatment of the iron ore feedstock and would involve a simplified downstream steelmaking process. The AEL process would require some additional processes in its production chain, including fine grinding and leaching of the iron ore feedstock, as well as a system for leach reprocessing and waste management, and would have to be coupled with an EAF for steelmaking. Both MOE and AEL are modular installations consisting of stacked cells which can be progressively scaled up, providing different advantages and business cases compared to the multi-million tonne production scale of existing primary steel plants and many H_2-DRI projects. This smaller scale offers a lower entry barrier and additional flexibility in terms of investment and infrastructure build-out for steelmakers, allowing them to initially deploy smaller capacities that can be gradually scaled up. This could translate into a possible business case for smaller (regional) markets or for the production of smaller volumes of specialised primary steels.

in most types of steel. For the H_2-DRI routes to emit close to zero fossil CO_2 emissions, the respective carbon input would need to be provided by biomass, for example in the form of charcoal. In that case, the H_2-DRI-SMELT-BOF route would require 1.4 GJ charcoal per tonne of crude steel in the smelter, while the H_2-DRI-EAF route would need 0.5 GJ of carbon input per tonne of crude steel in the EAF. The EAF process itself has a much lower final energy demand, consuming around 2.5 GJ (680 kilowatt hours) of electricity per tonne of steel if fully electrified.

However, to accurately compare the energy demand of the different production routes, the energy necessary to produce the hydrogen required on the DRI routes also needs to be factored in. If the processes run on a reducing gas feed consisting of 100% renewable hydrogen produced by electrolysis, this would result in a total electricity consumption of 13.8 GJ/t (3.8 MWh/t) for the H_2-DRI-EAF route and 12.8 GJ/t (3.6 MWh/t) for the H_2-DRI-SMELT-BOF route. This would put the H_2-DRI routes in a comparable range to the direct electrification processes via iron electrolysis, which are estimated to require around 13.3 GJ/t (3.7 MWh/t) to 14.8 GJ/t (4.1 MWh/t) of low-CO_2 electricity for the AEL and MOE processes respectively.

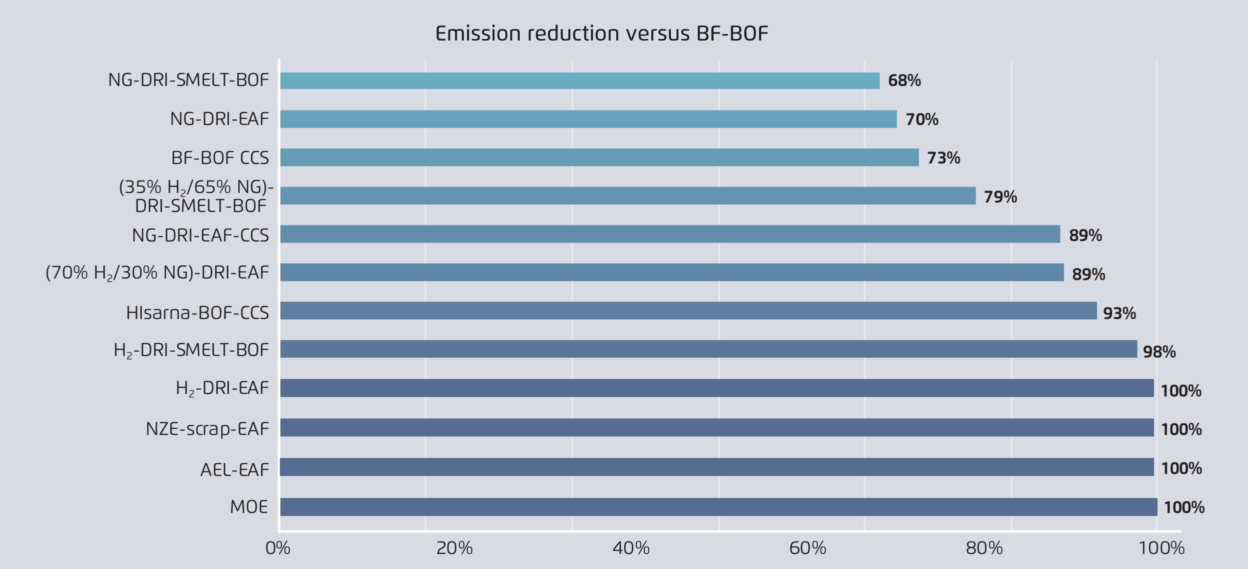
As can be seen in Figure 3, the scrap-EAF route requires significantly less energy than all other routes because it is a secondary steelmaking route in which only scrap needs to be melted and no reduction of iron ore or other agglomeration steps are required. Approximately 2.5 GJ of electricity per tonne of crude steel is needed in the EAF to melt the scrap. Only minor additional amounts of energy (0.4 GJ/t of crude steel) in the form of coal or natural gas are needed to create a foamed slag, which protects the refractory lining of the EAF and increases its service life. Today this results in direct emissions of 0.06 tCO_2/t of crude steel, while the larger share of emissions are currently indirect emissions which depend on the CO_2 intensity of electricity. As the electricity grid is gradually decarbonised, these indirect emissions will also be reduced. In the future, switching to biogenic sources to provide the necessary carbon input for the EAF may allow direct fossil CO_2 emissions to be reduced to an absolute minimum (0.01 tCO_2/t of crude steel) – this is referred to as the NZE-scrap-EAF route in our analysis.

In summary, the specific final energy demand per tonne of steel varies greatly depending on the primary route and ranges from around 11 to 23 GJ/t of crude steel. While the energy carriers are very different from route to route, it is clear from an energy intensity perspective that the BF-BOF route performs significantly worse than the breakthrough technologies, which can reduce the energy requirement by up to half in some cases. Interestingly, both the fully hydrogen-based DRI routes and the direct electrification routes for iron electrolysis have a comparable energy requirement. Moreover, this analysis also clearly shows the advantages of the secondary route in terms of energy efficiency. The more the share of secondary steel can be increased in the future as more and more steel scrap becomes available, the lower the overall final energy consumption of the steel sector will be.

2.3 CO_2 abatement potential and residual emissions

Of the breakthrough technologies analysed in this study, all routes offer a significant reduction potential in CO_2 emissions compared to the reference BF-BOF route (1.87 tCO_2/t of crude steel). Five production routes even have the potential to almost completely eliminate the CO_2 emissions from steelmaking. In the case of primary steelmaking, these are the DRI-based routes (DRI-EAF and DRI-SMELT-BOF) operated with 100% renewable hydrogen, and the electricity-based steelmaking technologies alkaline iron electrolysis (AEL) and molten oxide electrolysis (MOE). On these routes, the iron ore is no longer reduced by carbon; instead, the reduction process can use hydrogen thermochemically or electricity via electrochemical processes. The minimal residual emissions generated by these routes, corresponding to 1–2% of the BF-BOF process emissions, result from the graphite electrode consumption in the EAF, the use of limestone as fluxes and from the small amount of carbon needed in the EAF/smelter as a slag foaming agent

CO_2 abatement potential of different breakthrough technologies compared to the blast furnace route (BF-BOF) — Figure 4



Agora Industry and Wuppertal Institute (2024)

and to provide the carbon content required for BOF operation in the case of the DRI-SMELT-BOF route. Due to the early-stage TRL of the direct electrolysis technologies, it is not yet clear what form the entire steelmaking process via the MOE route would take.

Another option to eliminate virtually all emissions from the steelmaking process is to use the electric arc furnace powered with renewable electricity for secondary steelmaking (NZE-scrap-EAF). The secondary route is not a direct equivalent to primary steelmaking, however, since it recycles steel scrap by melting it into crude steel, while the production steps to turn iron ore into iron are omitted. In order to reduce the remaining direct emissions of this process to near zero, the carbon used for slag-foaming purposes in the EAF would need to come from biogenic sources.

Unlike these technologies, carbon capture technologies have been found in our analysis to be unable to reduce emissions to zero since they are not capable of capturing all the emissions of the iron and steelmaking process. The HIsarna-BOF-CCS process could in theory reduce emissions by 93% compared to the integrated BF-BOF since it replaces the blast furnace, coke oven, sinter and pelletising plants with two point sources with a high CO_2 concentration. However, retrofitting the existing BF-BOF plants with post-combustion CCS would only allow around 73% of CO_2 emissions to be captured. This is because only the main emission sources of the plant – coke oven underfiring, blast furnace hot stoves and the onsite power plant – would be equipped with carbon capture technology, as capturing the emissions from all the other point sources of the BF-BOF route, such as sintering and diffuse sources/flares with low CO_2 concentrations in the exhaust gas, would in reality probably prove too costly to be economically viable. The risks associated with these high residual emissions in the BF-BOF-CCS route are further explored in our deep dive in Section 4.

The DRI production routes show significant differences in terms of their CO_2 avoidance potential, achieving reductions ranging from 68% (DRI-SMELT-BOF with 100% natural gas) to 100% (DRI-EAF with 100% H_2), depending on whether natural gas or renewable hydrogen is used in the process. When operated on 100% natural gas, the DRI routes show an emission reduction potential of 68–70%, compared to the BF-BOF route. This emission reduction potential is thus comparable to that achieved by BF-BOF with CCS (73%). Unlike the BF-BOF-CCS route, however, the DRI route offers the potential to integrate rising proportions of renewable hydrogen to gradually replace natural gas and reduce its CO_2 emission intensity. Compared to the BF-BOF-CCS route, which locks in a relatively high residual emissions level with no possibility of further abatement, DRI plants have a clear pathway towards eliminating close to all emissions once they are operated with 100% renewable H_2. It must be noted however that if these decarbonisation pathways are not pursued, DRI plants running on natural gas nevertheless entail their own lock-in risk of continued reliance on fossil infrastructure and providing a continued business case for the production of natural gas. New DRI plants that run on natural gas must therefore have clear decarbonisation roadmaps to ensure that the uptake of H_2 occurs once it becomes available.

The natural gas-based DRI-EAF or DRI-SMELT-BOF route could also be combined with post-combustion CCS, since the DRI emits a stream of relatively highly concentrated CO_2. Based on our analysis, CCS would allow the process to reduce its emissions to 0.2 tCO_2/t of crude steel, which represents an 89% reduction compared to the BF-BOF route[1], but still has considerably higher emissions than 100% H_2-based DRI routes.

Overall, there are seven technologies that allow emissions to be reduced by 90% compared to the current BF-BOF route. Several other technology options could serve as transitionary solutions on the path to a climate-neutral steel sector. These include CCS on DRI-based steelmaking routes when operated with natural gas or a mixture of natural gas and renewable or low-carbon hydrogen.

Residual emissions

Bearing in mind the climate-neutrality target of 2050, a key aspect to consider in the decarbonisation of the steel sector will be the residual emissions of the various breakthrough technologies. After all, if there are technology options that allow residual emissions to be reduced to a minimum or even eliminated altogether, wouldn't these be clearly preferable to technologies with high residual emissions in a 1.5°C-compatible steel decarbonisation pathway?

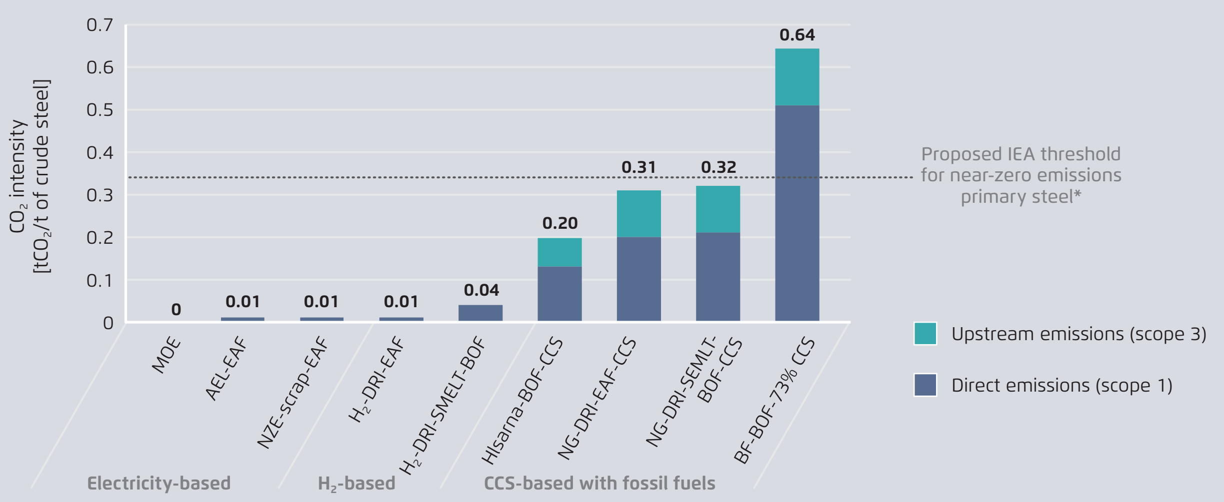
Determining CO_2 emission thresholds that enable a standardised definition of low-CO_2 steel is a key aspect when it comes to accelerating the sector's decarbonisation. The International Energy Agency (IEA) proposed a threshold for near-zero emissions steelmaking (IEA 2022a). For primary steel production with zero scrap use, this threshold is set at 0.4 tCO_2eq/t of crude steel and includes direct emissions from the production process (scope 1) and indirect emissions from electricity used in production (scope 2); for secondary steel from 100% scrap, the threshold is 0.05 tCO_2eq/t of crude steel. If these or similar definitions are to be adopted, as can be expected over the next two to five years given the flurry of activity on setting a green steel label, this will pave the way for two very important demand-side instruments that can drive steel decarbonisation: green lead markets and product carbon requirements. In their most straightforward form, product carbon requirements would allow governments to set minimum requirements for embedded CO_2 in final products, thereby mandating steel companies to sell only steel that was produced below a certain CO_2 emission threshold. As such, this policy route provides an important mid- to long-term alternative or complement to carbon pricing. Given global climate-neutrality targets, it is not unreasonable to assume that only steel produced below the near-zero emissions threshold would be allowed to be sold by 2050.

Based on our technical assessment of breakthrough technologies, eight primary steel production routes would allow direct CO_2 emissions to be reduced below the IEA's near-zero emission steel threshold (see Figure 5). They range from electricity-based and hydrogen-based technologies, which have close to zero residual emissions when using zero-carbon electricity, to routes that combine CCS with natural gas-based DRI or the HIsarna-BOF smelting technology.

1 In our calculations for the NG-DRI-CCS route, 90% CO_2 capture is applied to the DRI stream, but the EAF off-gas is not captured.

Residual CO_2 emissions (scope 1 and 3) of breakthrough technologies and proposed IEA near-zero emission threshold for primary steel

Figure 5



Agora Industry and Wuppertal Institute (2024), based on own analysis and IEA (2022). Note: All primary steel production technologies in this figure have been calculated with a share of 17% scrap. *Due to scrap share adjustment the IEA threshold for near-zero emissions primary steel is around 0.34 tCO_2/t of crude steel. Upstream emissions for CCS technologies are retrieved from IEA (2022) based on 2050 values for *indirect emissions of fossil fuels*. They assume already large cuts of methane emissions relative to today. Indirect emissions (scope 2) are assumed to be zero if only zero-carbon electricity is used.

This is not the case for other primary production technologies: post-combustion CCS on the BF-BOF route leaves relatively high direct emissions of 0.51 tCO_2/t of crude steel, similar to those generated by the current fully natural gas-based DRI production routes (0.55 to 0.59 tCO_2/t of crude steel). With these technologies, the direct CO_2 emissions alone would already exceed the proposed near-zero emission threshold for primary steel of 0.34 tCO_2/t of crude steel (adjusted for 17% scrap content). If the potential indirect emissions generated by these technologies are added, the gap grows even wider. Using offsets to compensate these residual emissions is an inadequate approach if the costs and trade-offs of using negative emissions are taken into account (see Box: Compensating residual emissions in the

→ Compensating residual emissions in the steel sector with CO_2 offsets

The vast majority of scenarios show that limiting global warming to levels compatible with the Paris agreement target to achieve net-zero emissions by 2050 will require negative emissions, for two distinct reasons:

- → to offset the last remaining residual emissions once all GHG mitigation measures have been deployed (e.g. livestock farming, cement and lime production[1]), thereby achieving the “net” in “net zero”;
- → to remove additional CO_2 from the atmosphere, thereby correcting for any overshoot of CO_2 emissions compared to a Paris-compatible CO_2 budget.

1 There are process-based CO_2 emissions inherent to the chemical reaction in manufacturing cement and lime. Even if these are addressed with carbon capture and storage (CCS), they will not be fully abated due to imperfect capture rates.

The amount of negative emissions required depends on the assumptions about the speed and scale of emissions reduction, leading to wide ranges, from 1.9 $GtCO_2$ (IEA 2021b) and 4.5 $GtCO_2$ (IRENA 2022) to between 3.5 and 16.5 $GtCO_2$ per year by 2050 (IPCC 2018). Negative emissions will play an important but limited role in achieving our net-zero targets and can in no way be counted on to substitute emissions reduction measures. This is partly because negative emission technologies entail complex trade-offs from a cost, sustainability and storage permanence perspective.

Nature-based solutions – storing carbon in natural ecosystems via re/afforestation and restoration of degraded ecosystems such as peatlands for instance – can have wide-ranging benefits on climate, biodiversity and nature-restoration goals, and are projected to belong to the cheaper carbon removal options (ETC 2021a). Given the potential co-benefits with regards to other sustainability objectives, nature-based solutions have a crucial role to play. However, the long-term storage potential of nature-based solutions can be at risk due to adverse events such as wildfires, droughts, pests and diseases. These risks are impacted by changing land management practices and will be exacerbated by climate change, leading to uncertainties regarding the permanence of carbon sequestration achieved by these measures (Anderegg et al. 2020).

Apart from nature-based solutions, several technological solutions for negative emissions, involving the capture and permanent underground storage of CO_2, are being considered. Technologies to directly capture CO_2 from the atmosphere (direct air CCS or DACCS) are currently being trialled. However, filtering CO_2 out of the ambient air, which has a very low concentration of CO_2, is an extremely energy intensive and thus costly process. Another negative emissions technology involves using biomass for energetic purposes and capturing and storing the resulting CO_2 emissions, called bioenergy carbon capture and storage (BECCS). These could in certain cases be considered negative emissions, since the CO_2 in question is atmospheric carbon that was absorbed by the biomass during its growth phase. In reality, these emissions can only be viewed as truly negative emissions under a very stringent set of conditions that take into account the true CO_2 footprint of biomass, including the GHG emissions along the value chain of biomass production, as well as the carbon opportunity costs and indirect land use change impacts. Due to the considerable uncertainties regarding the total sustainable biomass supply, the extent to which BECCS solutions can be deployed is not clear. Furthermore, the use of sustainable biomass will compete with several use cases; as a general rule of thumb, direct material uses of biomass should be prioritised over direct-to-energy uses of biomass, the integration of BECCS into a biomass usage cascade being an additional important principle (see Agora Industry 2023a).

It is clear that there are important trade-offs between different options that can generate negative emissions and that they will remain a limited option in the future. As such, negative emissions should be prioritised wherever they can generate the greatest benefits for climate mitigation. Using them merely to compensate the residual emissions of CO_2-intensive processes that have alternative decarbonisation options, as is the case in the steel sector, should be discouraged, since this entails high opportunity costs by comparison with applications that would have generated net-negative emissions. In a world that will find itself scrambling to achieve sufficient negative emissions in order to limit the worst effects of an escalating climate crisis, it is hard to imagine that there will still be room for technologies that run contrary to this effort by 2050.

steel sector with CO_2 offsets). It is therefore highly questionable whether those technologies with comparatively high residual emissions should still be in operation by 2050.

2.4 Production and CO_2 abatement costs

In the absence of policy instruments such as carbon pricing or subsidies, the breakthrough technologies will be significantly more expensive than conventional steelmaking via the coal-based BF-BOF route. This has key implications for the medium term until 2030 and the long term until 2050.

Production and CO_2 abatement costs by 2030

Near-zero CO_2 primary steelmaking routes using hydrogen with DRI-based technologies – DRI-EAF and DRI-SMELT-BOF – will reach market readiness before 2030[2]. In the absence of a CO_2 price, these technologies will still be considerably more expensive than the BF-BOF routes by 2030, with a 54–74% cost premium on the basis of our assumptions.

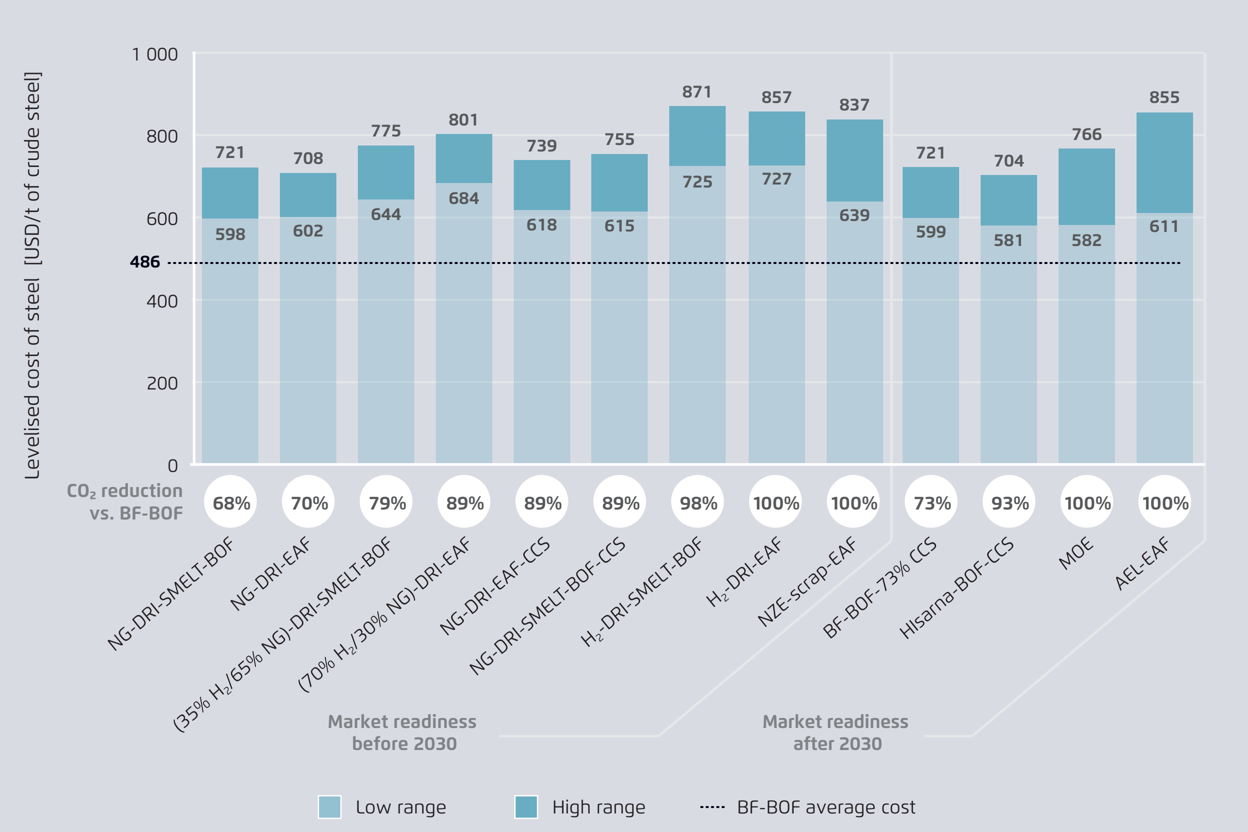
Complementing primary steel production, a growing supply of steel scrap will allow for a significant expansion of scrap-based EAF production. This is an established, mature technology whose costs vary greatly according to the electricity and scrap prices, which in turn depend on the steel quality required for end-use applications. Based on our assumptions, the costs of NZE-scrap-EAF steel production would be 35–68% higher than the BF-BOF route. Producing scrap-based EAF steel that can serve the same markets and substitute hydrogen-based primary steel will thus entail a similar cost premium. In this case, the higher costs are largely due to the need for high-purity steel scrap, as well as the use of biogenic carbon as a source of carbon for slag-foaming purposes in the EAF. For the bulk of ordinary scrap-based steel production that is used for infrastructure and has lower quality requirements, scrap-based steel production in EAFs is expected to be significantly cheaper than the USD 639–837/t of crude steel calculated here.

Apart from these options that would eliminate close to all CO_2 emissions from the steelmaking process, the DRI routes can also run on natural gas, as is already the case today, or on a mixture of hydrogen and natural gas. This is an important option when it comes to ramping up DRI technologies by 2030, since DRI plants can already be operated even if a supply of low-carbon hydrogen or a connection to a hydrogen infrastructure are not available from the outset. Even without access to renewable hydrogen, operating DRI plants with 100% natural gas can reduce emissions by around 70% compared to the BF-BOF route. By 2030, our analysis indicates that DRI-based processes running on natural gas will still be likely to have lower costs than the breakthrough technologies that can reduce CO_2 emissions close to zero[3]. Due to the flexibility of DRI plants and the need to ramp up renewable hydrogen supply and infrastructure, a large number of DRI plants can be expected to be operating with varying mixtures of natural gas and low-carbon hydrogen by 2030. This is illustrated in our analysis by the (70% H_2 / 30% NG)-DRI-EAF and the (35% H_2 / 65% NG)-DRI-SMELT-BOF cases. As is to be expected, the costs of using these input combinations give rise to steelmaking costs that lie between those entailed by fully natural gas-based and fully hydrogen-based DRI routes. The flexibility of DRI plants is an important factor given that our input cost assumptions suggest that 100% H_2-based routes will probably still be among the most expensive technologies in 2030. It is worth highlighting that the hydrogen-based production routes are particularly sensitive to the cost assumption for low-CO_2 hydrogen, since this is the main driver of the range of levelised production costs shown in Figure 6. The hydrogen input costs used in this analysis represent a

2 Natural gas-based DRI combined with CCS could also achieve low CO_2 emissions under certain stringent conditions (very high capture rates, low upstream emissions and permanent CO_2 storage).

3 This analysis is based on an average range of natural gas costs. Some countries with abundant natural gas resources will have particularly cheap running costs, while other regions relying on LGN imports will face structurally higher prices.

Production costs of selected steel production routes in 2030 Figure 6



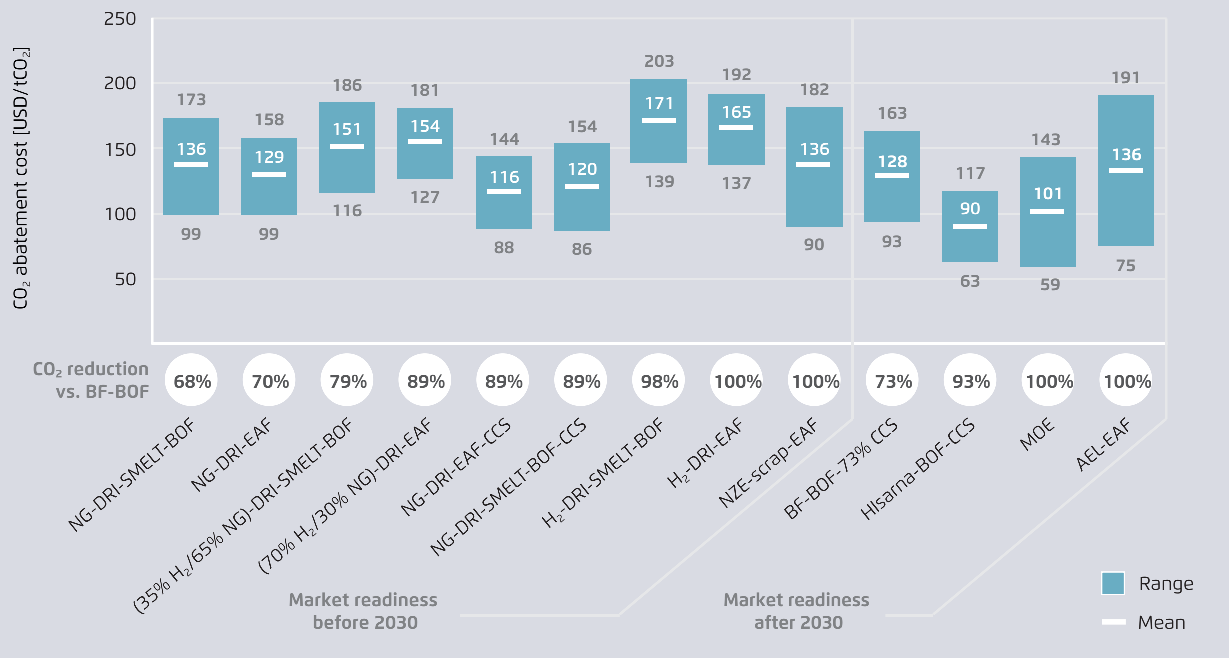
Agora Industry and Wuppertal Institute (2024). Note: Agora and Wuppertal Institute's cost assumptions are based on a literature review and a *middle-of-the-road* approach, in which the lowest and the highest costs are excluded from the cost range. Input assumptions for 2030 are: USD 50–80/MWh for delivered zero-carbon electricity; USD 2–3/kg of delivered low-carbon H_2; USD 13–31/MWh natural gas; USD 30–60/tCO_2 for CO_2 transport and storage excluding CO_2 capture for CCS-based technologies; no carbon pricing is included in the costs.

global average "middle-of-the-road" range, including areas that will have particularly favourable low-CO_2 hydrogen production conditions. Section 5 of this report provides an overview of the input assumptions and how these global average prices were derived.

Our analysis of production costs also shows the potential – from a cost perspective – of both MOE and AEL once they reach sufficient technological readiness. By combining very high CO_2 reductions (>90%) with lower costs than purely H_2-based technologies, they can be potential game changers for the global steel transformation. However, since these projects are still at an early stage in their development, it is important to note that there is considerable uncertainty associated with the actual capital investments required to deploy these technologies, and with the total operating costs (based on energy demand) required to run these processes at industrial scale. Our analysis includes a wide range of capital expenditures (Capex) costs for both MOE and AEL that reflects this uncertainty. As described in Section 2.1, we do not expect iron ore electrolysis technologies, based on current project developments, to become available at the necessary scale before 2030. The retrofit of CCS to BF-BOF steelmaking, with high capture rates, is also not expected to be a technology that can be deployed before 2030.

By comparing the levelised production costs and the CO_2 emission reduction potential of each new technology with the BF-BOF route, the CO_2 abatement costs of each technology can be calculated. This provides an indication of the CO_2 price that would be necessary to make new technologies competitive with the current CO_2-intensive process.

CO_2 abatement costs of selected technologies versus the BF-BOF route in 2030 — Figure 7



Agora Industry and Wuppertal Institute (2024). Note: Agora and Wuppertal Institute's cost assumptions are based on a literature review and a *middle-of-the-road* approach, in which the lowest and the highest costs are excluded from the cost range. Input assumptions for 2030 are: USD 50–80/MWh for delivered zero-carbon electricity; USD 2–3/kg of delivered low-carbon H_2; USD 13–31/MWh natural gas; USD 30–60/tCO_2 for CO_2 transport and storage excluding CO_2 capture for CCS-based technologies; no carbon pricing is included in the costs.

While the future cost of technologies is uncertain, our analysis indicates that, by 2030, the average CO_2 abatement costs of all breakthrough technologies expected to be commercially available will be well above USD 100/tCO_2. They range from USD 116/tCO_2 (NG-DRI-EAF-CCS) to USD 171/tCO_2 (100% H_2-DRI-SMELT-BOF). This means that a CO_2 price of USD 100/tCO_2, in isolation, would likely not be enough to make these technologies competitive with the current BF-BOF route, even though this is a price level some countries are expected to achieve by 2030 from today's point of view. This points to the need for a broader policy package, including supply side policies that can enable a low-CO_2 energy and hydrogen infrastructure rollout and provide Capex/Opex support for the green steel production process, such as carbon contracts for difference, combined with demand side instruments that can unlock private sector demand as well as green public procurement via definitions and standards for near-zero emissions steel, thereby enabling a business case for these new technologies in the short to medium term.

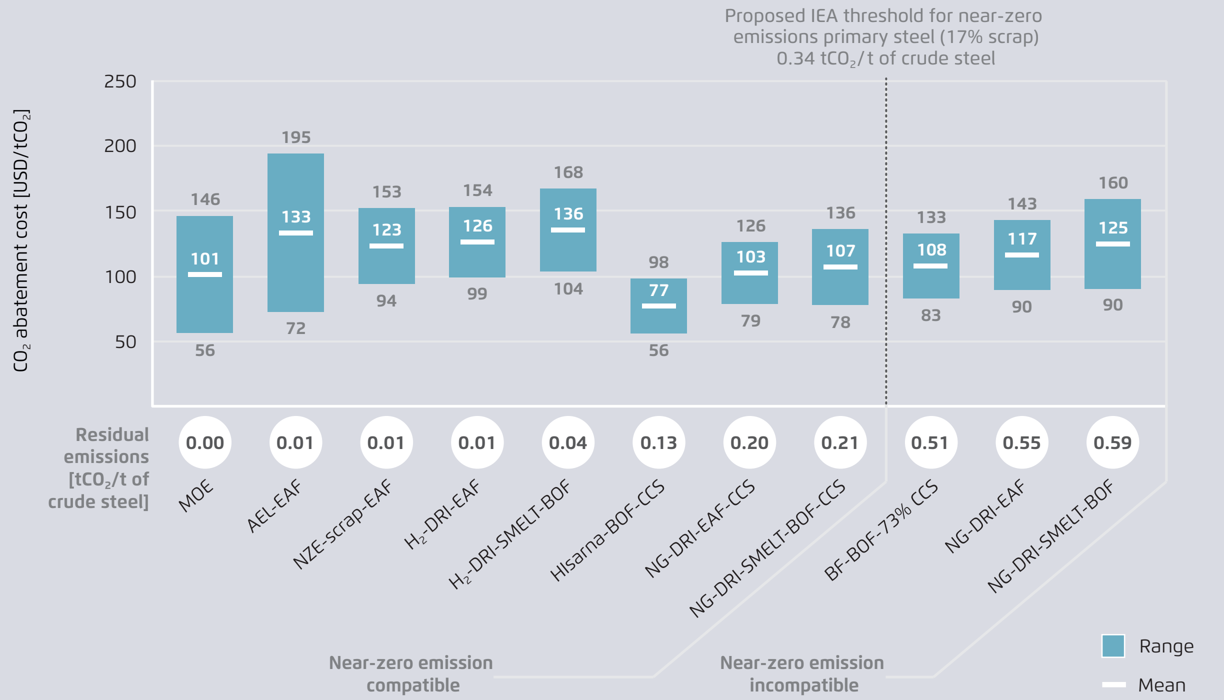
CO_2 abatement costs by 2050

Based on our cost assumptions, the average CO_2 abatement costs of hydrogen-based breakthrough technologies relative to the BF-BOF route will be significantly lower by 2050 than in 2030, mainly thanks to a decrease in low-CO_2 hydrogen costs between 2030 and 2050. The average CO_2 abatement costs in 2050 range from USD 77/tCO_2 (HIsarna-BOF-CCS) to USD 136/tCO_2 (100% H_2-DRI-SMELT-BOF) (see Figure 8); in other words, a CO_2 price above USD 136/tCO_2 in 2050 would make all breakthrough technologies more competitive than the current BF-BOF route, based on the average costs in our analysis.

To put this into perspective, it is worth comparing this to the CO_2 prices that are assumed in 1.5°C-compatible scenarios by 2050. For example, the IEA *Net Zero Emissions by 2050 Scenario* uses a CO_2 price of USD 250/tCO_2 for advanced economies, USD 200/tCO_2 for selected emerging market and developing economies with net-zero emissions pledges (including China, India, Indonesia, Brazil and South Africa) and USD 180/tCO_2 in other emerging markets and developing economies in its model (IEA 2023b). In a world that adopts the necessary measures to reach climate neutrality, a carbon price driven phase-out of unabated coal-based blast furnaces would thus be possible well before 2050.

A second important aspect is that the global iron and steelmaking landscape in 2050 will most likely look significantly different from today's. Our analysis considers relatively wide ranges of average global production costs in order to encompass region-specific cost factors that will impact production and abatement costs. Especially when it comes to electricity-based processes, the difference between the lower end and the average CO_2 abatement costs shows that regions with cheap and abundant renewables have significant potential to produce low-CO_2 steel competitively. At a delivered lower range electricity price of USD 50/MWh, for example, the CO_2 abatement costs of the iron ore electrolysis technologies MOE and AEL would be among the lowest of all the technologies we analysed. Assuming that these iron ore electrolysis technologies reach a sufficient maturity level by 2050, we would on the basis of these costs expect some steel production from MOE- or AEL-based technologies to be located in places with cheap and abundant renewables. Similarly, when looking at the lower range of H_2-DRI-based steelmaking routes (based on USD 1/kg of delivered renewable hydrogen), the CO_2 abatement cost versus the BF-BOF route is only USD 100/tCO_2, which is similar to the prices we are already seeing in the EU ETS market today. In that sense, H_2-DRI technologies will be highly competitive in locations with access to very cheap hydrogen and renewable electricity. The difference to MOE and AEL electrolysis technologies

CO_2 abatement costs of key technologies versus the BF-BOF route in 2050 — Figure 8



Agora Industry and Wuppertal Institute (2024). Note: Agora and Wuppertal Institute's cost assumptions are based on a literature review and a *middle-of-the-road* approach, in which the lowest and the highest costs are excluded from the cost range. Input assumptions for 2050 are: USD 50–80/MWh for delivered zero-carbon electricity; USD 1–2/kg of delivered low-carbon H_2; 9–25/MWh natural gas; USD 20–30/tCO_2 for CO_2 transport and storage excluding CO_2 capture for CCS-based technologies; no carbon pricing is included in the costs. All primary technologies use a share of 17% scrap. The IEA's proposed near-zero emission threshold of 0.34 tCO_2/t of crude steel is adjusted to a 17% scrap input.

is that H_2-DRI is already commercially available at scale this decade, and can thus take advantage of the vast differences in renewable electricity and hydrogen prices around the world.

Phasing out steel production routes with high residual emissions and minimising the risk of stranded assets will require a set of measures, including an appropriate regulatory framework to build up capacities compatible with near-zero emissions and the associated infrastructure. The emergence of technologies relying on renewable hydrogen and electricity could reshape the current steelmaking landscape. Countries with the potential for cheap renewable electricity and low-CO_2 hydrogen, as well as access to iron ore, will have structural cost advantages when it comes to producing and exporting green iron. At the same time, for steelmakers with higher renewable hydrogen costs, importing cheaper green iron to turn into steel could play an important role in safeguarding their competitiveness (see Box: Green iron trade). In order to shift investments towards net-zero-compatible steel production, overcome major obstacles to the transition and lower the costs of the global steel transformation, international coordination and cooperation will be essential – and must already happen this decade. This is especially important in order to avoid the risk of stranded assets given that new coal-based steel mills are in the pipeline in several emerging economies. Agora Industry's recent publication *15 Insights on the Global Steel Transformation* further develops the key arguments in favour of enhanced international cooperation.

Our cost analysis shows that hydrogen-based DRI routes will have a similar CO_2 abatement cost to NG-DRI-based routes by 2050 due to the high level of residual emissions on the natural gas-based route. As discussed in Section 2.3, one considerable advantage of the DRI route is that this technology can

→ Green iron trade

The cost drivers of low-CO_2 steelmaking technologies differ hugely from those of today's BF-BOF route. Since the costs of renewable electricity and low-CO_2 hydrogen production in particular will play such an important role, this implies that countries with structurally higher costs of low-CO_2 hydrogen production could be at a competitive disadvantage, unless they can tap into the world's cheapest H_2 costs. While H_2 imports by pipeline will already be much cheaper than importing H_2 or H_2 carriers by ship (Agora Industry and TU Hamburg 2023), there is an additional option for the steel sector which could allow it to take advantage of some of the world's cheapest H_2 costs. Compared to the current primary steelmaking process via the BF-BOF route, which involves integrated iron- (BF) and steelmaking (BOF) in one location, a move towards increased DRI-EAF or DRI-SMELT-BOF steelmaking would allow the iron- (DRI) and steelmaking (EAF or SMELT-BOF) steps to be decoupled. This is because DRI can be turned into hot briquetted iron (HBI), a bulk commodity that can be readily transported. HBI could be produced in iron ore exporting countries with cheap and abundant renewables such as Australia or Brazil and then used in other countries for steelmaking in EAFs or the smelter-BOF. Co-locating iron production with renewable H_2 production would have structural cost advantages compared to transporting H_2 or H_2 carriers by ship because it avoids the inherent conversion losses associated with shipping H_2 and considerably decreases the need for additional H_2-related infrastructure. Since the transport costs of HBI are roughly similar to those of iron ore, the cost of shipping HBI would in effect replace the cost of shipping iron ore if the iron ore were turned into HBI before export. The first international bilateral announcements of industrial partnerships to establish these new supply chains are emerging and gathering speed (Agora Industry 2023b). Our study *15 Insights on the Global Steel Transformation* (Agora Industry and Wuppertal Institute 2023) further explores the potential impacts on jobs in the iron and steel value chain for both exporters and importers of green iron.

flexibly take up increasing proportions of hydrogen to displace natural gas. Combining the NG-DRI route with CCS also has the potential to considerably reduce emissions (by up to 89% versus the BF-BOF route, according to our analysis) and incurs lower production and CO_2 abatement costs than the H_2-DRI routes in our analysis. While this configuration may seem attractive solely from a cost perspective, it is important to point out that the emissions scope in our analysis does not include upstream methane emissions from the natural gas supply chain, which can contribute substantially to the overall GHG emissions of steel. In order for NG-DRI CCS technologies to be considered net-zero-compatible routes, upstream emissions would need to be reduced to an absolute minimum, high CO_2 capture rates would be required at the DRI plant and the CO_2 would need to be stored in deep geological formations rather than used for EOR or other applications. Currently, none of these conditions is sufficiently fulfilled, meaning that any deployment of NG-DRI CCS would require strict regulation and careful monitoring to ensure that it is net-zero aligned.

Based on the above analysis of commercial readiness, energy demand, CO_2 abatement potential and cost, DRI-based steelmaking, especially in combination with hydrogen, will be one of the main levers used to decarbonise the global steel sector. Our technological analysis includes two different configurations in which a DRI plant can be used for steelmaking: DRI-EAF and DRI-SMEL-BOF. Both routes entail various benefits, as described in greater detail in the following section. A second deep dive describes the main factors and risks that need to be considered when assessing the role of CCS on the BF-BOF route.

3 Deep dive 1: A technical comparison of the DRI-EAF and DRI-SMELT-BOF routes

According to our analysis, the only near-zero CO_2-emission technologies for primary steelmaking that are expected to reach market readiness before 2030 are the hydrogen-based DRI-EAF and DRI-SMELT-BOF routes. These technologies will therefore be vital in the short term to kickstart the global steel transformation and, combined with hydrogen, will play a very important role in the medium to long term as well. Key aspects of these two technology routes will therefore be compared with each other below.

3.1 Technical advantages and disadvantages of the DRI-EAF route

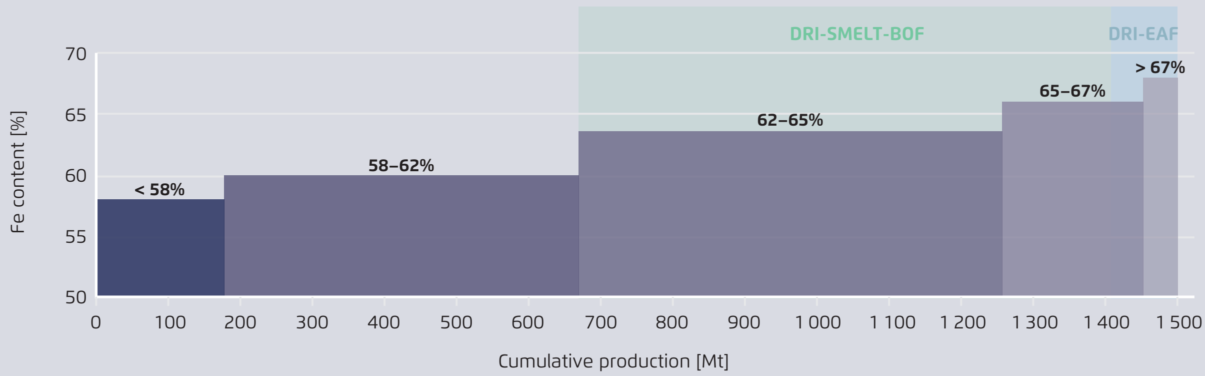
So far, most steelmakers that have announced plans to produce steel via direct reduction processes intend to go with the DRI-EAF route, which involves reducing iron ore to DRI in the direct reduction plant and subsequently turning it into steel in an EAF. The EAF is a combined melting and steelmaking unit and therefore well suited to handling DRI (or its compacted and shippable form HBI) and steel scrap in any ratio, as it already does today, though it is sensitive to the quality of both the DRI and the scrap inputs. This allows for some flexibility in operating the DRI-EAF process according to the availability and cost of input materials and the necessary quality of the steel outputs by adjusting the ratios of scrap and DRI inputs.

In view of the goal of climate neutrality, another important advantage of the EAF is the very low carbon input required relative to the DRI-SMELT-BOF route. It is important to note that some small amounts of carbon are inherently necessary in steelmaking, since steel is an alloy of carbon and iron (combined with other alloying materials). Carbon is additionally needed in the steelmaking process to form foaming slag, which improves the melting process in the EAF. Today's EAF operators that use DRI process carburised DRI – i.e. DRI containing some minimal amount of carbon – that comes from a DRI shaft furnace where natural gas is the reducing agent. From a technical perspective, however, the EAF can also handle an iron or scrap feed containing no carbon at all, which would be the case with DRI made with 100% renewable H_2 as the reducing agent in the DRI shaft furnace. The small quantity of carbon that is then required to form foaming slag and provide the carbon content of steel can be added directly into the EAF, either by injecting minimal amounts of coal or using biogenic carbon such as biochar to reduce the CO_2 emissions to an absolute minimum. Compared to a typical carburised DRI feed from a natural gas-based DRI plant, the power demand for melting CO_2-free DRI in the EAF would be higher but would also allow all CO_2 emissions in the DRI plant to be eliminated by using 100% renewable hydrogen. Given these parameters, the DRI-EAF route could reduce fossil CO_2 emissions to virtually zero (0.01 tCO_2/t of crude steel) while keeping carbon requirements to an absolute minimum.

One major constraint of using an EAF to process DRI is that it requires a higher-quality iron ore than the BF-BOF and the DRI-SMELT-BOF routes to make high-quality primary steel. The iron ore pellets market currently differentiates between BF-grade pellets that contain at least 62% iron (Fe), and DR-grade pellets with a minimum iron content of 66% (MIDREX 2022). This nomenclature is slightly misleading: it is actually the EAF that limits the use of lower-quality pellets in the DRI, since the majority of DRI are currently used in conjunction with EAFs. However, as new DRI-based steelmaking routes bypassing the EAF permit the use of lower-quality (BF-grade) ores, it would be more accurate to distinguish between BOF-grade and EAF-grade pellets. In any case, the availability of such DR/EAF grade pellets with a minimum iron content of 66% is currently very limited, representing only 3 to 4% of the global seaborne iron ore market (Vale in IEEFA 2022). EAFs require DRI feedstock made from high-quality iron ore since the EAF is not well suited to dealing with

Seaborne iron ore freight by grade (status quo)

Figure 9



Agora Industry and Wuppertal Institute (2024), based on MPP (2021)

the high levels of gangue impurities in lower-quality iron ore, which considerably impact its steel production and energy efficiency. Additional DR/EAF-grade iron ore supply can be made available by developing new high-grade iron ore mining projects and building up iron ore beneficiation[4] processes. However, these solutions will need to be urgently explored, as the limited availability of DR/EAF-grade pellets has the potential to pose a major obstacle to the global steel transformation. Insight 13 of the *15 Insights on the Global Steel Transformation* further investigates the iron ore supply forecasts and possible solutions to address this bottleneck issue (Agora Industry and Wuppertal Institute 2023).

3.2 Technical advantages and disadvantages of the DRI-SMELT-BOF route

As an alternative to the DRI-EAF route, the DRI process can be combined with a basic oxygen furnace (BOF). This requires an additional intermediary smelting and carburisation aggregate (hereinafter referred to as a smelter) to allow the metallic iron from the DRI to be processed in the BOF. Such units are available on the market as submerged arc furnaces (SAF) or open slag bath furnaces (OSBF) and use electricity to deliver the smelting energy (Cavaliere et al. 2022).

The key advantage of the DRI-SMELT-BOF route over the DRI-EAF route is that it permits the use of lower-quality ores that cannot be used efficiently on the DRI-EAF route. Unlike an EAF, a smelter is better suited to separating the gangue impurities in the iron, in the form of slag, to a similar extent as occurs in a blast furnace – which in turn also allows the use of the lower iron ore grades that are used in today's blast furnace route. Instead of being limited to ores containing at least 66% iron, the DRI-SMELT-BOF route makes it possible to use BF (or BOF) grade pellets with a minimum iron content of 62%. This seemingly small difference in iron content unlocks more than 50% of the current seaborne iron ore supply for use via the DRI, as opposed to the 3% market share to which the DRI-EAF route is currently confined (see Figure 9).

This difference in iron ore quality is also brought about by the differing chemical conditions inside the EAF and electric smelter on account of their respective designs. Whereas EAFs are not well suited to further reduce iron ore to iron, a reducing atmosphere prevails in the smelter. This is mainly due to the submerged electrodes and the slag surface creating a sealed environment with a low oxygen content within the smelter and to the addition of reducing agents, in the form of carbon, that are blown into the

4 Iron ore beneficiation is the process of enhancing the quality of and removing impurities from mined iron ore. Depending on the mined iron ore and the degree of impurities, this involves several physical or chemical separation steps and can require significant Capex into plants that upgrade low-grade ores to high-quality pellets.

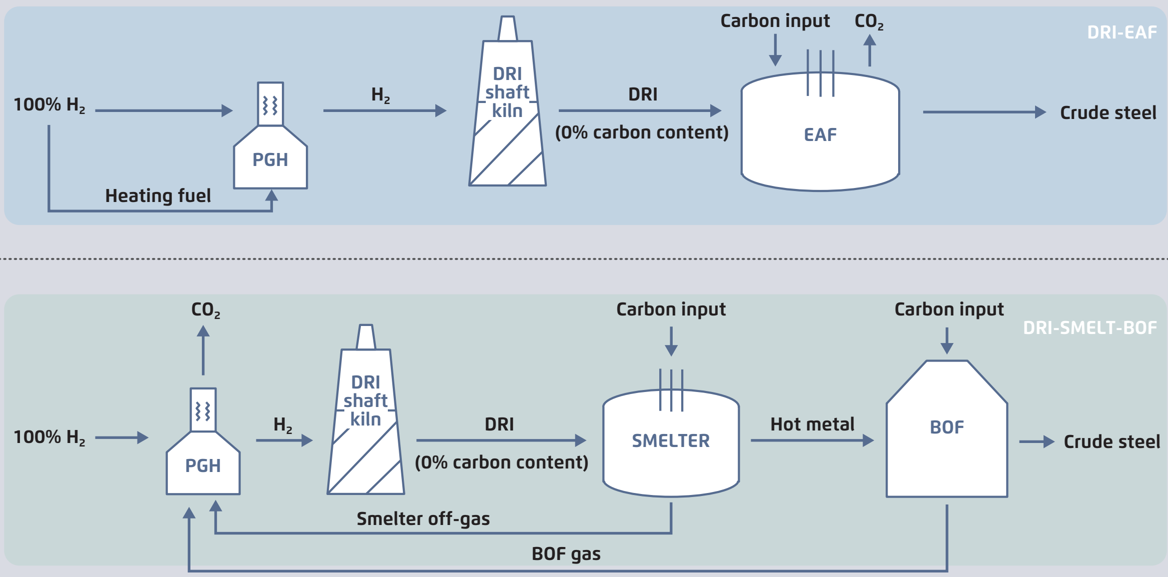
smelting unit. The DRI that is fed into the smelter has a relatively high degree of metallisation but still contains relevant proportions of non-reduced iron oxide; it then undergoes further reduction during smelting with the addition of carbon (coal or charcoal), resulting in a higher metallisation rate compared to the EAF. This has a considerable effect on the overall efficiency of the process, since more iron ore is converted to iron (higher metallisation rates) and less iron is lost to the slag.

Steelmaking via the DRI-SMELT-BOF route has the additional advantage of producing the same steel grades as the BF-BOF route at existing steel sites, thereby leveraging the existing steelmaking assets (the BOF) as well as the downstream refining and processing infrastructure and associated metallurgical know-how that has been developed in BOF steelmaking. The DRI-SMELT-BOF route could therefore be regarded as a partial "drop-in solution" for existing integrated steel sites, where new ironmaking components would be integrated with existing steelmaking and processing assets.

Another advantage worth pointing out is the slag quality produced in the smelter. In the traditional BF-BOF iron and steelmaking process, limestone is added as a so-called fluxing agent to facilitate the removal of impurities via the formation of slag. The resulting blast furnace slag is an important co-product for steelmakers that is sold as a raw material for the cement industry. The slag generated in the smelter is expected to have similar properties to that produced in the blast furnace and could therefore also be used by the cement industry as a clinker substitute.

However, the continued use of a BOF in the future also has the disadvantage of a higher overall carbon requirement than the DRI-EAF route. On the current BF-BOF route, pig iron leaving the blast furnace typically has a carbon content of about 4%. To substitute pig iron from the blast furnace with a similar product from the smelter, the DRI first has to be "carburised" for the BOF to work efficiently. This allows the production of an intermediate product that is very similar to pig iron and can thus be used in the same way in existing BOF installations. Eventually, the

Comparison of H_2-DRI-EAF and H_2-DRI-SMELT-BOF processes — Figure 10



Agora Industry and Wuppertal Institute (2024). Note: Simplified carbon flow in the H_2-DRI-EAF and H_2-DRI-SMELT-BOF routes, assuming the DRI is produced with 100% H_2. PGH = process gas heater major share of this carbon will become carbon dioxide or carbon monoxide during oxygen blowing in the BOF and off-gas from the smelter (see Figure 10). The management of the carbon flows therefore remains an important issue. Without any carbon recycling measures, CO_2 emissions of around 200 kg/t of crude steel occur in the off-gases of the smelter and the BOF, even if the DRI making is completely CO_2-free thanks to the use of 100% hydrogen. Compared to the BF-BOF route with 1.87 tCO_2/t of crude steel, this would allow for a CO_2 reduction of 89%.

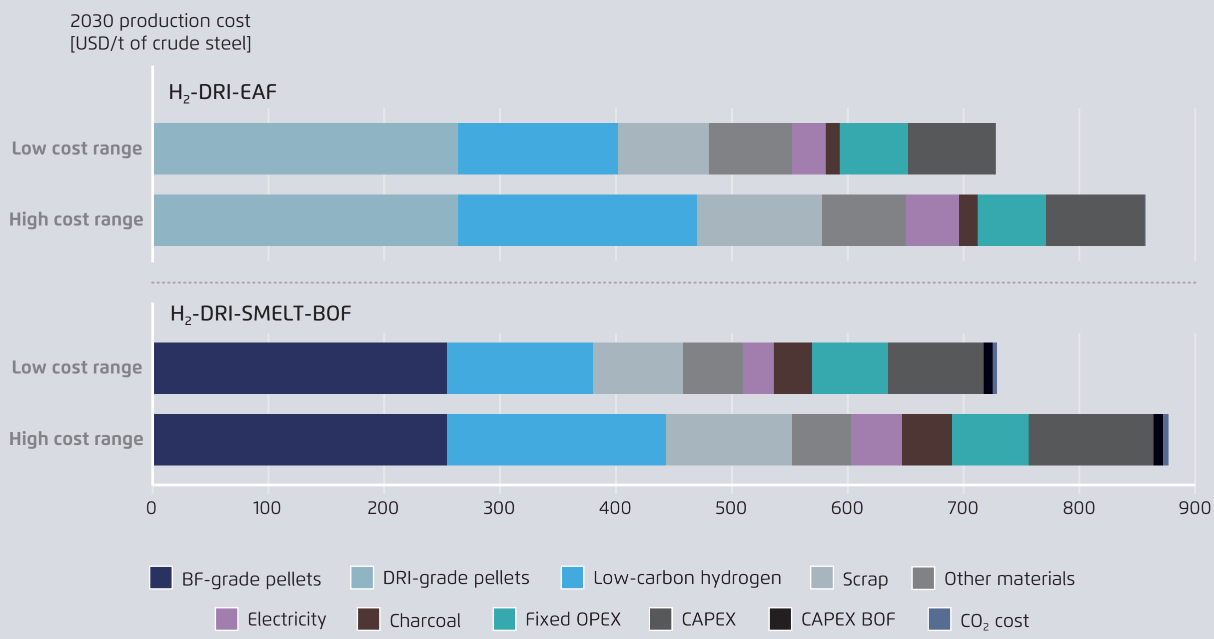
To reduce emissions to an absolute minimum, both the DRI-EAF route and the DRI-SMELT-BOF route will require the use of biogenic carbon to replace the carbon inputs in the DRI or SMELT-BOF. In this scenario, our analysis of the technologies calculates that the residual fossil CO_2 emissions of these routes can be brought down to 40 kg CO_2/t of crude steel in the case of the DRI-SMELT-BOF and 10 kg CO_2/t of crude steel on the DRI-EAF route; this is due to some residual emission sources such as the consumption of graphite electrodes in the EAF. This would correspond to a 98% to 99% reduction in CO_2 intensity versus the BF-BOF route. As these numbers show, both routes do offer the technical potential to eliminate almost all direct CO_2 emissions.

3.3 Comparison of production costs

Based on our analysis of the various cost components, the DRI-EAF and DRI-SMELT-BOF routes have very comparable total production costs, as can be seen in Figure 11 for the lower and higher cost cases for 2030; however, it is worth breaking down the various cost components to understand possible cost drivers.

Both routes require significant Capex investments, mainly for the direct reduction shaft and the electric arc or smelting furnace. While the investment requirements for both routes are in a similar range, the DRI-SMELT-BOF route would likely necessitate a higher capital expenditure, in part due to the

Comparison of hydrogen-based DRI production costs in 2030 — Figure 11



Agora Industry and Wuppertal Institute (2024). Note: Agora and Wuppertal Institute's cost assumptions are based on a literature review and a *middle-of-the-road* approach, in which the lowest and the highest costs are excluded from the cost range. Input assumptions for 2030 are: USD 50–80/MWh for delivered zero-carbon electricity; USD 2–3/kg of delivered low-carbon H_2; USD 412–572/t of scrap; USD 83–108/MWh charcoal; USD 90–130/tCO_2.

additional costs incurred by the BOF plant (based on the maintenance costs of an existing brownfield BOF plant). From an overall cost perspective, this is offset to some extent by the higher hydrogen costs involved in the DRI-EAF route. This is because the BOF off-gas can be used in the DRI-SMELT-BOF route as a heat source for the process gas heater, which preheats the hydrogen to the high temperatures needed for direct reduction. On the DRI-EAF route, we assume that part of the hydrogen will be used as energy directly in the process gas heater, thereby increasing the hydrogen demand of this route.

As can be seen in Figure 11, however, the main cost component on both routes are the iron ore inputs, which account for around one third of the total production costs of both production routes, according to our cost assumptions. As described above, the DRI-EAF route is confined to using DR-grade pellets, while the DRI-SMELT-BOF route is also able to use BF-grade pellets made from lower-grade iron ore feedstocks. Though DR-grade pellets historically trade at a premium to BF-grade pellets, this delta is variable and difficult to predict. At a premium of USD 15/t of pellets, we find that the impact on the total final costs of production is somewhat balanced out by the fact that more BF-grade pellets are needed for the same amount of steel production, due to their lower iron content. While it is highly uncertain how the spread between the two types of pellets will develop in future, as this will depend on many market factors, the DR-pellet premium can be expected to rise as the decarbonisation of the steel sector gathers speed and new DRI plants are built, thereby generating more demand for higher-quality DR-grade pellets, and because the limited availability of high-quality iron ore and the additional costs involved in the beneficiation of lower-quality iron ore impose constraints on supply growth.

Based on our assessment of the total costs of production, in a near zero-CO_2 operation, the impact of the iron ore feedstock is somewhat compensated by the cost of biogenic carbon, in the form of charcoal, that is required by the DRI-SMELT-BOF route to reduce emissions to a minimum. As with the iron ore spread, the cost of biomass feedstock can be very volatile and unpredictable; however, it can also be expected to increase as demand for biogenic carbon grows from a multitude of sectors as they aim to reach net zero. This exposure to the future availability and price fluctuations of charcoal represents a potentially significant cost factor that is less relevant to the DRI-EAF route, since its processes involve lower demand for carbon.

These differences in cost components between the two routes can be expected to have implications for the raw material market and the development of these technologies. For instance, when high demand for DR-grade pellets pushes up the price premium, there may be a business case for more iron ore beneficiation developments or higher-grade iron ore mining projects to fill that supply gap. On the other hand, this could also prompt more steel producers to opt for the DRI-SMELT-BOF rather than the DRI-EAF routes as a safeguard against an ever-increasing pellet premium. The different cost structures could also serve as regional drivers in the deployment of both steelmaking routes. Steel producers with better access to charcoal (e.g. in Brazil) for example might adopt the DRI-SMELT-BOF route with more extensive use of biomass as a reductant (partially replacing hydrogen), which has the potential, when combined with CCS, to generate negative emissions. The potential role of biomass in steelmaking is further discussed in insight 8 of the *15 Insights on the Global Steel Transformation* publication (Agora Industry and Wuppertal Institute 2023).

Besides the production costs and feedstock supply parameters, there are other factors that differentiate the two routes. In the short term, various technological aspects will also play a key role. For instance, steelmakers currently producing specific steel grades via the BOF might see the DRI-SMELT-BOF route as the lower-risk strategy for their product portfolio as it would allow them to utilise their existing downstream facilities and specialised know-how in BOF steelmaking, whereas the potential to manufacture similar steel grades in an EAF may not have been proven yet. On the other hand, the DRI-EAF is already a mature technology for primary steelmaking; its processes are well understood and its operation, with an increasing proportion of hydrogen, is being demonstrated in several projects around the world. The DRI-SMELT-BOF configuration is still novel; while similar types of smelters are already in use in other metal industries, the integration of a smelter into the steelmaking process entails specific design and engineering requirements whose practical viability still need to be demonstrated. In view of this variety of factors, it is likely that both the DRI-EAF and the DRI-SMELT-BOF route will play a very important role in the global steel transformation.

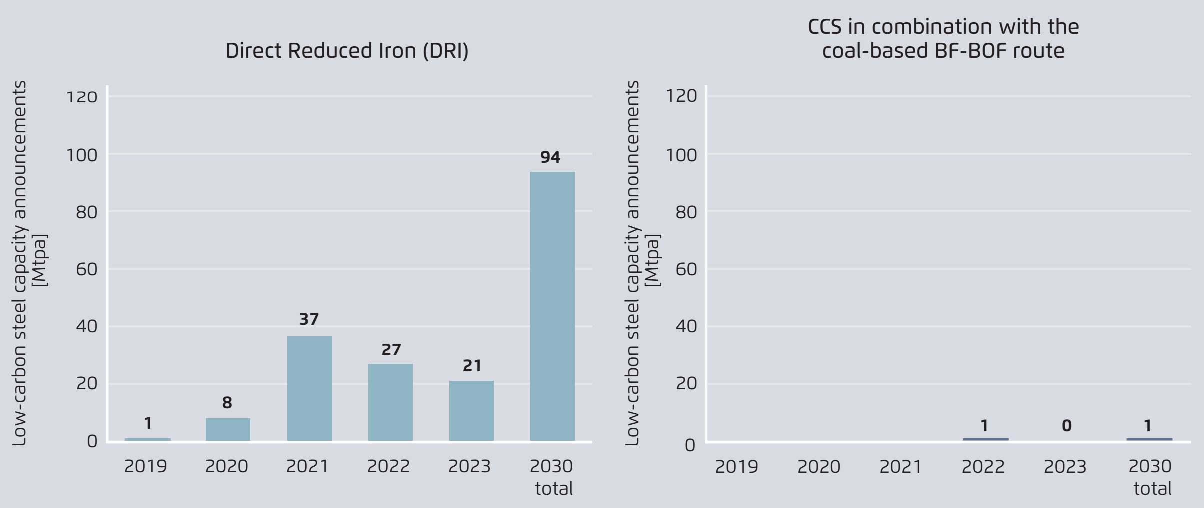
4 Deep dive 2: The role of post-combustion CCS on the BF-BOF route

Post-combustion CCS on the BF-BOF route plays a significant role in many many steel decarbonisation scenarios (E3G and PNNL 2021; IEA 2022b; MPP 2022). In theory, the narrative is quite compelling: once post-combustion CCS becomes available, it will allow existing (and future) highly CO_2-intensive BF-BOF plants to be retrofitted, thereby reducing the CO_2 emissions they release into the atmosphere and providing them with a business case in a (near) net-zero world. The BF-BOF route is currently responsible for roughly 70% of global steel production and more than 95% of the sector's CO_2 emissions, which explains why the promise of CCS is perceived as an extremely important technology option. At the same time, however, CCS on the BF-BOF route entails a unique combination of risks and challenges to overcome – including fundamental questions concerning its CO_2 emission reduction potential – that call into question whether it will actually play an important role in the global steel transformation.

4.1 Current state of play

A thorough understanding of the risks associated with post-combustion CCS on the BF-BOF route is key when it comes to assessing the trend in the project pipeline of breakthrough technologies in the steel sector. To illustrate the speed at which technological development can occur: in 2020, the 100% renewable H_2-based DRI-EAF route and BF-BOF-CCS technology were assigned the same technology readiness level (TRL 5) with an expected commercial readiness by 2030 in the IEA Iron and Steel Roadmap (IEA 2020b). In the last couple of years, however, project announcements and advances in both technologies have developed remarkably differently: to date, the vast majority of steel companies that plan to build low-carbon steelmaking capacity have opted for the DRI route, while there are hardly any BF-BOF-CCS projects being developed by industry.

Where the global steel industry is heading: 2030 pipeline of low-carbon steelmaking announcements — Figure 12



Agora Industry, Global Steel Transformation Tracker (2024). Note: The 2030 project pipeline of DRI plants includes H_2-ready DRI plants that may operate with natural gas initially.

The 2030 project pipeline of new DRI plants (including plants designed to run directly on hydrogen and those opting initially for natural gas, though the latter can be considered H_2-ready) has grown to 94 Mt (Agora Industry 2023b), and the first commercial-scale H_2-ready DRI plant (running on over 60% H_2) was built in China in 2023 (DANIELI 2023). Even announced H_2-DRI projects that plan to use 100% renewable H_2 from the outset already amount to 29 Mt. This is in stark contrast to the pipeline of commercial-scale projects aiming to develop CCS on the BF-BOF by 2030, which currently amounts to just 1 Mt (Figure 12). This very pronounced difference reveals the industry's intentions with regard to actual decarbonisation projects and may reflect the way steel companies view the risks and uncertainties associated with retrofitting CCS on the BF-BOF route in order to decarbonise their production. The following section takes a deeper look at some of the risk factors associated with the BF-BOF-CCS route.

4.2 The BF-BOF-CCS route has high residual emissions and infrastructure needs

Residual emissions of the BF-BOF-CCS route

Many steel decarbonisation scenarios assume that retrofitting the BF-BOF with CCS will eventually allow emissions to be reduced by around 90% (Bataille, Stiebert, and Li 2021; MPP 2022; IEA 2022b). While CO_2 capture systems can in theory capture large amounts of CO_2 (>90%) from specific CO_2 streams, our analysis of all emissions generated at a BF-BOF steel plant raises doubts about the feasibility of achieving a high capture rate for the process as a whole, as there would likely be an upper limit to the total amount of CO_2 captured for technical and economic reasons. This is because an integrated BF-BOF steelworks has several point sources of CO_2 emissions with different CO_2 concentrations in the waste gas streams.

In our assessment of a BF-BOF plant retrofitted with post combustion-CCS, CO_2 is captured at the three main emission sources with relatively high CO_2 concentrations of 15–27% CO_2 in the flue gases (IEAGHG 2013): the coke oven underfiring stack, where coke oven gas and other fuels are combusted to heat the coke ovens; the hot-blast stoves, which preheat the high-temperature air blown into the blast furnace; and the onsite power plant where the cogeneration gases are combusted. Our calculations show that up to 73% of a steel plant's CO_2 emissions can be captured from the resulting waste gas streams (around 1.36 tCO_2/t of crude steel captured), based on a 90% capture efficiency at each of these point sources. In addition, there are several other smaller point sources with low CO_2 concentrations at the steel plant, such as the sinter plant, lime kiln, venting flares and oxygen heaters for the BOF, as well as other CO_2 sources. The sinter plant is the largest of these remaining sources, producing CO_2 emissions of around 0.28 tCO_2/t of crude steel. However, the flue gas here has a CO_2 concentration of only 4% to 5%, which means that the capture unit would have to be considerably larger and use more energy to extract the CO_2 from the flue gas. Connecting these smaller and less concentrated CO_2 sources to the capture unit would require additional high integration costs for only marginal CO_2 reductions. This is especially true considering that modern BF-BOF plants are already highly integrated and optimised sites that operate at close to their theoretical energy efficiency limits. Integrating additional CO_2 capture units and transport pipelines into this energetically optimised flue gas processing system would increase the site's energy usage while at the same time decreasing its energy efficiency, incurring high integration costs. For these reasons, our assessment estimates that capturing CO_2 from the three main emission sources, resulting in up to 73% of CO_2 capture, would be the techno-economic maximum CO_2 capturing system that would be implemented at an integrated steel site.

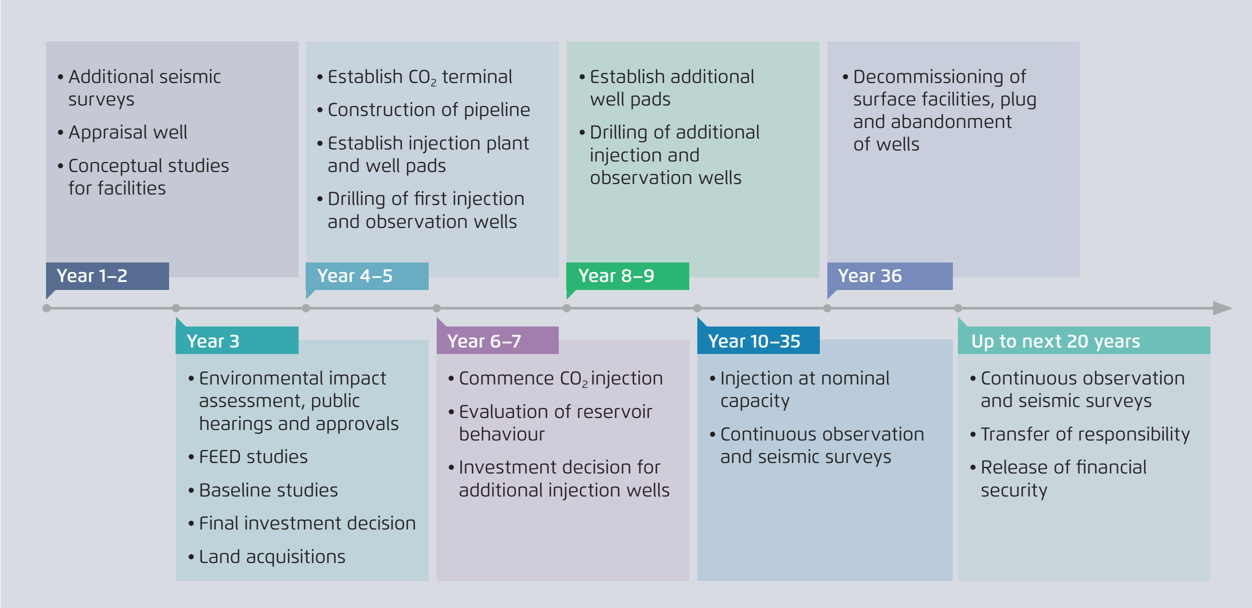
For a typical medium-sized BF-BOF steel plant with an annual production of 5 Mt of crude steel, a CCS retrofit under these conditions would still result in CO_2 emissions of around 2.5 Mt being released into the atmosphere each year. These high emissions levels would most likely mean that integrated steel plants, even when retrofitted with post-combustion CCS, would remain the major emitters in any country once coal-based power plants have been gradually phased out. Given that 90% of global steel capacity is now situated in countries with net-zero targets, this would put these plants at a very high risk of becoming stranded assets if regulatory authorities were to enforce their shutdown in order to achieve national climate targets. Put simply, CCS on the BF-BOF route would not be compatible with net-zero targets under these conditions; furthermore, given the desire to pursue 1.5°C-compatible steel decarbonisation pathways, there is a high risk that BF-BOF plants, even with CCS, would have to be phased out before 2050. At best, this would limit the potential time period in which post-combustion CCS could be used on the BF-BOF route from 2030 to around 2045. However, given the high investment costs involved in a CCS retrofit, plus the investments in the necessary CO_2 infrastructure, it is unlikely that this technology would be deployed for such a short period of time.

As with all CCS-based technologies, post-combustion CCS on the BF-BOF route will require a CO_2 infrastructure to be rolled out. Besides the actual CO_2 capture facilities at the steel plant, this includes moving compressed CO_2 by pipeline or ship (other modes of transport such as train or truck could also be considered but are considered less viable given the very high volumes of captured CO_2 that would need to be transported daily) from the steel site to suitable permanent CO_2 storage locations. Depending on its location, it is likely that the steel site will not yet be connected to a CO_2 transport network, unless it is possible to share or jointly develop the CO_2 infrastructure with other industrial plants that will need to develop CCS, such as the cement sector, which amongst other decarbonisation strategies will require CCS to address its process emissions. Developing a dedicated CO_2 infrastructure for just one steel plant will doubtless drive up the costs of CCS at that site. Furthermore, the availability of suitable CO_2 storage sites in sufficient proximity to allow for cost-effective CO_2 transport varies widely depending on the region in question. In fact, though the theoretical CO_2 storage volumes are estimated to be vast, there is still considerable uncertainty in many regions around the globe regarding the technical and commercial feasibility of suitable CO_2 storage sites close to steel plant locations, and more extensive geological analysis will be required to ascertain their CO_2 storage potential.

An additional point worth highlighting is that it takes a very long time and significant resources to develop CO_2 infrastructure, especially storage. This includes conducting initial surveys and studies and exploring and appraising resources (including exploration and appraisal wells) before an investment decision can even be made; only then can work on designing and developing the storage site begin, followed by construction of the site, including injection and observation wells, and construction of pipelines to connect the storage site to a CO_2 terminal. During and after operation of the storage site, monitoring, reporting and verification (MRV) are additional extremely important steps. Based on data from the Danish Energy Agency, it took between eight and ten years in the past to develop a CO_2 storage site and inject CO_2 at nominal capacity (Figure 13) (Danish Energy Agency and Energinet 2021). This development timeline is in addition to the need to acquire the necessary rights and permits to exploit underground space for CO_2 storage. While the rights to depleted oil fields and wells are often already held by the oil and gas companies that exploited them, the development of new wells or the transfer of rights to specific wells can constitute additional administrative and legal burdens. It is important to take these complex timelines into account, as they are an additional factor that could delay the implementation of CCS on the BF-BOF route to beyond 2030, by which time significant numbers of commercial-scale DRI projects are expected to have already come online.

Steel plant operators that reinvest in coal-based blast furnaces or build a new integrated BF-BOF plant with the intention of retrofitting it with CCS, as well as the investors and policymakers that enable this investment, must therefore consider that this plant will still have a high level of residual emissions, putting its operation in conflict with net-zero targets. They will also need to consider that the CO_2 capture facility is only one part of the CCS supply chain; transporting

Timeline to develop and operate onshore CO_2 storage — Figure 13



Agora Industry (2024), based on Danish Energy Agency (2021).

and storing CO_2 involves a number of additional risk elements in terms of investments, build-out, life-cycle emissions and long-term monitoring.

Upstream emissions from coal mine methane leakage

Another major risk for steelmakers that opt for post-combustion CCS on the BF-BOF is that this route will continue to entail upstream emissions from coal mine methane leakage. Based on data from the IEA Methane Tracker (IEA 2023a), Figure 14 shows that the methane leakage emissions of coking coal alone, which is used almost exclusively for steelmaking in the BF-BOF, are similar to the methane leakage of all global gas pipelines and liquefied natural gas (LNG) facilities combined. Methane emissions from coal mines are currently not taken into account by the iron and steel industry, since they are technically scope 3 emissions for this sector; however, it is important to accounts for these upstream emissions when considering the steel sector's emissions. Since methane is such a potent greenhouse gas, adding those emissions increases the steel industry's total emissions considerably. The IEA estimates that mining of coking coal emitted 10 Mt of methane in 2022, equivalent to 320 $MtCO_2eq$ based on a 100-year climate impact or 825 $MtCO_2eq$ based on a 20-year climate impact.[5] This increases the steel industry's GHG emissions by 10% to 30% (Ember 2023; IEA 2023a), without accounting for the fact that the steel industry also uses some thermal coal in its processes.

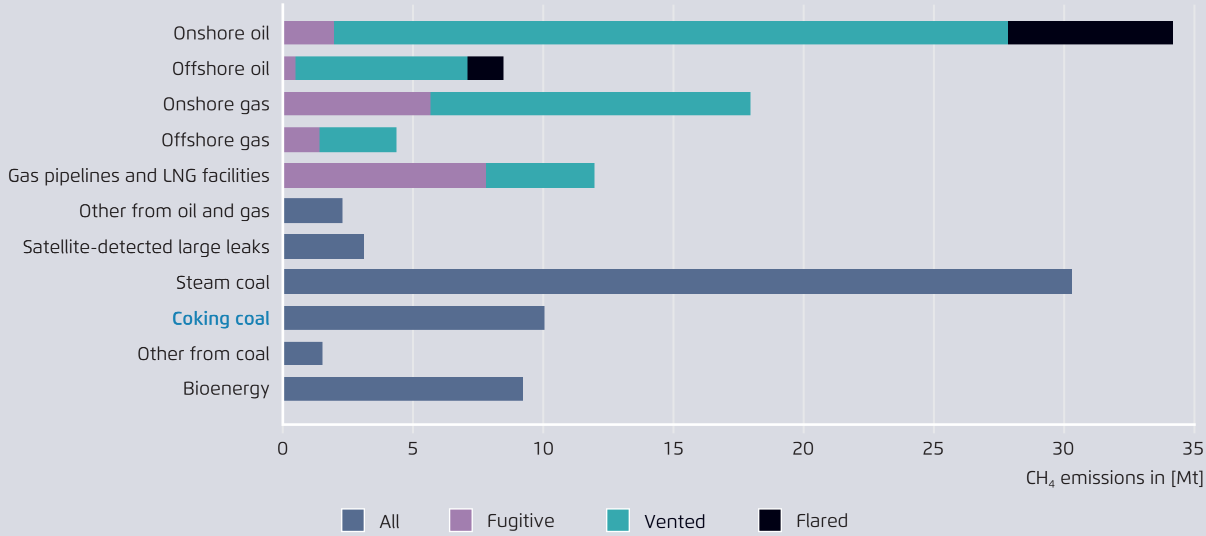
The IEA estimates that about 60% of coking coal mine methane can technically be abated by implementing a variety of measures. It is imperative that these measures should be taken, since steel will still be made via the coal-based route in the short term; even if these measures were to be fully implemented, however, residual emissions of the order of 125 $MtCO_2eq$ (100-year GWP) to 321 $MtCO_2eq$ (20-year GWP) would still remain per year (IEA 2023a).

In current proposed definitions of near-zero emission steel, such as those put forward by Agora Industry, IEA and Responsible Steel,

5 According to the IPCC, methane has a 20-year global warming potential (GWP) that is 82.5 times that of CO_2, or 32 times on the basis of a 100-year GWP (IPCC 2021).

Global methane emissions from energy sources

Figure 14



Agora Industry (2024), based on IEA Methane Tracker (2023).

scope 3 emissions related to steel production inputs (e.g. upstream methane emissions from coking coal mines, emissions from alloy processing etc.) are included in the accounting boundaries (see Agora Industry, 2023b and IEA, 2022a for details). If this approach to including scope 3 emissions from key inputs is adopted, then these emissions will come under increasing scrutiny from regulators, steel-consuming companies and investors. Indeed, in the case of methane, they are already coming under scrutiny, for instance in the EU's new Methane Regulation (European Council and Council of the European Union 2023) and the Inflation Reduction Act in the United States (Congressional Research Service 2022).

While regulators are already paying a lot of attention to assessing the CO_2 footprint of the renewable and low-carbon hydrogen that will be used in hydrogen-based steelmaking routes, the same needs to apply to the upstream emissions of coal-based steelmaking technologies in order to carry out a like-for-like comparison. For steel producers that rely on post-combustion CCS, upstream methane emissions present a major economic risk and future regulatory constraint if steelmakers are to be held accountable for these emissions.

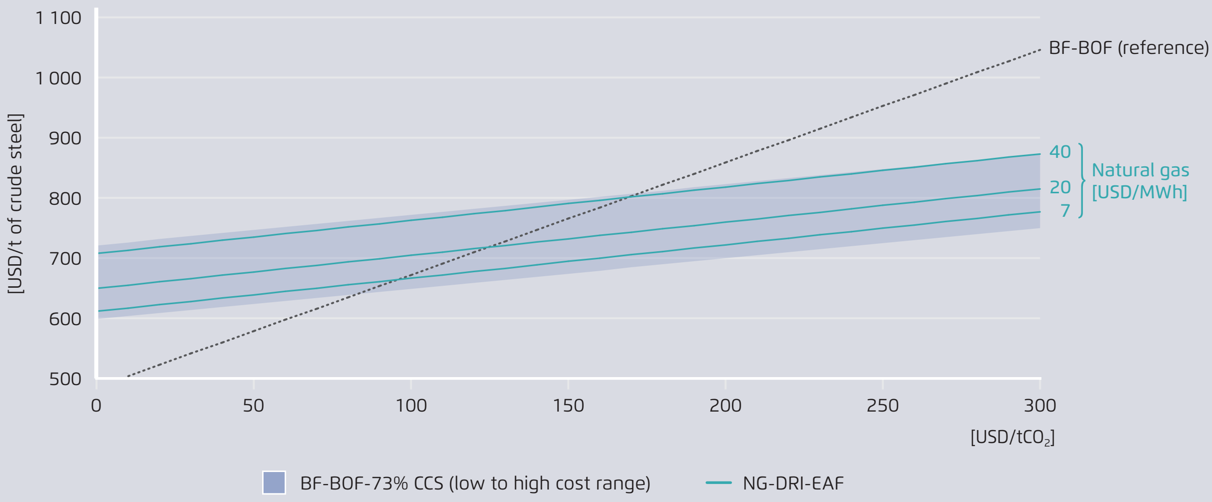
4.3 Production costs in the context of CO_2 prices and technology developments

For steel plant operators wishing to substantially lower the CO_2 footprint of their primary steel production, one of the key choices will be whether to invest in DRI plants or place their bets on a retrofit with post-combustion CCS on the BF-BOF route. Since running a DRI plant on natural gas results in a similar CO_2 intensity (0.55 tCO_2/t of crude steel) as our estimate of BF-BOF with CCS (0.51 tCO_2/t of crude steel), it is worth comparing the two alternatives with regard to their production costs.

Figure 15 shows that the two routes are also comparable from a cost perspective: at very low natural gas prices of USD 7/MWh (which could be the case in certain gas-producing countries, for example in the Middle East) and at the most favourable locations for CO_2 transport and storage, natural gas-based DRI plants are only 2 to 4 % more expensive, depending on the CO_2 price. At higher natural gas prices of USD 40/MWh, which are in line with the medium-term price expectation for LNG-importing countries after the current energy crisis triggered by

CO_2 and natural gas price impact on BF-BOF-73% CCS versus NG-DRI-EAF steelmaking cost in 2030

Figure 15



Agora Industry and Wuppertal Institute (2024). Assumptions: BF-BOF-73%-CCS (high): USD 60/tCO_2 transport and storage; USD 80/MWh delivered electricity. BF-BOF-73%-CCS (low): USD 30/tCO_2 transport and storage; USD 50/MWh delivered electricity.

Russia's invasion of Ukraine, the natural gas-based DRI-EAF route would still be in a range comparable to or lower than the higher range of production costs of CCS on the BF-BOF route. Overall, the production costs of both routes are in the same range, which has important implications.

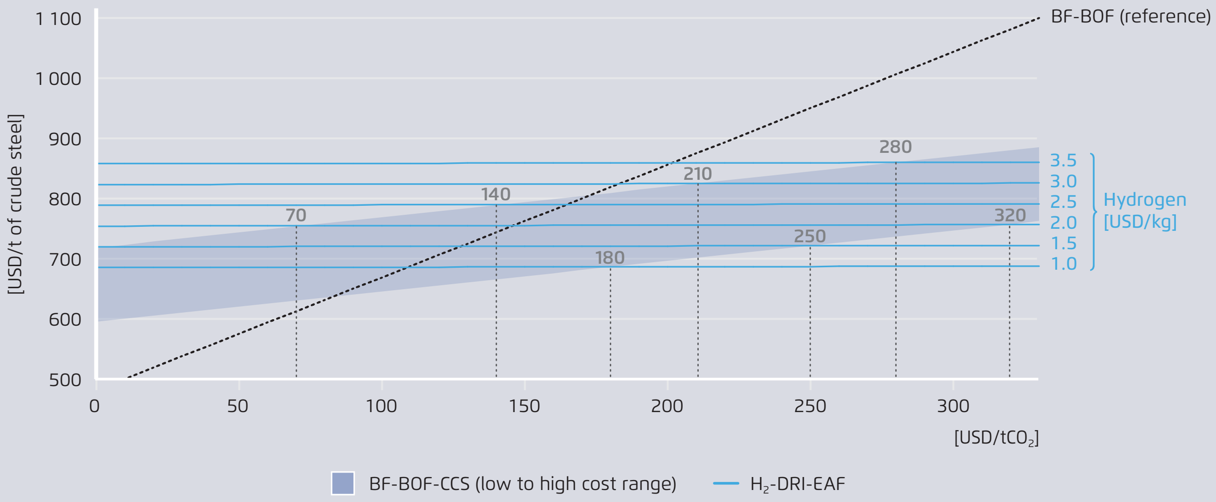
While new natural gas-based DRI plants can be considered H_2-ready and thus offer the potential to blend in increasing proportions of hydrogen and reduce emissions to near zero once low-carbon hydrogen becomes available in sufficient quantities, this is not the case for CCS on the BF-BOF route, since there is an upper limit to the CO_2 emissions that can be captured. Given that this technology option is not expected to offer any significant cost advantage over natural gas-based DRI production routes, it is questionable whether steel companies would opt for this route due to the carbon lock-in and stranded asset risk of the residual emissions.

Another important consideration is that CCS on the BF-BOF route will only reach market readiness by 2030 at the earliest, according to our estimations. The regulatory and market landscape will look significantly different by then. Several key steel-producing countries can be expected to have CO_2 prices (or policy measures with an equivalent effect) above USD 100/tCO_2. For reference purposes, the IEA *Net Zero Emissions by 2050 Scenario* models CO_2 prices of USD 140/tCO_2 in advanced economies, USD 90/tCO_2 for emerging market and developing economies with net-zero emissions pledges, including China and Brazil, and USD 15–25/tCO_2 in other emerging markets and developing economies by 2030 (IEA 2023b).

Comparing the BF-BOF-CCS route with an H_2-based DRI-EAF plant at varying CO_2 prices shows that the DRI-EAF route would be more competitive than our high-range BF-BOF-CCS production at CO_2 prices upwards of USD 70/tCO_2 and hydrogen costs of USD 2/kgH_2. When compared to the lowest BF-BOF-CCS cost range at a hydrogen cost of USD 2/kgH_2, H_2-DRI-EAF steelmaking would require a CO_2 price of USD 320/tCO_2 to be competitive, and USD 250/tCO_2 at an H_2 price of USD 1.5/kgH_2 (see Figure 16). While 100% H_2-DRI-based steelmaking may appear to be structurally more expensive than BF-BOF-CCS at high H_2 prices, it is important to note the implications that an evolving global steelmaking landscape could have on these technologies. If a share of the global

CO_2 and hydrogen price impact on BF-BOF-73% CCS versus H_2-DRI-EAF steelmaking cost in 2030

Figure 16



Agora Industry and Wuppertal Institute (2024). Assumptions: BF-BOF-73% CCS (high): USD 60/tCO_2 transport and storage; USD 80/MWh delivered electricity. BF-BOF-73% CCS (low): USD 30/tCO_2 transport and storage; USD 50/MWh delivered electricity.

production of green iron shifts to new iron hubs in locations with potential for cheap renewable H_2 and proximity to iron ore, then the world's cheapest renewable H_2 costs can be directly transferred to other steelmaking countries. By importing green HBI produced in such locations as a raw material for the downstream steelmaking value chain, countries with structurally higher H_2 costs could increase the overall competitiveness of their industry while safeguarding the majority of local jobs (see Box: Green iron trade and insight 6 in (Agora Industry and Wuppertal Institute 2023). In such a scenario, H_2-DRI-based steelmaking could outcompete BF-BOF-CCS on a cost basis, while also addressing the other risks associated with the post-combustion CCS route, such as the high level of residual and upstream emissions and the green lead market offtake risk.

Based on the expected market readiness of 2030 at the earliest for BF-BOF-CCS steelmaking, our analysis indicates that other breakthrough technologies such as MOE are likely to reach market readiness within a similar timeframe, and that hydrogen-DRI-based technologies will have benefitted from several years of commercial deployment and potential cost decreases due to nth-of-a-kind learning rates.

Figure 17 shows that even in the absence of a CO_2 price and a price of delivered electricity of between USD 40–45/MWh, MOE-based steelmaking would be cheaper than even the lower-range BF-BOF-CCS production costs. Even at USD 70/MWh, MOE would only need a CO_2 price above USD 190/tCO_2 to be cheaper than the BF-BOF-CCS in the most favourable CCS locations and would be cheaper than our high BF-BOF-CCS cost range even without a CO_2 price. While it is not yet fully clear at what speed and cost MOE and other direct electrolysis steelmaking technologies will develop and when exactly they will reach market readiness, this preliminary cost comparison highlights their potential disruptive game-changing character versus BF-BOF-CCS steelmaking.

CO_2 and electricity price impact on BF-BOF-73% CCS versus MOE steelmaking cost in 2030

Figure 17

Agora Industry and Wuppertal Institute (2024). Assumptions: BF-BOF-CCS (high): USD 60/tCO_2 transport and storage; USD 80/MWh delivered electricity. BF-BOF-CCS (low): USD 30/tCO_2 transport and storage; USD 50/MWh delivered electricity.

A look at higher CO_2 capture rates for BF-BOF-CCS and their economic viability

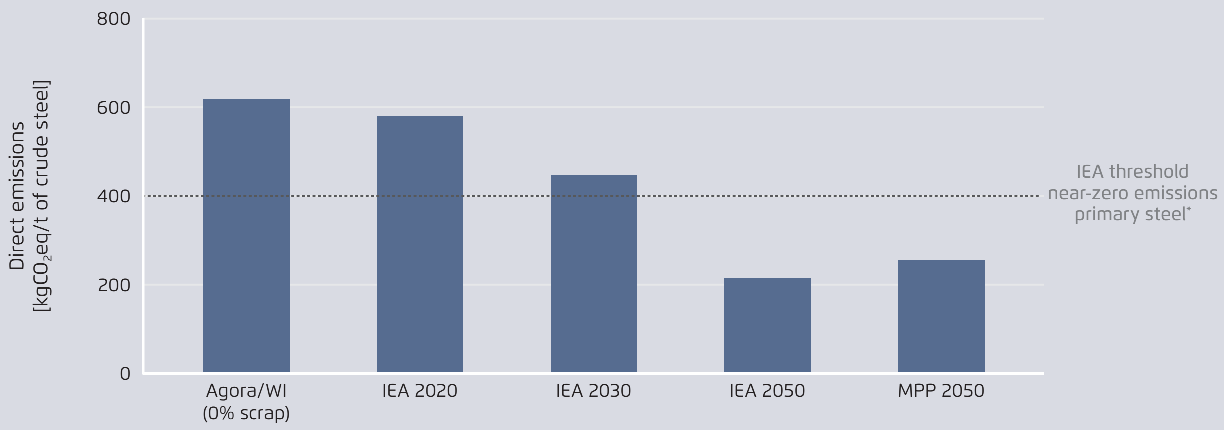
In theory, retrofitting the BF-BOF route with post-combustion CCS promises to significantly reduce the direct emissions of the BF-BOF route – though one key question is by how much and at what cost. Since the BF-BOF route has many different point sources of CO_2 emissions with different CO_2 concentrations in the waste gas streams, there are serious questions regarding both the technical feasibility of achieving high capture rates and the economic viability of applying carbon capture to those different point sources.

Our assessment of the emission reduction potential of CCS on the BF-BOF route tallies closely with the IEA's BF-BOF-CCS reference values for 2020: our analysis of BF-BOF-CCS estimates an emission reduction of 73%, with significant residual emissions of around 600 $kgCO_2$/t of crude steel (on a 0% scrap input basis) (see Figure 18). This is a similar emission reduction level to the IEA's current assessment of CCS on the BF-BOF route. In the IEA's assessments, however, the emission reductions achieved by this technology increase to approximately 80% in 2030 and 90% in 2050 (IEA, 2022a). Similarly, in its decarbonisation scenarios for the steel sector, the analysis by MPP assumes a 90% effective capture rate for BF-BOF-CCS in 2050, corresponding to residual emissions of approximately 250 $kgCO_2$/t of crude steel (MPP 2022).

It is worth bearing in mind that achieving a 90% effective capture rate for the whole BF-BOF process implies that CO_2 capture with an average efficiency rate of 90% is applied to every single CO_2 source of the steel plant – including emissions from a number of diffuse or low concentration CO_2 sources. This would entail substantial financial costs and technical efforts, raising the question of whether these high emission reduction rates assumed in scenarios can actually be achieved in practice. It should be noted that there are currently no large-scale projects aiming to achieve these high CO_2 emission reduction rates, and that a systematic review of studies analysing post-combustion CO_2 capture on the BF-BOF route has found reported emission reductions ranging between 11% and 77% (Perpiñán et al. 2023).

CO_2 intensity of the BF-BOF-CCS route in different scenarios

Figure 18



Agora Industry and Wuppertal Institute (2024), based on IEA (2022a) and MPP (2022). Note: The Agora/WI CO_2 intensity represents an adjusted BF-BOF-73% CCS route value with 0% scrap in order to ensure comparability with the other values. *The proposed IEA threshold for near-zero emissions primary steelmaking is 400 kgCO_2eq/t of crude steel in case of 0% scrap use. Note that the IEA near-zero emissions threshold is imposed on a direct and indirect emissions basis. For ease of comparison, the indirect emissions from fossil fuel and raw material supply are not depicted here, however these can significantly contribute to the emission intensity of crude steel production.

Even if very high capture rates of close to 90% were achievable, CCS on the BF-BOF route would still face several fundamental challenges. This route would still leave relatively high residual emissions (>0.2tCO_2/t of crude steel according to the IEA's and MPP's assumptions), which would need to be addressed in order to achieve net-zero emissions by 2050. According to our calculations, even a highly optimistic scenario for a BF-BOF-CCS retrofit, capable of reducing CO_2 emissions by 85%, would not meet the IEA's proposed near-zero emission threshold for primary steel unless indirect emissions from fossil fuel and material supply were reduced to close to zero and additional small CO_2 point sources from the BF-BOF route were also connected to CCS with the associated cost impacts described above.

The trade-offs and opportunity costs of offsetting the industry's emissions with carbon dioxide removal (CDR) technologies such as BECCS or DACCS are described in the box "Compensating residual emissions in the steel sector with CO_2 offsets". Furthermore, even with a high CO_2 capture rate on the BF-BOF route, the steel sector would still face high upstream emissions from coal mining methane that would increase the total CO_2 footprint of the steel and would need to be taken into account, including within the scope of near-zero emission steel labels and standards. With an even higher amount of CO_2 captured, BF-BOF-CCS becomes increasingly sensitive to CO_2 transport and storage constraints, in terms of both cost and physical infrastructure. The sheer volumes of CO_2 that need to be captured, transported and stored every year, mean that expensive CO_2 sites and an unfavourable geographical location relative to such sites could quickly make this route uncompetitive. Finally, due to the lack of large-scale developments, there is still considerable uncertainty over the costs and feasibility of implementing CCS along all aspects of the value chain: brownfield integration of CO_2 capture at existing steel sites and construction of the infrastructure to transport, store and monitor CO_2. CCS on the BF-BOF route at high capture rates is not expected to be available before 2030, at which point it would be competing with DRI-based technologies that will probably have been commercially deployed for some time and will have benefitted from learning rates as well as the prospect of cheaper energy inputs in the future.

4.4 Green lead market offtake risk

The high carbon cost incurred by the residual emissions on the BF-BOF-CCS route due to high CO_2 prices is not the only factor to consider with regard to the competitiveness of CCS on the BF-BOF route. Even before high CO_2 and low hydrogen and electricity prices are reached, which is projected to happen in the late 2030s or 2040s, green lead markets and product carbon requirements will be another key driver to complement or substitute carbon pricing in the green industrial transformation. If green steel standards and labels such as the thresholds proposed by the IEA or other organisations (see Section 4.1 on residual emissions and Agora Industry, 2023b, for details) are to be adopted in the future, this will also serve as guidance for private and public procurement, thereby putting steel products unable to meet the near-zero emission performance label at a disadvantage.

This context is important in order to understand the interplay between CO_2 prices and green lead markets as push-pull instruments: the CO_2 price will play an important role on the demand side, forcing unabated blast furnace operators to switch to breakthrough technologies as they will otherwise face increasingly high emission costs. At the same time, however, it will be the requirements of steel-consuming sectors wishing to decarbonise their supply chains that will be the most influential factor in creating a low-carbon steel market. The key question is where post-combustion CCS on the BF-BOF would fit in here. According to our analysis, it is not likely to be market ready before 2030, at which point it would have a similar production cost level as natural gas-based DRI routes. Whereas new DRI plants have the potential to blend in increasing amounts of H_2 and become climate-neutral once sufficient quantities of low-carbon or renewable hydrogen are available, however, post-combustion CCS on the BF-BOF plants would lock in residual CO_2 emissions of 0.51 tCO_2/t of steel (and additional upstream coal mine methane emissions) for as long as they continue to run. Furthermore, given the rapid development of near-zero emissions steelmaking technologies today, H_2-based DRI routes will be firmly established and other promising options such as MOE (and other electrolysis technologies) may reach market readiness by 2030. Against this backdrop, it is questionable whether steel-consuming companies that are planning to address and decarbonise their supply chain emissions would be willing to sign a ten-year offtake agreement for steel produced via the BF-BOF-CCS route, as this would incur a considerable remaining carbon footprint and lack any clear path to climate neutrality.

To assess the possible effects green markets could have on steelmaking in more detail, it is worth splitting the offtake market into two main segments: the private sector and the public sector.

As far as the private sector is concerned, there is a risk that steel-consuming companies wishing to decarbonise their supply chain will not want to be associated with CCS on coal-based technologies at all. This applies particularly to those sectors that market their products directly to end-consumers and where the green properties of the products can be a distinct differentiating advantage, as is the case with cars or household appliances. For the manufacturing companies and their brands, there may be a considerable marketing and reputational risk in being associated with coal-based projects along their supply chains, which may not align with their decarbonisation strategy. This is in addition to the fact that these steel-using sectors may seek to enter into offtake agreements with material suppliers that have a clear reduction pathway to climate-neutral production, which could also represent an important element of communication strategies regarding corporate "net-zero visions". Unlike DRI-based steelmaking, BF-BOF-CCS would not offer this potential to move towards climate-neutral production. This green demand driver is likely to become increasingly important as policies such as the EU's proposed Green Claims Directive (European Commission 2023b) come into force, regulating the green claims companies can make about the environmental properties of their products, including their carbon footprint. Even now in the 2020s, different market segments are already emerging for steel products: one for conventional steel with a high CO_2 footprint and one for low-carbon steel with a substantially lower CO_2 footprint. Several major players in the automotive industry have already signed offtake agreements with steelmakers to source low-carbon steel for their vehicles from the mid-2020s onwards, which is already fuelling demand for low-CO_2 steel and helping de-risk green steel projects. This is partly driven by regulation, such as the EU's regulation of CO_2 emission performance standards of vehicles, the scope of which is being expanded to encompass full life-cycle CO_2 emissions (European Commission 2023a). As steel is a key input material in vehicles, shifting towards near-zero CO_2 steel would significantly reduce the CO_2 emissions associated with the production of cars. Manufacturing-related emissions will play an increasingly large role in the life-cycle emissions of EVs as electricity supply is decarbonised. At the same time, while the production of near-zero CO_2 steel will be more expensive in the medium-term than conventional production is today without a CO_2 price, steel input accounts for only a small proportion of the total cost of a car, so switching to near-zero emission steel would only increase the production costs of a car, or indeed of other engineering or household appliances, by 1 to 2% (MPP 2022). Though the automotive sector is particularly active in securing green offtake agreements, it is not the only industry to do so. As of May 2023, some 48 green steel supply agreements had been announced according to BNEF (2023), including consumer products, energy companies and even shipping companies. More than 40 companies from various sectors have signed up to the SteelZero Initiative that requires its member companies to source 50% of their steel from certified low-carbon sources by 2030, and 100% net-zero steel by 2050 (SteelZero 2023). These developments illustrate that the demand for low-carbon steel is growing rapidly.

The public sector also procures very significant quantities of steel and could have a considerable impact on the market for green steel. While green public procurement policies will play an important role in ramping up demand for low-carbon steel, it is not clear how the BF-BOF route with CCS will be treated in these policies. The majority of steel that is consumed in the public sector is used for infrastructure and construction projects. Such grades of steel are typically well suited to being supplied via the scrap-based EAF route and, depending on the regional steel industry structure and scrap supply, will for the most part be supplied by EAFs. Furthermore, the proportion of secondary steel production and the supply of scrap is expected to increase globally, including in countries which are currently still very reliant on BF-BOF steel. Given that the scrap-based EAF route already has much lower direct CO_2 emissions (0.06 tCO_2/t of crude steel) than the BF-BOF route with CCS could ever achieve, and that indirect emissions from electricity are slated to decrease as power production decarbonises, BF-BOF-CCS-based steel will not be able to compete with scrap-based EAF steel in a green market with stringent embedded carbon regulations. If upstream emissions from coal mine methane leakage are included in the GHG methodologies that will be used in public procurement policy, as seems increasingly likely, any coal-based steel production route will face an additional disadvantage versus other steelmaking routes. Steel is not publicly procured only in the construction sector, but also in other applications such as renewable energy infrastructure or public transport vehicles. For those applications, which require high-quality primary steel that cannot currently be provided by the scrap-based EAF route, BF-BOF-CCS faces the same risk as described above.

The methodologies used to calculate CO_2 intensities, as well as the ensuing standards and labels, are still being developed and will require international harmonisation to be effective (Agora Industry 2023c). However, assuming that standards and labels similar to those proposed by the IEA or ResponsibleSteel are adopted, there is a strong likelihood that steel from the BF-BOF-CCS route would be simply unable to achieve the best near-zero emissions label, as opposed to other decarbonisation processes. Consequently, it is possible that BF-BOF-CCS might at best fail to command a similar premium as H_2-DRI steel for instance, or might even face a more extensive offtake risk on green markets, especially as supply chains emission reporting and corporate climate targets become more stringent.

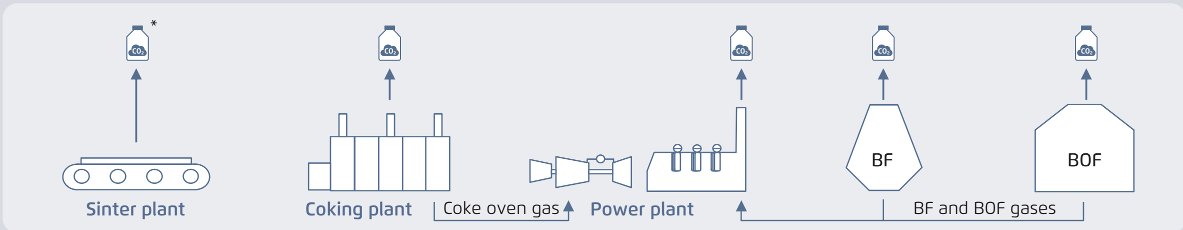
Conclusions about the role of CCS on the BF-BOF route

These findings have extremely far-reaching implications for the global steel transformation: there is a considerable risk that retroactively equipping the BF-BOF route with post-combustion CCS may never be a competitive technology option. If this technology option does not materialise in the future, any investment in the coal-based BF-BOF route faces a high risk of eventually ending up as a stranded asset. This is especially important when it comes to the large project pipeline of new coal-based integrated steel mills that are currently planned in emerging economies with rapidly rising steel demand, such as India and Southeast Asia. Core assets of these new integrated steel plants have lifetimes of 50 to 60 years. What will be the future for those steel plants in the 2040s if CCS on the BF-BOF route does not materialise by then because it is outcompeted by other technologies and is not compatible with net-zero targets?

As this analysis has shown, kicking the can down the road by investing in coal-based steelmaking capacities and waiting until CCS becomes commercially available as a retrofit option is an extremely risky strategy for steel companies due to a combination of factors.

The risks of both stranded assets and carbon lock-in are enormous. Immediate strategies to minimise the risks of stranded assets are therefore necessary and need to include shifting investments away from coal-based steelmaking and accelerate a coal phase-out in the steel sector. This will only be possible by simultaneously and rapidly deploying key steelmaking technologies, building out the renewable energy and H_2 supply and addressing important potential bottlenecks that pose obstacles to the transition, including the supply of DR-grade pellets and DRI construction capacity. Our recent study *15 Insights on the Global Steel Transformation* (Agora Industry and Wuppertal Institute 2023) analyses these bottlenecks as well as the factors that will enable the transition, such as the role that de-risking financial tools plays in unlocking investments in emerging economies and the potential for enhanced international cooperation and strategic partnerships to unlock international green iron trade.

Several risk factors make CCS in combination with the BF-BOF route unattractive — Figure 19



BF-BOF-CCS...

... leaves high residual emissions
- BF-BOF-CCS will likely only reduce direct CO_2 emissions by 73% compared to the BF-BOF route
- While higher emission reductions are technically possible, it is questionable whether they are economically viable

... will be prone to disruptive technology cost developments
- Direct electrification technologies such as molten oxide electrolysis could be cheaper once they become commercially available in the 2030s
- There is a risk that the combination of cost factors (CO_2 transport, storage and residual emissions compensation) will make BF-BOF-CCS uncompetitive

... cannot address upstream emissions
- Upstream emissions from coal mine methane leakage currently add ~12% in addition to the current direct CO_2 emissions of the steel industry**
- BF-BOF-CCS cannot address upstream emissions directly and if they are included in the future regulation of the steel industry, they may worsen the business case for BF-BOF-CCS

... faces an offtake risk in green lead markets
- Progressive companies that strive to decarbonise their supply chains (i.e. automotive, household appliances) and want to advertise this fact to their customers may not want to be associated with coal-based technologies

Agora Industry and Wuppertal Institute (2024). Note: BF-BOF-CCS has several uncertain cost facts, depending on which CO_2 point sources are included in capture, whether the CO_2 is stored onshore or offshore and the distance to storage sites. Offshore CO_2 storage tends to be more expensive than onshore CO_2 storage. *The figure illustrates the capture of CO_2 from the sintering plant which is technically feasible, but may not be economically viable. **Upstream methane emissions from coking coal are estimated to be 320 $MtCO_2eq$ based on a GWP 100 measurement and 825 $MtCO_2eq$ based on GWP 20 (author's calculations based on IEA 2023a).

5 Low-carbon technologies for the global steel transformation: factsheets

For each technology, a comprehensive factsheet highlights a selection of current projects and provides an overview of key facts, including the CO_2 reduction potential, estimated production costs, expected market availability and energy and infrastructure requirements. The information in the fact sheets has been developed on the basis of the following sources and strategies:

1. **Scientific literature:** The assumptions and reference data used for calculations and projections were generally based on scientific studies. Where applicable, the fact sheets relied on information from papers in established academic journals such as *Journal of Cleaner Production* (Elsevier) and *metals* (MDPI). For the main input cost assumptions, the fact sheets also refer to studies that use recent data, including the *IEA World Energy Outlook 2022* (IEA 2022b) and *Net Zero by 2050* (IEA 2021b), and reports by Bloomberg New Energy Finance, the Hydrogen Council and the Global CCS Institute.
2. **Assumptions and results of internal calculations:** For numerous key technologies, we carried out our own internal calculations of expected future production and CO_2 abatement costs based on published scientific studies and our own work, including the *Transformation Cost Calculator for Steel* that was part of the project *Transforming industry through carbon contracts* (Agora Energiewende 2022).
3. **Parameters and process descriptions:** Process parameters and descriptions, especially relating to novel technologies at an early stage of development and for which only limited literature is available, such as MOE and AEL, were mainly derived from information published by companies developing these projects. Information on pilot and demonstration projects was obtained from companies operating these projects and/or participating research institutions, as well as from relevant websites and press releases.

Methodological approaches and assumptions:

→ **Input costs:**

Cost calculations use input cost ranges based on literature and our own work, including the *Transformation Cost Calculator for Steel* (Agora Energiewende 2022) for current costs. Future expected price developments were based on literature sources or frozen at a constant level when credible future price development estimates were not available. Energy costs are shown as delivered costs to the plant (including high full load hours with typically reduced grid charges for energy-intensive industries) rather than levelised costs of production. To represent realistic average costs that can be applied globally, cost ranges were adopted with extreme outliers omitted. This avoids excessively large cost ranges which would have yielded meaningless results, but is unable to provide the full scope of costs, which may diverge significantly in different regions of the world.

For example, the electricity price used in the fact sheets is derived from the levelised cost of electricity figures taken from the IEA's *Net Zero Emissions* scenario assumptions about combined production from solar as well as onshore wind power. However, a certain cost component for backup electricity during hours of no wind or sun was included, as were grid fees for electricity transmission of USD 10/MWh. Overall, our assumption of the cost of delivered electricity ranges from USD 50 to USD 80/MWh for 2030. On a global scale, however, electricity prices may be substantially lower in some parts of the world than assumed here. For example, Scandinavia is already seeing power purchase agreements being concluded for wind power to industry at USD 36/MWh, whereas the available literature regards USD 30 to USD 42/MWh as a likely price in these countries from around 2030 to 2040 (IEA 2021b).

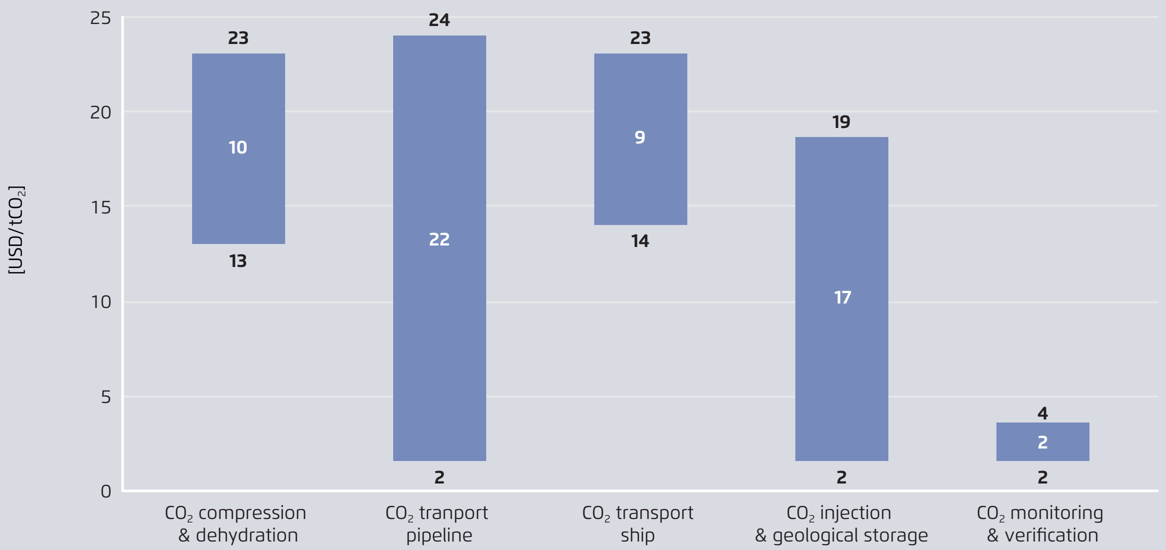
We followed a similar approach when calculating the costs of renewable low-carbon hydrogen. As a first step, we conducted a literature review which included the following studies: *Net Zero by 2050* (IEA 2021b), *Hydrogen Insights 2021* (Hydrogen Council 2021), *The Green Hydrogen Economy* (PWC 2021), *Making the Hydrogen Economy Possible* (ETC 2021b) and *Hydrogen Economy Outlook 2020* (BNEF 2020). Next, we identified a middle-of-the-road cost range that cuts out the outliers. The costs of hydrogen stated here are the costs of delivered hydrogen, including the costs of production, potential storage to allow for high full load hours, and transport. In this study we do not distinguish between the costs of renewable hydrogen and those of low-carbon hydrogen produced from fossil-based hydrogen with carbon capture, utilisation and storage (CCUS). The costs of delivered hydrogen represent a global average approach, but may deviate significantly in different world regions and countries.

→ CO_2 transport and storage costs

The transport and storage of CO_2 is a very important cost component of various CCS-based technologies in the steel sector. The CCS value chain contains several distinct elements which need to be considered. After capturing CO_2 at the steel plant, the CO_2 transport and storage value chain includes CO_2 compression and dehydration, CO_2 transport by pipeline, ship or other transport modalities, plus possible intermediary storage hubs, CO_2 injection into geological storage and CO_2 monitoring and verification over a long time period.

Based on the cost ranges indicated by the Global CCS Institute (2022), the lowest possible costs of CO_2 transport and storage would amount to USD 18/tCO_2. This case would involve a 20 Mt per year CO_2 onshore pipeline for 180 km and a good quality onshore geological CO_2 storage reservoir. The highest costs of CO_2 transport and storage would total USD 70/tCO_2. In this case the CO_2 would be transported by a 1 Mt

Indicative cost ranges for CCS value chain components — Figure 20



Agora Industry and Wuppertal Institute (2024), based on Global CCS Institute (2022).

per year pipeline or by ship over a distance of 300 km and stored in an offshore CO_2 storage site (Global CCS Institute, 2022). As a middle-of-the-road approach, we defined a range of USD 30 to USD 60/tCO_2 for transport and storage for 2030.

It needs to be noted in this context that the actual costs vary greatly depending on the use case. Two aspects appear particularly worth mentioning. First, offshore CO_2 storage tends to be significantly more expensive than onshore CO_2 storage. While the upper limit (USD 18.6/tCO_2) in the category CO_2 injection and geological storage is defined for offshore CO_2 storage, onshore CO_2 storage costs at suitable sites could be as low as USD 1.6/tCO_2. These findings are also in line with some of the literature on CCS costs (Danish Energy Agency and Energinet 2021; IEA 2020a; 2021a). In view of these considerable differences, we suggest differentiating between onshore and offshore CO_2 storage costs in the future.

Second, it is important to compare the costs of the first real-world CO_2 storage projects with literature values. Projects often tend to become more expensive than the literature values indicate as they move closer to final implementation. For example, the Northern Lights project in Norway – one of the most advanced CO_2 offshore storage projects in Europe – is targeting costs of USD 35 to USD 50/tCO_2 for CO_2 transport and storage, which would only cover part of the CO_2 transport and storage value chain (Global CCS Institute 2021). Based on these figures, CO_2 transport and offshore storage in 2030 may turn out to be more expensive than our upper limit of USD 60/tCO_2.

This overview highlights the importance of tracking the costs of the first real-world CO_2 storage projects and the need to differentiate between onshore and offshore CO_2 storage costs, which has significant implications for the CO_2 abatement costs of CCS-based technologies in the steel transformation.

→ Selection of breakthrough technologies

Due to the scope of this report, we settled on a selection of key breakthrough technologies to feature in the fact sheets. Although our selection gives a good overview of the most important future steelmaking technologies, not every single technology or conceivable plant configuration could be considered. Our first screening criterion in the selection process was to select technologies that could reduce CO_2 emissions by 90% compared to the BF-BOF route, to be compatible with a climate-neutral future. Due to the development of DRI projects aiming to use natural gas until a sufficient supply of low-carbon hydrogen becomes available, possibly in combination with CCS, and due to the important role played by CCS on the BF-BOF in many decarbonisation scenarios, CCS-based technologies on the DRI and the BF-BOF were included in the analysis even though their CO_2 reduction potential is below 90%. Several potentially promising technologies were not included in the fact sheets, such as hydrogen-based direct reduction routes based on fluidised bed reactors such as HYFOR®, Circored® and HYREX®, novel bio-based steelmaking routes such as Tecnored®, and technologies designed to improve the efficiency of the BF-BOF route such as EasyMelt. They could be the subject of a future analysis.

→ Parameters of the reference BF-BOF route

The abatement cost and potentials of the breakthrough technologies were all calculated in relation to the existing reference process. The parameters for this technology were based on an integrated blast furnace-basic oxygen furnace (BF-BOF) steelworks located in the coastal region of Western Europe, producing 4 Mt of crude steel per year using processes typical of an average steel mill, such as sintering, coke oven, blast furnace and basic oxygen furnace. It should be noted that the reference does not necessarily represent the best available technology (BAT), but rather a typical configuration of an average western European plant.

Input price assumptions for all technologies

→ Table 1

Price assumption	Lower range 2030 [USD/unit]	Upper range 2030 [USD/unit]	Lower range 2050 [USD/unit]	Upper range 2050 [USD/unit]	Source
Delivered electricity	50/MWh	80/MWh	50/MWh	80/MWh	Own estimate Agora, WI based on IEA 2021b
Delivered low-carbon H_2	2/kg	3/kg	1/kg	2/kg	Own estimate Agora, WI based on BNEF 2020; Hydrogen Council 2021; IEA 2021b
Natural gas	3.5/GJ	8.6/GJ	2.5/GJ	7.0/GJ	Own estimate Agora, WI based on IEA 2022b
Coking coal	5.5/GJ	5.5/GJ	5.5/GJ	5.5/GJ	Own estimates based on VDKi 2020
Scrap*	412/t	571/t	421/t	513/t	Own estimate Agora, WI, see "scrap price assumptions" below.
Raw biomass	7/GJ	17/GJ	7/GJ	17/GJ	Own estimate Agora, WI based on MPP 2022
Charcoal	23/GJ	30/GJ	23/GJ	30/GJ	Own estimate Agora, WI based on MPP 2022
Alloys**	0.02/tCS	0.02/tCS	0.02/tCS	0.02/tCS	Vogl, Åhman, and Nilsson 2018
CO_2 price	90/tCO_2	130/tCO_2	200/tCO_2	250/tCO_2	Based on emerging market and advanced economies in IEA 2022b; 2021b
CO_2 transport & storage	30/tCO_2	60/tCO_2	20/tCO_2	30/tCO_2	Own estimate Agora, WI based on Danish Energy Agency and Energinet 2021; Global CCS Institute 2021; IEA 2021a; 2020a

* Assuming a price correlation between primary steel production and scrap.
** Same number of alloying elements assumed for all routes, resulting in identical costs.

For the sake of comparability, the 17% proportion of scrap used in the BOF feed of the reference configuration is also taken as the basis for the calculations of all other breakthrough technologies, assuming that an equivalent scrap input into the process is technically feasible.

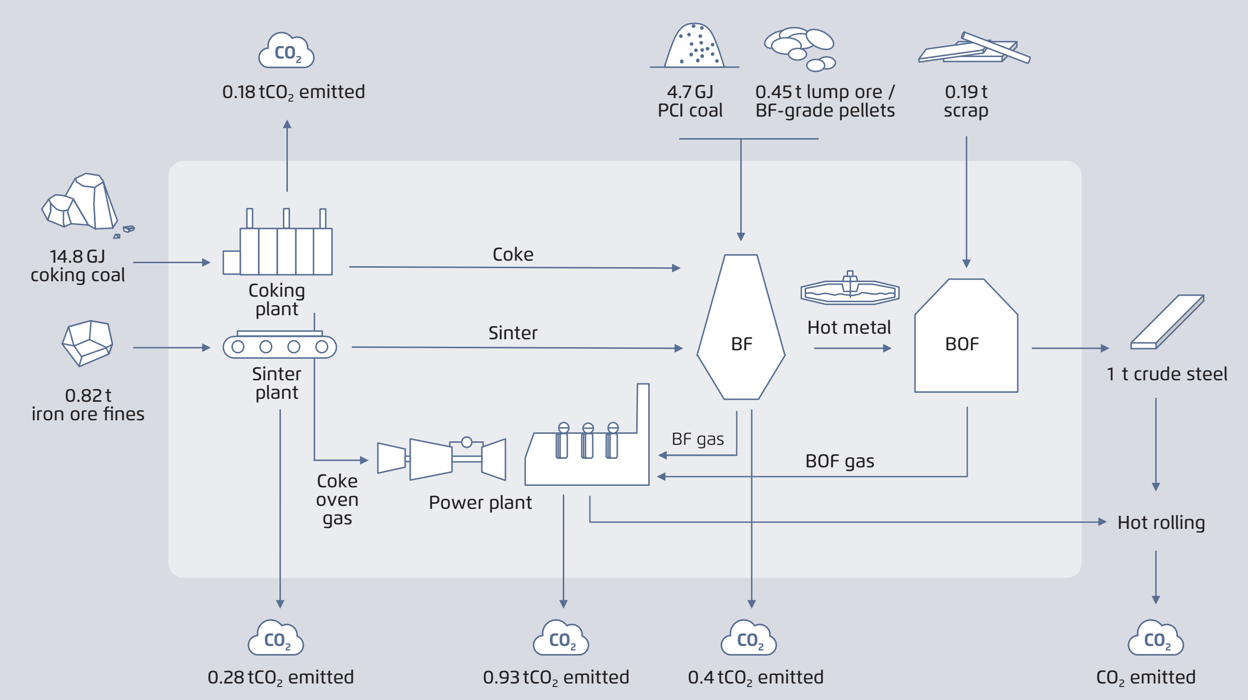
Scope 1 emissions of this reference route, which are used as a benchmark for calculating the abatement potential of all breakthrough technologies, amount to 1.87 tCO_2/t of crude steel. On the basis of similar system boundaries, this emission intensity is in line with recent publications on modern BF-BOF plants (Bataille, Stiebert, and Li 2021; Fan and Friedmann 2021; GEI 2022; Worldsteel Association 2021). The basic plant configuration of our reference technology, the system boundary of our analysis (grey box) and major material, energy and emissions flows are outlined in Figure 21.

→ Production system boundary

All calculations refer to the production of 1 tonne of crude steel. Subsequent finishing in secondary metallurgy has only minor impacts on costs and emissions and is therefore ignored. No further crude-steel processing, namely casting and hot-rolling, is covered by this analysis. In plant configurations that generate large amounts of steelworks gases (such as BF-BOF-based routes), however, minor proportions of these gases may be used to supply heat for hot rolling furnaces, thereby creating fossil emission flows outside the boundaries of our analysis.

BF-BOF reference technology

Figure 21



Agora Industry and Wuppertal Institute (2024). Note: Process diagram shows emissions from major point sources only. Additional emissions from distributed sources amount to 0.08 tCO_2/t of crude steel.

→ CO_2 emissions boundary

For both the reference technology and the key breakthrough technologies, we considered only the direct CO_2 emissions (scope 1) from on-site stacks. We did not take into account the indirect scope 2 upstream emissions from the use of purchased energy such as hydrogen or electricity. Our calculations likewise do not include the indirect scope 3 upstream emissions (generated for example by the extraction and transportation of coal, iron ore or natural gas, the pelletising of iron ore or the production of fluxes such as lime or of alloying elements) or downstream emissions from the use and disposal of steel products. We consider this emissions boundary because direct CO_2 emissions constitute the largest source of emissions and because of the uncertainties regarding upstream and downstream emissions. From the perspective of a transformation towards climate neutrality, it can be assumed that non-fossil energy inputs (electricity, hydrogen and biomass) will also trend towards low-CO_2 emission footprints. This means that the emission reductions stated for breakthrough technologies vis-à-vis the conventional route can only be achieved if low-carbon electricity and hydrogen are used.

→ Production costs

The production costs of all technologies in 2030 and 2050 are calculated according to the assumed capital and operational expenditure per tonne of crude steel produced and are expressed as ranges based on the cost inputs as listed in Table 1. The stated production costs should be interpreted as total costs in the absence of policy instruments and direct subsidies.

→ CO_2 abatement costs

Data on CO_2 abatement costs are based on calculations that compare the production costs of key breakthrough technologies with the conventional GHG-intensive reference technology and on findings from the technical literature. To calculate the CO_2 abatement costs, the difference in production costs is divided by the net CO_2 emissions reduction of the breakthrough technology. In view of the considerable uncertainties about future CO_2 abatement, we estimated plausible cost ranges.

→ **Earliest possible availability (technology readiness level, TRL)**

Assumptions about the earliest possible availability of individual technologies are based on the academic literature and on information from companies and research institutions involved in pilot and demonstration projects. The current state of development of individual technologies is assessed by the TRL rating system. This approach classifies technologies that are still at the research and laboratory stage as TRL 1 to 3. Technologies that have entered the pilot phase are rated TRL 4 or 5, while technologies in the demonstration phase are TRL 6 or 7. Technologies that can be deployed at an industrial scale are in the range 8 to 9. The TRL alone does not assess commercial viability, however, which will depend on additional factors such as the necessary supply chains, certification and regulatory compliance being in place.

→ **Balance of on-site electricity generation and carbon capture operation of the BF-BOF**

For steelmaking without carbon capture, we assume that cogenerated steelmaking gases are primarily used for on-site processes such as coke oven underfiring, hot blast or process gas preheating. Excess steelmaking gases are co-fired in a captive power plant to generate electricity and heat. To simplify the accounting, it is assumed that the captive power plant produces exactly the amount of electricity required by the entire steel mill, so that there is neither a surplus of energy nor any need to import electricity (IEAGHG 2013).

Consequently, adding carbon capture to the BF-BOF generates additional external energy demand for the capture processes. Both electricity and heat are required for amine-based CO_2 capture. We have assumed that this heat requirement would be covered by an electric heater with an efficiency of 98% and that the total energy requirement could therefore also be covered only by external electricity.

→ **Integration costs**

Regarding the necessary adaptations of existing plant configurations, we applied integration cost factors to the respective investment cost of the plant components to be added to an integrated steel plant. These factors were determined for the integration of DRI plants, as well as for different types of carbon capture processes, and vary according to the assumptions regarding the expected complexity of plant integration.

→ **Scrap price assumptions**

The scrap price is the single most important cost component of scrap-based EAF steelmaking and therefore needs to be taken properly into account in the respective cost calculations. Since statistics show that the scrap and steel price (hot rolled coil / rebar) are well correlated even during a shock (such as COVID-19 in Q1 2020), we assume a price correlation between primary steel production and scrap. This correlation is expected to result in a scrap price that rises until the scrap EAF route reaches the steel production cost level of a defined primary production route. The assumed scrap cost range is based on the following considerations:

- For the *lower scrap cost range*, the steel price is expected to be set by the cheapest primary production technology in 2030, which will be the DRI-EAF route with natural gas (when including a CO_2 price)
- For the *upper scrap cost range,* the upper production cost range of the cheapest climate-neutral route (DRI-EAF with H_2) is expected to set the steel price. This development of the steel and respective scrap prices might be seen in selected markets in which carbon-neutral production is mandatory or stimulated by a higher regional CO_2 price. In this case, climate-neutral secondary and primary production will find themselves in direct competition with one another.

Notes on the fact sheets:

- → The cost calculations or estimates in these fact sheets are geared towards private businesses. For example, we apply a discount rate of 8% to capital expenditure calculations for steelmaking facilities, which is typically enjoyed by private investors, rather than the much lower social discount rate used in economic analyses.
- → Estimates of future costs are based on real 2020 prices.
- → The aim of the technology fact sheets is to assess and compare the complex physical and economic aspects of key breakthrough technologies and create a basis for discussions of their role and deployment. Though we are aware that the abbreviated presentation is a simplification, we nevertheless hope that the synthetic compilation will support constructive dialogue. We invite all experts to provide us with feedback about our assumptions and calculations so that we can further refine our evidence base for breakthrough steelmaking technologies.

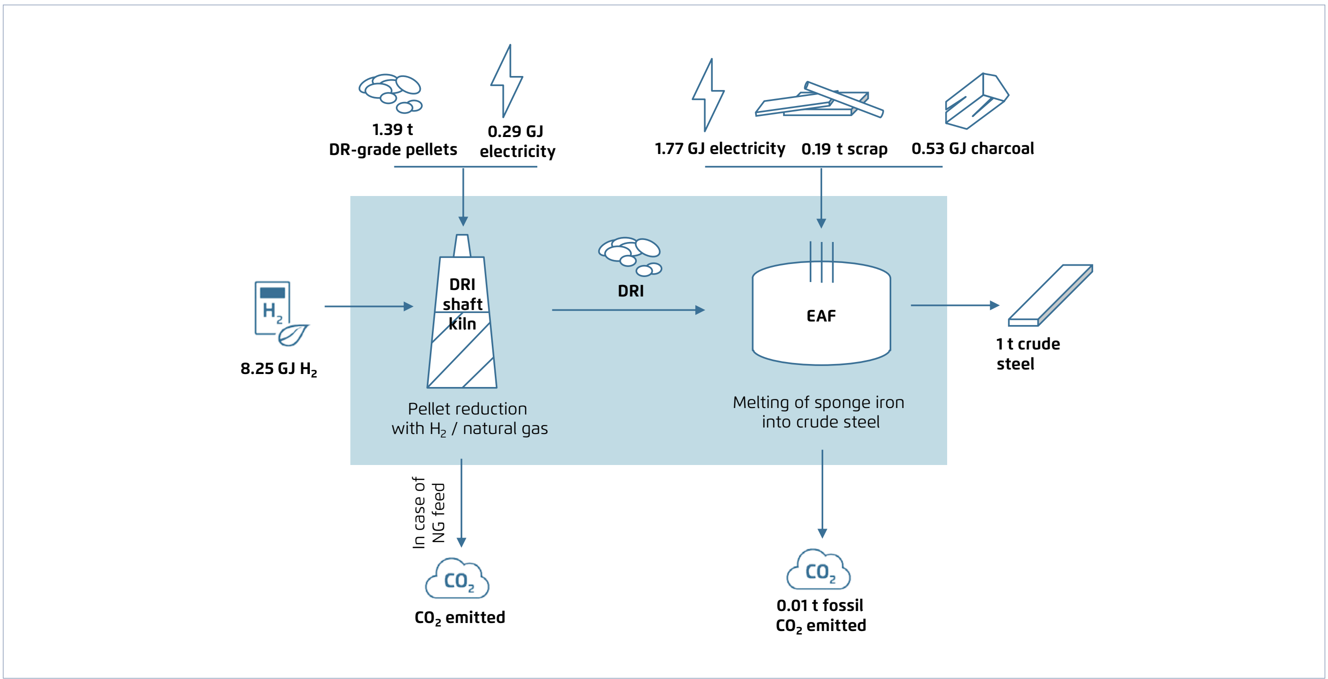
5.1 HYDROGEN-BASED DIRECT REDUCTION – ELECTRIC ARC FURNACE ROUTE (H_2-DRI-EAF)

HYBRIT direct reduction pilot plant, Luleå   Photo: Hybrit

In the direct reduction process, iron ore pellets are reduced to iron in DRI plants. DRI technologies using natural gas are already established processes. In the net-zero technology route, hydrogen is used as the reductant in the DRI plants (H_2-DRI). The resulting sponge iron (direct reduced iron, DRI) is melted into crude steel in an EAF. DRI can also be compacted into hot briquetted iron (HBI) for shipping. If zero-CO_2 electricity is used for hydrogen production and to run the EAF, this route is close to CO_2-free. A certain amount of carbon input (e.g. charcoal) is needed for slag formation when processing direct reduced iron to steel in the EAF.

Simplified H_2-DRI-EAF process flow

Figure E.1



Agora Industry and Wuppertal Institute, 2024

Example pilot and demonstration projects

Commercial

Project: HBIS (Hebei, China)
Hebei Iron & Steel Group China, Tenova
Status / Outlook: Construction of a 1.2 Mt DRI plant completed in 2022.

The Energiron DRI technology will use a reduction gas mixture composed of 30% metallurgical gases from the existing integrated steel plant and 70% hydrogen supplied by external sources. The residual CO_2 will be recovered by a CO_2 removal unit and reutilised in downstream processes (CCU).

Commercial (announced)

Project: ArcelorMittal Gijón (Sestao, Spain)
ArcelorMittal
Status / Outlook: 2.3 Mt H_2-DRI plant will start operation in 2025.

ArcelorMittal will build a new H_2-DRI plant to substitute the existing blast furnace and use the sponge iron in a newly built EAF as well as in the existing EAF in Sestao. The plant will initially run on natural gas, before gradually switching to hydrogen.

Pilot

Project: HYBRIT (Luleå, Gällivare, Sweden)
SSAB, LKAB and Vattenfall
Status / Outlook: H_2-DRI pilot plant with a production capacity of 10 000 t per year was commissioned in 2020 (TRL 5) and produced the first batch in 2021.

The H_2-DRI pilot project includes a pilot DRI plant, hydrogen electrolysis and hydrogen storage projects.
SSAB announced plans to build a large-scale DRI demonstration plant in Gällivare with a capacity of 1.3 Mt DRI per year in 2026 and to expand to 2.7 Mt DRI per year with a further H_2-DRI plant in 2030, operating on renewable electricity.

Key facts

Technology
Hydrogen-based direct reduction and EAF steelmaking (H_2-DRI-EAF)

Current stage of development
Announcements of commercial plants (TRL 8–9)

Expected readiness for use
2025–2030 for 100% H_2, before 2025 with NG/H_2

Energy and infrastructure requirement
- Total energy demand: 10.8 GJ/t of crude steel (of which 8.3 GJ H_2/t of crude steel)
- Large-scale green hydrogen production, transport and storage infrastructure
- Iron ore mining and beneficiation capacities to produce DRI-grade pellets

Possible policy instruments
- Carbon price and carbon border adjustment
- Carbon contracts or CCfDs
- Green public procurement
- Quotas for low-carbon materials and embedded carbon limits
- Clean hydrogen support policies

CO_2 abatement costs vs BF-BOF

2030	2050
137–192 USD/tCO_2	**99–154** USD/tCO_2

2030: USD 98–158/tCO_2 (100% NG)

Challenges
The production of renewable hydrogen requires large amounts of renewable electricity as well as new infrastructure for hydrogen production, transport and storage. Another challenge is the availability of high-grade iron ores with high iron content (>67%), which are required as the DRI-EAF process is not well suited to removing impurities or to achieving full reduction of the iron ore, affecting the steelmaking process in the EAF.

Evaluation of technology for steel sector decarbonisation
The technology can be available before 2025, providing an opportunity to partially substitute the large capacity of blast furnaces (1090 Mt) that will reach the end of their campaign life before 2030. Modern DRI plants are fully H_2-ready – and thus compatible with climate neutrality – but can also run on natural gas initially, before clean H_2 becomes available.

Comparison of technology with current production pathway

CONVENTIONAL TECHNOLOGY		KEY LOW-CARBON TECHNOLOGY
BF-BOF		**H_2-DRI-EAF**
1.87 tCO_2/t of crude steel	**-99.6%** → Specific emission reduction	**0.01** tCO_2/t of crude steel
472-499 USD/t of crude steel (2022)	**+54 to +72%** → Specific additional costs (no CO_2 cost)	**727-857** USD/t of crude steel (2030)

Main assumptions to determine the range of production costs (2030)

Assumption		Lower range [USD/t of crude steel]	Upper range [USD/t of crude steel]
Specific capital costs		75	85
Operating costs of renewable hydrogen		138	206
Operating costs of electricity		29	46
Operating costs of metallic feed	DRI pellets Steel scrap Alloys	264 78 33	264 108 33
Fixed operating costs		59	59
Other costs (refractories, fluxes, charcoal, electrodes)		52	55
Production costs (+ costs of residual CO_2 emissions*)		**727 (+1)**	**857 (+1)**

Source: Compiled by Wuppertal Institute and Agora Industry based on various sources.
*Additional CO_2 costs of residual emissions based on a CO_2 price of USD 90–130/tCO_2.

5.2 HYDROGEN-BASED DIRECT REDUCTION-SMELTER ROUTE (H_2-DRI-SMELT-BOF)

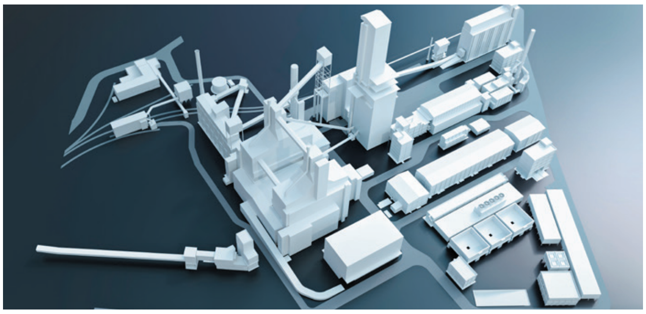
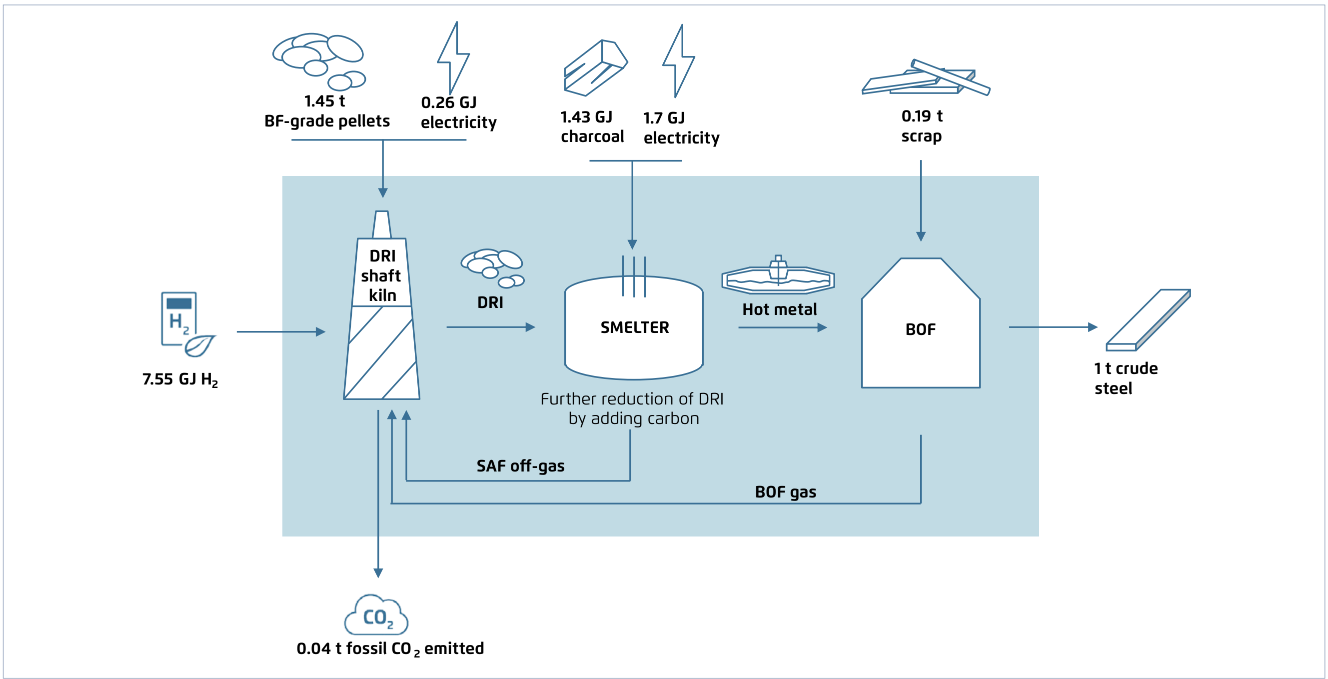


Illustration of the tkH2Steel project currently in construction in Duisburg Photo: thyssenkrupp

The DRI route can also be combined with the BOF steelmaking process. This requires an intermediate smelting stage so that the solid DRI leaving the shaft furnace is fed into the BOF in a liquid state. Two similar smelter technologies are on the market: the submerged arc furnace (SAF) and the open slag bath furnace (OSBF). Since impurities in the iron ore can be removed in both the smelter and the BOF and since further iron ore reduction occurs in the smelter, this route allows high-quality steel to be made with lower-grade iron ores compared to the DRI-EAF route.

Simplified H_2-DRI-SMELT-BOF process flow Figure E.2



Agora Industry and Wuppertal Institute, 2024

Example pilot and demonstration projects

Commercial (announced)

Project: tkH_2Steel (Duisburg, Germany)
Thyssenkrupp
Status: EPC contract awarded
Outlook: Operation of 2.5 Mt commercial-scale DRI plant (TRL 9) by 2026.

Thyssenkrupp has awarded a €1.8 billion contract to the plant builder SMS for the construction of a Midrex hydrogen-capable DRI plant with two innovative smelting units/submerged arc furnaces, to be integrated with the existing basic oxygen furnaces.

Pilot (announced)

Project: ESF pilot (Australia)
BHP, Rio Tinto, BlueScope
Status: Framework agreement for pre-feasibility study of an electric smelting furnace (ESF) plant
Outlook: Commissioning of pilot ESF plant by 2027.

Australia's two largest iron ore miners BHP and Rio Tinto have partnered with steelmaker BlueScope to develop an electric smelting furnace plant, which combined with a DRI plant could process low-grade Australian iron ore to produce green iron.

Key facts

Technology
Hydrogen-based direct reduction, electric smelter (SAF/OSBF) and BOF

Current stage of development
System testing (TRL 8–9)

Expected readiness for use
2027–2030

Renewable electricity and infrastructure requirement
- Total energy demand: 11.0 GJ/t of crude steel (of which 7.6 GJ H_2/t of crude steel)
- Large-scale green hydrogen production, transport and storage infrastructure
- Renewable carbon source for carburisation

Possible policy instruments
- Carbon price and carbon border adjustment
- Carbon contracts or CCfDs
- Green public procurement
- Quotas for low-carbon materials and embedded carbon limits
- Clean hydrogen support policies

CO_2 abatement costs vs BF-BOF

2030: **139–203** USD/tCO_2

2050: **104–168** USD/tCO_2

2030: USD 116–186/tCO_2 (65% natural gas and 35% hydrogen)

Challenges
This route requires large amounts of renewable electricity to produce renewable hydrogen, as well as the installation of an additional smelting unit between the DRI and BOF. The BOF process requires higher carbon inputs than an EAF to carburise the DRI, generating carbon-rich off-gas streams. These can be addressed by deploying CCS at the BOF and/or using a biogenic carbon source.

Evaluation of technology for steel sector decarbonisation
Existing BF-BOF steelmaking sites can be transformed by integrating the H_2-DRI technology with existing BOFs, allowing for the same steel quality and downstream production processes and the use of lower-quality iron ores compared to the DRI-EAF route. There are residual emission risks if not enough sustainable biomass is available for the carbon inputs.

Comparison of technology with current production pathway

CONVENTIONAL TECHNOLOGY		KEY LOW-CARBON TECHNOLOGY
BF-BOF		**H_2-DRI-Smelt-BOF**
1.87 tCO_2/t of crude steel	-98% → Specific emission reduction	**0.04** tCO_2/t of crude steel
472-499 USD/t of crude steel (2022)	+54 to 75% → Specific additional costs (no CO_2 cost)	**725–871** USD/t of crude steel (2030)

Main assumptions to determine the range of production costs (2030)

Assumption		Lower range [USD/t of crude steel]	Upper range [USD/t of crude steel]
Specific capital costs		90	116
Operating costs of renewable hydrogen		126	189
Operating costs of electricity		27	44
Operating costs of metallic feed	Iron ore pellets	254	254
	Scrap	78	109
	Alloys	33	33
Fixed operating costs		66	66
Other costs (refractories, fluxes, charcoal, electrodes)		54	64
Sales (slags)		–3	–3
Production costs (+ costs of residual CO_2 emissions*)		**725 (+4)**	**871 (+5)**

Source: Compiled by Wuppertal Institute and Agora Industry based on various sources.
*Additional CO_2 costs of residual emissions based on a CO_2 price of USD 90–130/tCO_2.

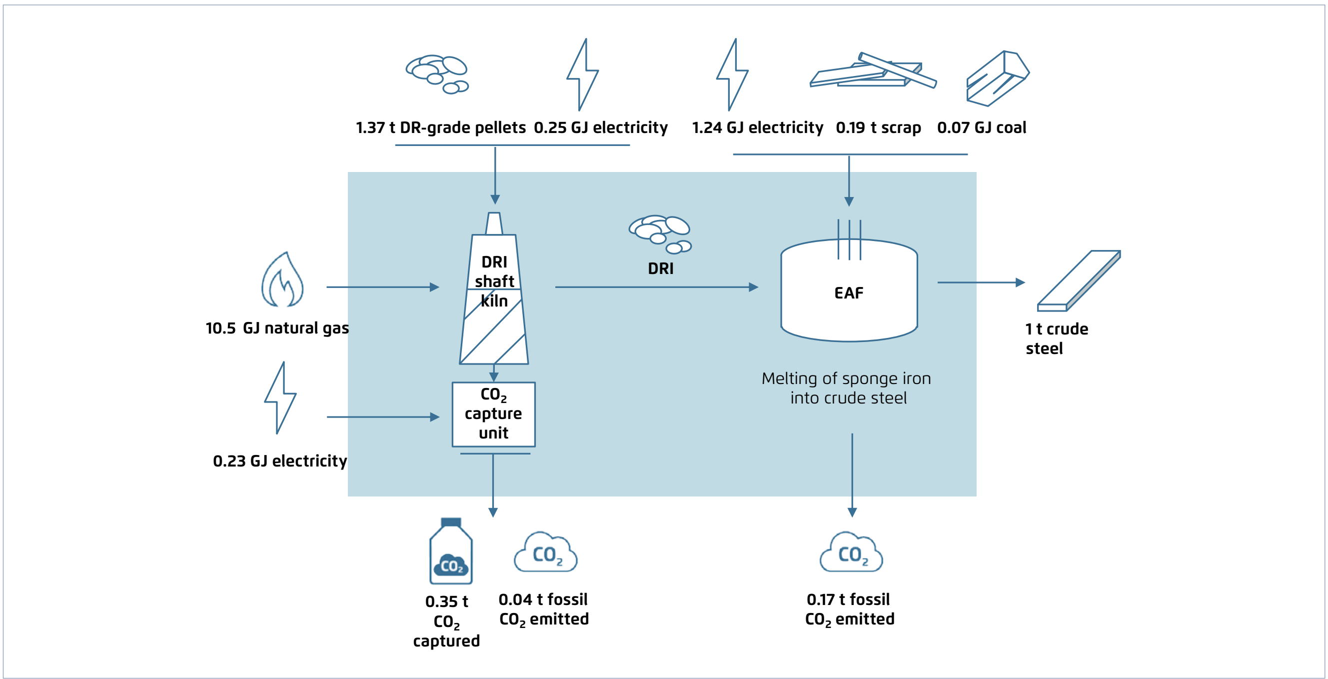
5.3 DIRECT REDUCTION WITH NATURAL GAS AND CCS (NG-DRI-CCS)

Emirates Steel and Al Reyadah DRI-EAF and CCS plant Photo: ADNOC

The commercially available direct reduction ironmaking process using natural gas (NG-DRI) can be supplemented with CCS technology to capture the CO_2 emissions from the shaft kiln in both the DRI-EAF and the DRI-SMELT-BOF route. Using amine (MEA) absorption CO_2 capture with 90% efficiency could capture around 64% of CO_2 emissions from the DRI kiln, which would lead to emission reductions of 89% versus the BF-BOF process.

Simplified NG-DRI-CCS process flow

Figure E.3



Agora Industry and Wuppertal Institute, 2024

Example pilot and demonstration projects

Commercial

Project: Al Reyadah (Abu Dhabi, UAE)
Abu Dhabi National Oil Company, Emirates Steel Arkan
Status: 3.5 Mt DRI-EAF steel plant retrofitted with CO_2 capture for EOR since 2016.

The Al Reyadah CCS facility is the world's first commercial carbon capture steel project, capturing CO_2 from a natural gas-based DRI-EAF plant owned by Emirates Steel Arkan. The CCUS facility has been operating since 2016, with an announced capture potential of up to 0.8 $MtCO_2$/year, which is used for enhanced oil recovery (EOR) in nearby oil fields.

Commercial (announced)

Project: Convent (Louisiana, USA)
Nucor, ExxonMobil
Status: 2.5 Mt DRI-EAF steel plant retrofitted with CO_2 capture, to be commissioned in 2026.

American steelmaker Nucor has signed an agreement with ExxonMobil to capture up to 0.8 $MtCO_2$/year from Nucor's existing DRI plant and to transport and store the CO_2 at an ExxonMobil-owned facility in Louisiana. The project is planned to be commissioned in 2026.

Key facts

Technology
Natural gas-based direct reduction with CCS (NG-DRI-CCS)

Current stage of development
First fully commercial plant operating (at low CO_2 capture rate) (TRL 8–9)

Expected readiness for use
2025–2030 (for high CO_2 capture rates)

Energy and infrastructure requirement
- Total energy demand: 12.2 GJ/t of crude steel (of which 10.5 GJ natural gas/t of crude steel)
- CO_2 transport and storage infrastructure
- Iron ore mining and beneficiation capacities to produce DRI-grade pellets

Possible policy instruments
- Carbon price and carbon border adjustment
- Carbon Contracts for Difference
- Green public procurement
- Quotas for low-carbon materials and embedded carbon limits

CO_2 abatement costs vs BF-BOF

2030	2050
88–144 USD/tCO_2	**79–126** USD/tCO_2

Challenges
This route faces challenges regarding the use of CCS (see the BF-BOF-CCS factsheet), including the need for CO_2 transport and storage infrastructure, low public acceptance, fossil fuel technology lock-in and upstream methane emissions. The DRI-EAF process also entails challenges regarding the availability of high-grade iron ore (see H_2-DRI-EAF factsheet).

Evaluation of technology for steel sector decarbonisation
Though the technology is already available, residual emissions from low CO_2 capture rates and upstream methane emissions need to be addressed. If these residual emissions are minimised, CCS technology can be added as a retrofit solution to existing DRI plants, and modern H_2-ready DRI plants could run on natural gas initially with further emission abatement via CCS before switching to H_2.

Comparison of technology with current production pathway

CONVENTIONAL TECHNOLOGY		KEY LOW-CARBON TECHNOLOGY
BF-BOF		**NG-DRI-EAF-CCS**
1.87 tCO_2/t of crude steel	-89% → Specific emission reduction	**0.2** tCO_2/t of crude steel
472–499 USD/t of crude steel (2022)	+31 to +48% → Specific additional costs (no CO_2 cost)	**618–739** USD/t of crude steel (2030)

Main assumptions to determine the range of production costs (2030)

Assumption		Lower range [USD/t of crude steel]	Upper range [USD/t of crude steel]
Specific capital costs		77	90
Operating costs for electricity		23	37
Operating costs for metallic feed	Iron ore pellets	261	261
	Scrap	78	108
	Alloys	33	33
Other costs (natural gas, refractories, fluxes, electrodes, MEA)		77	130
Fixed operating costs		59	59
Operating cost of CO_2 transport & storage		10	21
Production costs (+ costs of residual CO_2 emissions*)		**618 (+19)**	**739 (+27)**

Source: Compiled by Wuppertal Institute and Agora Industry based on various sources.
*Additional CO_2 costs of residual emissions based on a CO_2 price of USD 90–130/tCO_2.

5.4 MOLTEN OXIDE ELECTROLYSIS (MOE)

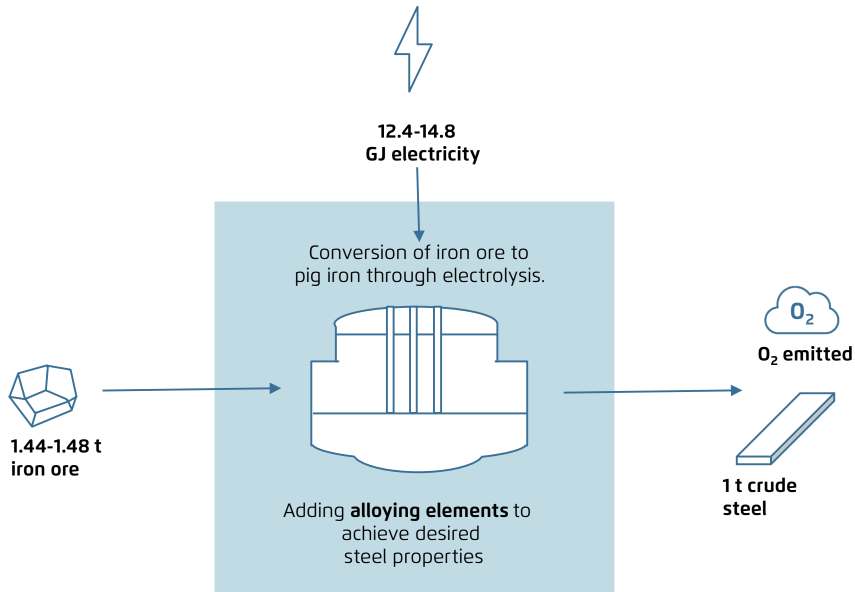
Boston Metal's MOE pilot facility in Woburn, Massachusetts

Photo: Boston Metal

In the MOE process, iron ore is converted electrochemically to its elementary components oxygen (O_2) and iron (Fe) in an electrolysis cell without a carbon-based reducing agent. In the electrolysis cell, the iron ore is dissolved at about 1 600 degrees Celsius in a liquid electrolyte and an electrical current is passed through the solution, reducing the molten iron ore to metallic iron. The process generates no CO_2 emissions and only oxygen as a byproduct. Alloying elements (including carbon) are subsequently added to the iron to achieve the desired steel properties.

Simplified MOE process flow

Figure E.4



Agora Industry and Wuppertal Institute, 2024

Example pilot and demonstration projects

Pilot

Project: MOE (Woburn, USA)
Boston Metal
Status: Planned pilot plant in 2024 to produce 25 000 t of metal per year (TRL 4).
Outlook: The company aims to build a commercial-scale plant (TRL 9) before 2030.

The start-up Boston Metal is working on the commercialisation of molten oxide electrolysis (MOE). Boston Metal plans to start using its MOE technology for high-value ferroalloy production while continuing to develop the technology for iron- and steelmaking.

Key facts

Technology
Molten oxide electrolysis

Current stage of development
Pilot plant (TRL 3–4)

Expected readiness for use
2035–2040

Energy and infrastructure requirement
- Total energy demand: 12.4–14.8 GJ/t of crude steel (all from electricity)
- A dedicated electricity infrastructure, including storage, may be required

Possible policy instruments
- Support for research, pilot and demonstration plants

CO_2 abatement costs vs BF-BOF

2030	2050
not applicable	**56–146** USD/tCO_2

Challenges
The MOE process requires a continuous supply of large amounts of electricity. The extent to which the electrolysis can be flexibly operated to accommodate variable electricity supply from renewables still requires further study. The scale-up of the process, including self-heating cells and an inert anode able to withstand the high temperature and corrosive effects of the molten oxide bath, is a technological challenge.

Evaluation of technology for steel sector decarbonisation
The MOE process is capable of producing steel from low-grade iron ore with zero CO_2 emissions if it runs on carbon-neutral electricity. The technology will probably not play a role in the upcoming 2020s investment window, but may be commercially available around 2035. As it is a modular technology, it could allow for smaller-scale, decentralised steel production.

Comparison of technology with current production pathway

CONVENTIONAL TECHNOLOGY
BF-BOF

KEY LOW-CARBON TECHNOLOGY
MOE

1.87 tCO_2/t of crude steel → -100% Specific emission reduction → **0** tCO_2/t of crude steel

472–499 USD/t of crude steel (2022) → +23 to 54% Specific additional costs (no CO_2 cost) → **582–766** USD/t of crude steel (2050)

Main assumptions to determine the range of production costs (2050)

Assumption		Lower range [USD/t of crude steel]	Upper range [USD/t of crude steel]
Specific capital costs		60	122
Operating costs of electricity		205	328
Operating costs of metallic feed	Iron ore Alloys	215 33	215 33
Fixed operating costs		69	69
Production costs (+ costs of residual CO_2 emissions*)		**582 (+0)**	**766 (+0)**

Source: Compiled by Wuppertal Institute and Agora Industry based on various sources.
*Additional CO_2 costs of residual emissions based on a CO_2 price of USD 90–130/tCO_2.

5.5 ALKALINE ELECTROLYSIS + EAF (AEL-EAF)

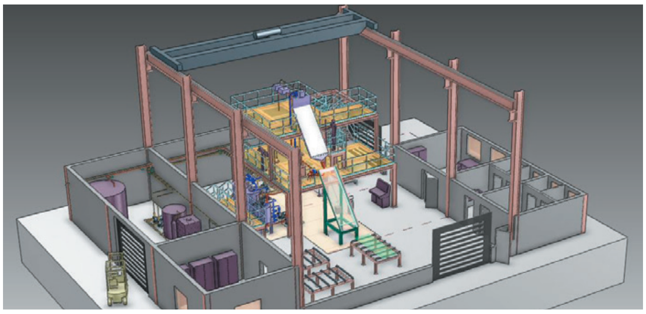
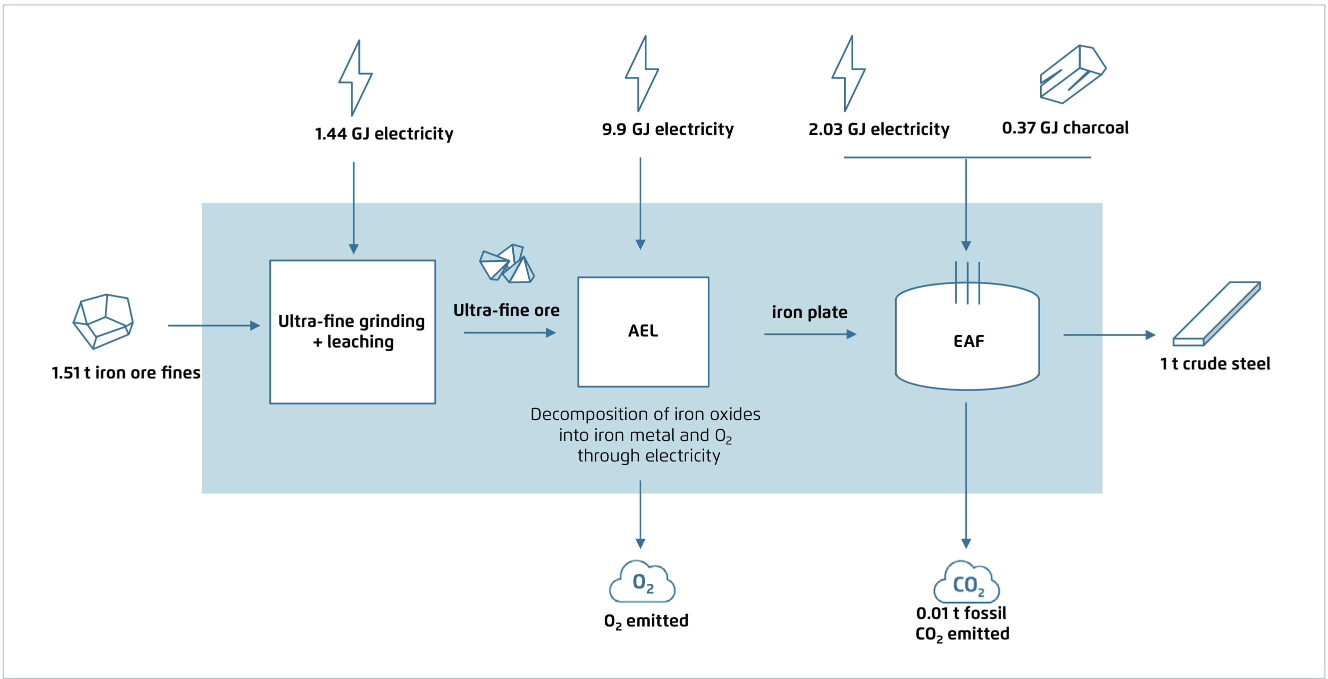


Illustration of the SIDERWIN pilot plant, constructed in Maizières-lès-Metz Photo: ArcelorMittal

The electrowinning of iron is based on the decomposition of iron oxides into iron and oxygen by passing an electric current through a highly alkaline aqueous sodium hydroxide solution at about 110 degrees Celsius. In contrast to the MOE process which melts the iron ore, the iron ore grains are reduced while in their solid state (below their melting point). The solid iron (iron plate) is then fed into an electric arc furnace to be processed into steel.

Simplified AEL process flow

Figure E.5



Agora Industry and Wuppertal Institute, 2024

Example pilot and demonstration projects

Pilot

Project: Volteron (France)
ArcelorMittal, John Cockerill
Status: Development and construction of a pilot plant (40–80 kt steel/year) by 2027 (TRL 4).
Outlook: Increase the pilot plant's annual capacity to between 300 kt and 1 Mt/year by 2030.

As part of the SIDERWIN project, a consortium led by ArcelorMittal has developed a prototype iron electrolysis plant. In the next stage of the project, named Volteron, ArcelorMittal and John Cockerill aim to build a 40–80 kt/year low-temperature, iron electrolysis pilot plant by 2027.

Key facts

Technology
Alkaline electrolysis + EAF (AEL-EAF)

Current stage of development
Pilot plant (TRL 3–4)

Expected readiness for use
2040–2045

Energy and infrastructure requirement

- Total energy demand: 13.7 GJ/t of crude steel (all from electricity)
- A dedicated electricity infrastructure, including storage, may be required

Possible policy instruments

- Support for research, pilot and demonstration plants

CO_2 abatement costs vs BF-BOF

2030	2050
not applicable	72–195 USD/tCO_2

Challenges
The AEL process requires large amounts of low-carbon electricity. Further research is required to find the optimal technology design. Especially developing an electrode that constitutes a good compromise between mechanical strength and open porosity, and scaling up the technology from pilot to industrial scale production could pose challenges.

Evaluation of technology for steel sector decarbonisation
Provided large amounts of renewable electricity are available, the AEL process could produce steel with close to zero CO_2 emissions. However, the technology is unlikely to be available for widespread commercial use before 2040.

Comparison of technology with current production pathway

CONVENTIONAL TECHNOLOGY		KEY LOW-CARBON TECHNOLOGY
BF-BOF		AEL-EAF
1.87 tCO_2/t of crude steel	-99.6% Specific emission reduction	0.01 tCO_2/t of crude steel
472–499 USD/t of crude steel (2022)	+29 to 71% Specific additional costs (no CO_2 costs)	611–855 USD/t of crude steel (2050)

Main assumptions to determine the range of production costs (2050)

Assumption		Lower range [USD/t of crude steel]	Upper range [USD/t of crude steel]
Specific capital costs		75	152
Operating costs of electricity		186	297
Operating costs of metallic feed	Iron ore	219	219
	Alloys	33	33
Fixed operating costs		51	104
Other costs (refractories, fluxes, charcoal, electrodes)		48	50
Production costs (+ costs of residual CO_2 emissions*)		**611 (+1)**	**855 (+2)**

Source: Compiled by Wuppertal Institute and Agora Industry based on various sources.
*Additional CO_2 costs of residual emissions based on a CO_2 price of USD 90–130/tCO_2.

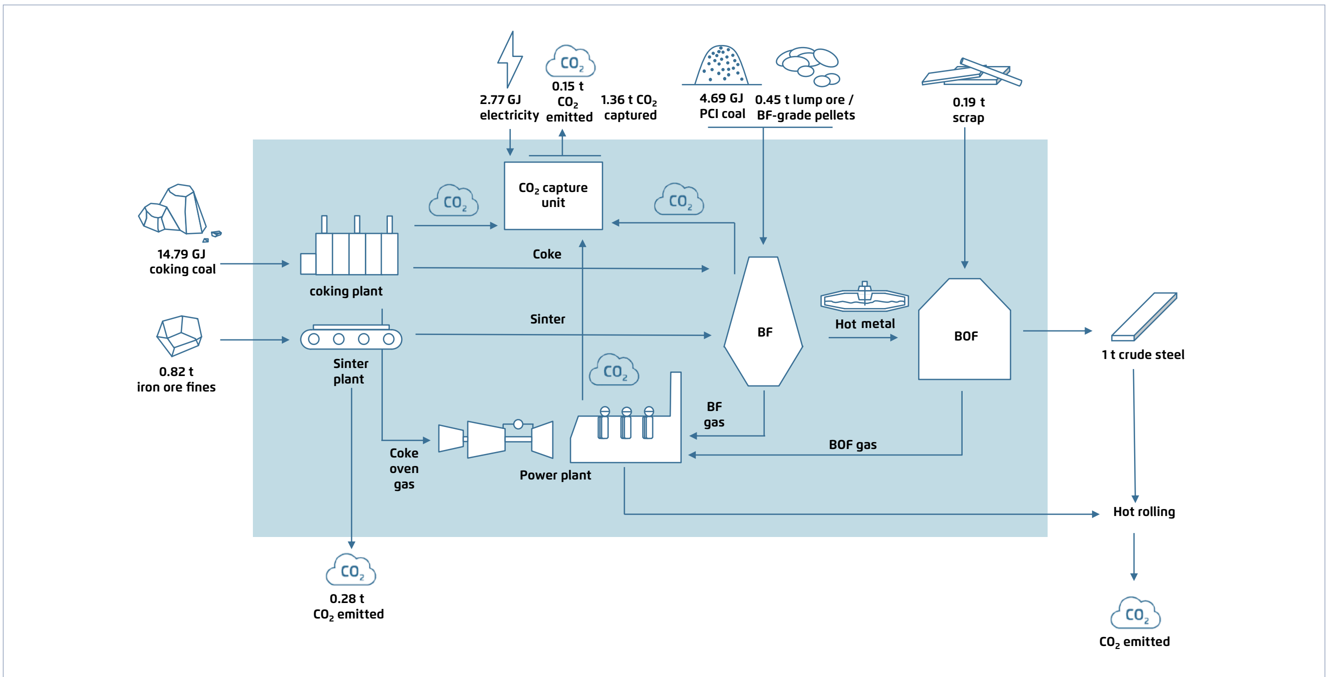
5.6 BLAST FURNACE-BASIC OXYGEN FURNACE ROUTE WITH CCS (BF-BOF-CCS)

Tata Steel BF-BOF site in Jamshedpur Photo: Tata Steel

This process retrofits integrated steelworks (BF-BOF route) to allow the capture of CO_2 emissions from several major point sources: coke oven underfiring, BF hot stoves and the onsite power plant. Using amine scrubbing (MEA)-based CO_2 capture with a 90% capture efficiency results in only 73% on-site CO_2 emission reduction, due to the remaining multiple CO_2 sources. Increasing the CO_2 capture rate across the steelmaking site to include for instance the sinter plant emissions would incur substantial additional costs.

Simplified BF-BOF-CCS process flow

Figure E.6



Agora Industry and Wuppertal Institute, 2024; Note: Process flow diagram shows emissions from major point sources only. Additional emissions from distributed sources total 0.08 tCO_2/t of crude steel.

Example pilot and demonstration projects

Pilot

Project: CO_2 capture from blast furnace gas (Jamshedpur, India)
Tata Steel, Carbon Clean, Veolia
Status: Operation of CCU pilot plant (TRL 3–4)
Outlook: Tata Steel have announced their intention to scale up CCU plants in the future.

A pilot carbon capture plant at the Jamshedpur steel plant is capturing 5 tCO_2 per day directly from the blast furnace gas using amine-based technology and making it available for onsite reuse (CCU).

Pilot

Project: 3D/DMX (Dunkirk, France)
ArcelorMittal and project partners
Status: Pilot CCS plant constructed in 2022.
Outlook: 1 $MtCO_2$/year demonstration CCS plant by 2025

The 3D project aims to demonstrate the DMX CO_2 capture process at ArcelorMittal's Dunkirk steelmaking site and integrate it with the European-North Sea CCS cluster. The first pilot plant aims to capture 0.4 $ktCO_2$ per year from the steel mill, with the aim of implementing an industrial size (1 $MtCO_2$/year) CCS unit after 2025.

Key facts

Technology
BF-BOF route with CCS

Current stage of development
Pilot plant (TRL 3–4)

Expected readiness for use
2030–2035

Energy and infrastructure requirement
- Total energy demand: 22.8 GJ/t of crude steel (of which 19.5 GJ coal/t of crude steel)
- 2.8 GJ of renewable electricity per tonne of crude steel
- CO_2 transport and storage infrastructure

Possible policy instruments
- Carbon price and carbon border adjustment
- Carbon Contracts for Difference
- Green public procurement
- Quotas for low-carbon materials and embedded carbon limits

CO_2 abatement costs vs BF-BOF

2030: **93–163** USD/tCO_2

2050: **83–133** USD/tCO_2

Challenges
Extensive CO_2 infrastructure will be required to transport large volumes of compressed CO_2 from dispersed point sources to remote large-scale storage sites. In many regions, public acceptance of CCS projects is low. Concerns include the risk of locking in fossil fuel-intensive production pathways (with negative environmental and climatic effects) and the availability and long-term safety of storage sites.

Evaluation of technology for steel sector decarbonisation
The technology will likely achieve a CO_2 reduction of only 73%, making it incompatible with climate neutrality. Since no company is currently working on an industrial-scale plant, the technology is not expected to be available before 2030. Upgrading BF-BOFs with CCS at a later stage is possible but would require substantial modifications to achieve a high capture rate.

Comparison of technology with current production pathway

CONVENTIONAL TECHNOLOGY
BF-BOF

KEY LOW-CARBON TECHNOLOGY
BF-BOF-CCS (73%)

1.87 tCO_2/t of crude steel → -73% Specific emission reduction → **0.51** tCO_2/t of crude steel

472–499 USD/t of crude steel (2022) → +27 to +45% Specific additional costs (no CO_2 costs) → **599–721** USD/t of crude steel (2030)

Main assumptions to determine the range of production costs (2030)

Assumption		Lower range [USD/t of crude steel]	Upper range [USD/t of crude steel]
Specific capital costs		34	66
Operating costs of electricity		38	62
Operating costs of metallic feed	Iron ore	197	197
	Scrap	78	109
	Alloys	33	33
Operating cost of CO_2 transport & storage		41	82
Fixed operating costs		69	69
Other costs (coal, coke, natural gas, refractories, fluxes, MEA)		121	123
Sales (slags, tar, offgas)		–12	–18
Production costs (+ costs of residual CO_2 emissions*)		**598 (+46)**	**721 (+66)**

Source: Compiled by Wuppertal Institute and Agora Industry based on various sources.
*Additional CO_2 costs of residual emissions based on a CO_2 price of USD 90–130/tCO_2.

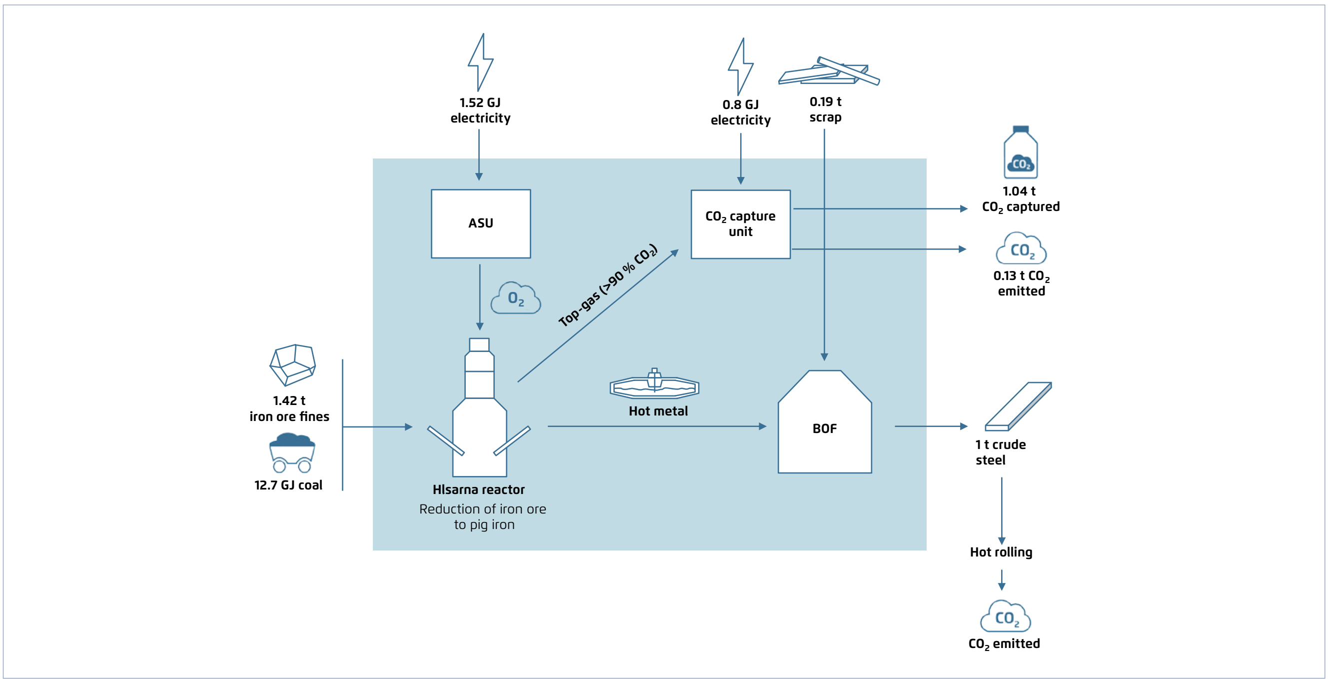
5.7 THE HISARNA® PROCESS + BOF WITH CCS

HIsarna® pilot plant, Tata Steel in IJmuiden Photo: Tata Steel

HIsarna® is an ironmaking process that replaces the BF with a simplified carbon-based smelting reduction process, eliminating the iron ore agglomeration steps (from sinter or pelletising plants) and the need for coke (from the coke oven). Compared to BF-BOF, lower iron ore and coal qualities can be used and the energy demand and CO_2 emissions are reduced. The process is suitable for combination with CCS because of the high CO_2 concentrations in the off-gases and fewer CO_2 point sources. Combined with CCS, CO_2 reductions of up to 93% are possible compared to the BF-BOF route (without CCS, HIsarna® can reduce CO_2 emissions by 38%).

Simplified HIsarna-CCS process flow

Figure E.7



Agora Industry and Wuppertal Institute, 2024; Note: The electricity demand for the air separation unit (ASU) includes all electricity demand from the HIsarna reactor and the BOF.

Example pilot and demonstration projects

Pilot

Project: HIsarna® (IJmuiden, the Netherlands) Tata Steel
Status: Sustained campaign from 2017–2018 (TRL 6).
Outlook: Tata Steel have announced that they will not build a commercial-scale HIsarna® reactor at the IJmuiden site.

The pilot plant has a nominal annual capacity of 60 000 t of crude steel. A number of tests for the production of pig iron and steel have been carried out since 2011. A long-term test in 2018 integrated the HIsarna® reactor into an existing steelmaking plant. The next phase of the pilot project to implement carbon capture has been cancelled as the company has announced that it will pursue the H_2-DRI route at the IJmuiden site.

Demo

Project: HIsarna® (Jamshedpur, India) Tata Steel
Status: Demo plant was planned for 2022 (TRL 5).
Outlook: Unclear.

The construction of the HIsarna plant was announced in November 2018 with an annual capacity of 500 000 t of pig iron. Further development plants to upscale the HIsarna process to industrial scale by 2030 seem to have been halted.

Key facts

Technology
HIsarna® + BOF with CCS

Current stage of development
Pilot plant (TRL5- 6)

Expected readiness for use
2030–2035 (current development status unclear)

Energy and infrastructure requirement
- Total energy demand: 15.4 GJ/t of crude steel (of which 12.7 GJ coal/t crude steel)
- CO_2 transport and storage infrastructure

Possible policy instruments
- Carbon price and carbon border adjustment
- Carbon Contracts for Difference
- Green public procurement
- Quotas for low-carbon materials and embedded carbon limits

CO_2 abatement costs vs BF-BOF

2030	2050
63–117 USD/tCO_2	**56–98** USD/tCO_2

Challenges
The development prospects of the technology are unclear since the demonstration phase of the project in Europe has been cancelled. As far as the use of CCS is concerned, challenges relating to suitable CO_2 storage sites and infrastructure as well as public acceptance need to be clarified (see BF-BOF-CCS factsheet). While HIsarna with CCS could reduce emissions by up to 93%, capturing the remaining residual emissions incurs much higher costs.

Evaluation of technology for steel sector decarbonisation
HIsarna with CCS could achieve CO_2 reductions of around 93% while being a comparatively low-cost option. However, the remaining emissions would need to be compensated. The technology is not likely to be available before the mid-2030s since no company is currently working on its commercialisation.

Comparison of technology with current production pathway

CONVENTIONAL TECHNOLOGY		KEY LOW-CARBON TECHNOLOGY
BF-BOF		**HIsarna-CCS**
1.87 tCO_2/t of crude steel	-93% Specific emission reduction	**0.13** tCO_2/t of crude steel
472–499 USD/t of crude steel (2022)	+23 to +41% Specific additional costs (no CO_2 costs)	**581–704** USD/t of crude steel (2030)

Main assumptions to determine the range of production costs (2030)

Assumption		Lower range [USD/t of crude steel]	Upper range [USD/t of crude steel]
Specific capital costs		41	85
Operating costs of electricity		32	52
Operating costs of metallic feed	Iron ore fines	206	206
	Scrap	78	109
	Alloys	33	33
Fixed operating costs		97	97
Operating cost of CO_2 transport & storage		31	62
Other costs (coal, refractories, fluxes)		68	68
Sales (slags, offgas)		–6	–8
Production costs (+ costs of residual CO_2 emissions*)		**581 (+11)**	**704 (+16)**

Source: Compiled by Wuppertal Institute and Agora Industry based on various sources.
*Additional CO_2 costs of residual emissions based on a CO_2 price of USD 90–130/tCO_2.

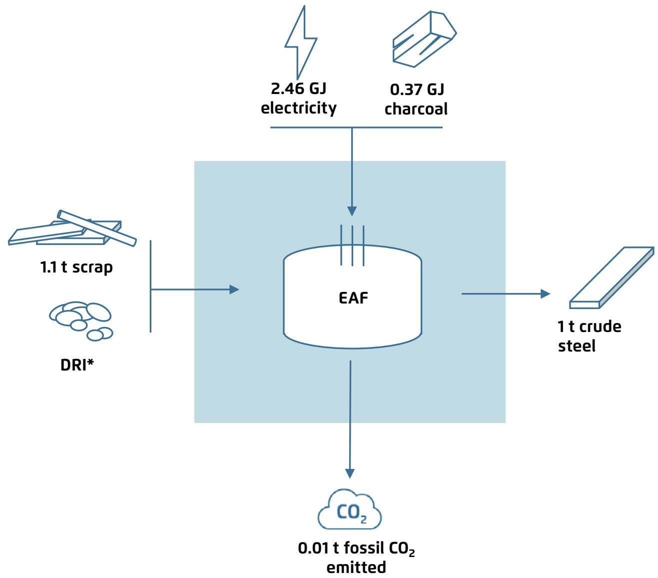
5.8 NEAR-ZERO EMISSIONS SCRAP ELECTRIC ARC FURNACE ROUTE (NZE-SCRAP-EAF)

Electric arc furnace at a Nucor steel plant Photo: Nucor

Roughly 20% of today's world steel production is based on scrap. The EAF is operated with electricity to melt the scrap and small amounts of coal and lime are added to produce slag in order to remove impurities. For direct and indirect CO_2 emissions to be below the proposed IEA near-zero emissions threshold (<50 kg CO_2/t of crude steel), the EAF must use zero-carbon electricity and the carbon input must come from sustainable biomass.

Simplified NZE-Scrap-EAF process flow

Figure E.8



Agora Industry and Wuppertal Institute, 2023; * DRI is not a required input but can be used as additional metallic feed depending on scrap availability and desired steel quality.

Example pilot and demonstration projects

Commercial

Project: Evraz (Pueblo, USA)
EVRAZ, BP, Xcel
Status: Operational since 2021.

EVRAZ is operating the world's first solar-power steel mill. The EAF-based steel mill is powered by a 300 MW solar PV farm. The project will reduce carbon emissions by 0.43 Mt/year.

Commercial

Project: Econiq™ (various locations, USA)
Nucor
Status: Commercial scale (TRL9) - Econiq™ steel supplied to first customer in Q1 2022.

Nucor is operating various EAF-based steel mills across the US. The company is offering steel products labelled as net-zero steel under the brand Econiq™. The steel is made using 100% renewable electricity via VPPAs. The direct emissions (scope 1) from the steelmaking process are compensated by carbon offsets.

Demo

Demo

Project: GreenEAF2/RETROFEED (Italy, Romania)
Consortium of research institutes and steelmakers
Status: GreenEAF2 concluded in 2016.
Outlook: RETROFEED ongoing until 2023.

The GreenEAF2 project and its predecessor GreenEAF1 demonstrated feasibility and validated the utilisation of char from biomass as a substitute for coal in the EAF. The follow-up project RETROFEED aims to enable the use of bio-based feedstocks in several process industries, including steelmaking.

Key facts

Technology
Near-zero emissions scrap-based EAF steel production

Current stage of development
TRL 9 (7 with charcoal) replacing fossil carbon inputs

Expected readiness for use
Ready

Energy and infrastructure requirement
- Total energy demand: 2.8 GJ/t of crude steel (of which 2.5 GJ electricity/t of crude steel)
- Decarbonisation of electricity system
- Optimised recycling infrastructure
- Biomass and charcoal supply

Possible policy instruments
- Carbon price and carbon border adjustment
- Standards for end-of-life sorting
- Standards for design for recycling
- Quotas for low-carbon materials and embedded carbon limits

CO_2 abatement costs vs BF-BOF

2030	2050
not applicable	**not applicable**

The scrap price is likely to adjust to a level that results in cost parity

Challenges
Impurities currently limit the use of scrap steel to low-value steel grades. With better product design and recycling, more scrap could be used in higher-value steel products. This will be an important lever in the long term as the available scrap amounts will rise compared to overall steel demand. R&D is required to address the consumption of graphite electrodes, which contributes to residual CO_2 emissions.

Evaluation of technology for steel sector decarbonisation
If the electricity supply is decarbonised, the secondary route can produce near-zero emissions steel and represents a no-regret option for countries with large steel scrap supplies, especially when combined with measures that address scrap quality. However, in a world of rising demand and limited scrap supply, both primary and secondary steelmaking will be needed.

Comparison of technology with current production pathway

CONVENTIONAL TECHNOLOGY
BF-BOF

KEY LOW-CARBON TECHNOLOGY
Secondary route (scrap)

1.87 tCO_2/t of crude steel → **99.6%** Specific emission reduction → **0.01** tCO_2/t of crude steel

472–499 USD/t of crude steel (2022) → **+35 to +68%** Specific additional costs (no CO_2 costs) → **639–837** USD/t of crude steel (2030)

Main assumptions to determine the range of production costs (2030)

Assumption		Lower range [USD/t of crude steel]	Upper range [USD/t of crude steel]
Specific capital costs		22	22
Operating costs of electricity		34	55
Operating costs of metallic feed	Scrap	453	628
	Alloys	33	33
Fixed operating costs		45	45
Other costs (charcoal, refractories, fluxes, electrodes)		51	54
Production costs (+ costs of residual CO_2 emissions*)		**639 (+1)**	**837 (+1)**

Source: Compiled by Wuppertal Institute and Agora Industry based on various sources.
*Additional CO_2 costs of residual emissions based on a CO_2 price of USD 90–130/tCO_2.

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Agora Industry develops scientifically sound and politically feasible concepts for successful pathways to a climate-neutral industry – in Germany, Europe and internationally. The organisation, which is part of the Agora Think Tanks, works independently of economic and partisan interests. Its only commitment is to climate action.

Agora Industry
Agora Think Tanks gGmbH
Anna-Louisa-Karsch-Straße 2
10178 Berlin | Germany
P +49 (0) 30 7001435-000

www.agora-industry.org
info@agora-industrie.de

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