Summary
Steel is a critical component of the energy transition, yet remains one of the most challenging sectors to decarbonise. An important part of the EU’s economy, employing over 300,000 people directly, the industry faces considerable technical and economic challenges as it seeks to reduce the 190 million tonnes of CO₂ which contribute 5% of the EU’s annual emissions. There are growing efforts to shift primary steel production from coal-based production methods to cleaner alternatives using hydrogen, which will depend on the availability of large volumes of low-carbon hydrogen. Carbon capture and storage offers a complementary approach to cutting emissions from the sector in the near term, but significant investment in CO₂ transport and storage infrastructure is needed to realise this potential. Ultimately, a variety of pathways to net-zero steel exist, each with their own risks and challenges. Various options must be explored and supported to ensure the industry’s transformation to climate neutrality takes place at the necessary pace and scale.

Overview of the steel sector
Steel is one of the fundamental building blocks of modern society, used in buildings, infrastructure, vehicles, and countless other applications. However, the iron and steel sector is also the largest source of industrial emissions in the European Union (EU), accounting for over 5% of total CO₂ emissions.¹ Steel is an iron alloy that can be made through two main routes: ‘primary steel’ from the processing of iron ore, and ‘secondary steel’ from the recycling of scrap steel in an electric arc furnace (EAF). Around 95% of global primary steel production is based on the highly carbon-intensive blast furnace route using coal, with the remaining 5% produced via the ‘direct reduced iron’ (DRI) process, which mostly uses natural gas and can be around two thirds as carbon intensive (Figure 1).²

¹ Somers J (2022) Technologies to decarbonise the EU steel industry, EUR 30982 EN
Secondary steel is much less carbon intensive than primary steel, and currently represents around 44% of European production. Although over 85% of steel is recycled at end of life and the global stock of scrap is rising relative to demand, the role of secondary steel remains limited both by scrap availability and the quality requirements of many end products, and a significant proportion of primary steel will continue to be required in future. Despite rising global demand for steel, production and demand in Europe is projected to remain relatively flat in both business-as-usual and net-zero scenarios, with the contribution from recycled scrap rising to around 60% in 2050 in the latter.

The EU is currently a net exporter of scrap and could therefore increase its domestic secondary production; however, as long as global demand continues to grow, this shift has little impact on global efforts to decarbonise steel, as it merely increases demand for carbon-intensive primary steel in the importing countries.

New technologies will be needed to decarbonise primary steel production and retain this vital industry in the EU, which directly employs over 300,000 people and supports a further 2.27 million indirect and induced jobs.

Nearly all the EU’s primary steel is produced via the blast furnace route, in which iron ore is chemically reduced with coking coal at high temperatures, before it is further processed to steel in a basic oxygen furnace. There are 27 such ‘integrated steel plants’ across 14 EU Member States, and only one DRI plant (Figure 2).

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2. Martin C (2023) Buy clean and steel’s tricky “standards” for environmental performance
Decarbonising steel with hydrogen

Many of the EU’s steel plants are now actively pursuing a shift towards the DRI route, which (unlike blast furnaces) can be operated on 100% low-carbon hydrogen – a technology with the potential to cut CO₂ emissions to near zero. The JRC identifies 18 projects in the EU which are currently developing new DRI-based production, either for immediate use with hydrogen or with natural gas with the intention to switch to renewable hydrogen when it becomes available. Most notably, the Hybrit project in Sweden (SSAB, LKAB, and Vattenfall) has tested small-scale DRI production at 100% hydrogen and has plans to commission a plant with 1.3 Mt/year capacity in 2025. Also in Sweden, ‘H2 Green Steel’ plans to produce 2.5 Mt/year through hydrogen DRI by 2025 using 700 MW of electrolysis capacity, and to double this output by 2030. Northern Sweden is well placed for developing hydrogen DRI at large scale, as there is suitable iron ore and the potential to deploy dedicated low-carbon energy such as wind power. Following these pioneering projects, around 40 Mt/year of hydrogen-based steel projects are now targeted in Europe by 2030, involving nearly all major manufacturers.

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6 https://www.hybritdevelopment.se/en/
7 Maria Persson Gulda (2023) H2 Green Steel
The principal challenge in transitioning all blast furnace production to a low-carbon form of DRI is in sourcing sufficient volumes of low-carbon or renewable hydrogen. Approximately 57 kg of hydrogen are required to produce one ton of crude steel, meaning that over 54 billion m³ (4.9 Mt) of hydrogen would be needed to meet the 85 Mt of primary steel production in the EU in 2021 – equivalent to half of the target for domestic hydrogen production target under REPowerEU. If derived entirely from renewable-powered electrolysis, this would require nearly 300 TWh of renewable generation, or almost double the EU’s total solar power output in 2021. Using grid-powered electrolytic hydrogen would result in an overall carbon intensity of around half that of the blast furnace route, based on the average carbon intensity of the EU grid in 2020. If the supply of new renewable electricity is limited, devoting that energy to hydrogen production for steel could end up significantly slowing the decarbonisation of the electricity grid. In its recent ‘Energy Technology Perspectives 2023’, the IEA highlighted the dominance of DRI-based plans in steel sector decarbonisation, but noted that many of the plans lack a clear plan or timeline for a transition to 100% renewable hydrogen. An alternative option is to obtain hydrogen from natural gas reforming that has been decarbonised with carbon capture and storage; currently, this route is only being explicitly pursued by Thyssenkrupp through the H2morrow project. The overall climate benefit of this pathway will also depend on the extent to which methane emissions can be eliminated from the natural gas supply chain.

**Decarbonising steel with carbon capture**

Carbon capture and storage is another route to decarbonising primary steel production that has also been developed in the EU through research initiatives such as the ‘Ultra-low CO₂ steel making’ project (ULCOS). It has been estimated to require 10-25% of electrical energy used by the hydrogen DRI route. Blast furnace-based steel plants are complex, with several emissions sources and flows of carbon-containing waste gases between different processes for use as fuel. Most research and pilot-scale projects have focused on capture from the blast furnace itself, which is the largest and most concentrated source of CO₂. Current plans include ArcelorMittal’s proposal to capture 1 Mt/year of CO₂ from a blast furnace in Dunkirk, for permanent storage in the North Sea, although this represents only 8% of the plant’s total CO₂ output. A smaller pilot facility capturing 0.5 tCO₂/hour is already operating in Dunkirk, and a similar size facility was demonstrated in Sweden as part of the H2020 project STEPWISE.

There are also several initiatives to convert the carbon in blast furnace gas to fuels and other chemicals – known as carbon capture and utilisation – including a recently commissioned project at the Ghent plant, which uses a biological process to convert carbon monoxide from the blast furnace to ethanol. As this carbon can be re-emitted through use of the product, a life cycle analysis is required to assess the CO₂ abatement relative to a counterfactual scenario.

Scaling up carbon capture to achieve complete decarbonisation of an integrated steel plant would be challenging, but technically possible. The Horizon research project C4U aims to develop capture technologies and process configurations that can achieve up to 89% CO₂ capture over the plant.

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8 Based on Sasiain Conde et al. (2022) Decarbonization of the steel industry. A techno-economic analysis and World Steel Association (2022) World Steel in Figures
9 Greenhouse gas emissions intensity of electricity generation in Europe
10 IEA (2023) Energy Technology Perspectives 2023
13 Tata Steel IJmuiden. Presentation at: CCUS technologies in industrial systems, IEAGHG webinar, 1 Mar 2022
14 Stepwise, https://www.stepwise.eu/project/
16 C4U, https://c4u-project.eu/
Carbon capture can also play a role in decarbonising natural gas-based DRI plants, particularly in the event of limited hydrogen availability. Some DRI technologies include integrated separation of around 60% of the CO₂ produced, and large-scale capture and storage has been demonstrated at a DRI plant in Abu Dhabi since 2016.\textsuperscript{17} Smaller-scale tests for DRI capture are planned at an ArcelorMittal site in the U.S.\textsuperscript{18} Moving to higher capture rates would likely be more straight-forward than for integrated steel plants, but attention will also need to be paid to upstream methane emissions.

\textbf{Even using 100% hydrogen-DRI, it will be challenging to completely eliminate carbon emissions from the process, due to the need for alloying carbon and emissions from EAF electrodes.} ArcelorMittal and Tata Steel have both recognised that there will likely be an additional need for CO₂ capture to address residual emissions, with ArcelorMittal indicating these could amount to up to 0.5 tonnes per tonne of steel. In the U.S., steel producer Nucor are developing CO₂ capture from an electric arc furnace.\textsuperscript{19}

\section*{An ’all of the above’ approach to decarbonisation}

The IEA estimates that carbon capture-based routes have the potential for significantly lower production costs than the hydrogen-DRI route, although such comparisons are highly sensitive to the future cost of green hydrogen, which will in turn depend on the speed and scale of renewables deployment (Figure 3).

Modelling of decarbonisation scenarios for the EU steel sector generally show a range of low-carbon technologies deployed for remaining primary steel production in 2050 (Figure 4).\textsuperscript{3} This technology mix reflects the challenge of replacing the region’s existing blast furnace-based fleet and the uncertainty in future hydrogen availability.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig3}
\caption{Cost of Steel Production Via Conventional and Decarbonised Routes\textsuperscript{20}}
\end{figure}

\textbf{Note: NZE denotes a hydrogen cost in line with the IEA’s ‘Net Zero Emissions by 2050’ decarbonisation scenario; 2022 represents the impact of higher gas prices}

\textsuperscript{16} Achieving carbon free emissions via the Energiron DR process (Duarte et al, 2010); Case study Al Reyadah steel project, CSLF
\textsuperscript{17} BusinessGreen (2022) ArcelorMittal, BHP, and Mitsubishi trial carbon capture technologies for steelmaking
\textsuperscript{18} Cision PR News Wire (2023) Nucor and University of Kentucky receive federal grant for carbon capture R&D at Gallatin mill
\textsuperscript{19} CCUS in Clean Energy Transitions (IEA, 2020)
\textsuperscript{20} IEA (2023) CCUS policies and business models
A comprehensive policy approach to steel sector decarbonisation should reflect this technology mix and encourage the development of all technologies which can deliver large-scale CO\textsubscript{2} reduction in the necessary timeframe. This strategy will:

- Minimise the risk that one technology fails to deliver carbon abatement at the necessary speed and scale, due to resource or infrastructure limitations or to technical failings;
- Ensure the development of a portfolio of low-carbon technologies that can be deployed to a broader range of facilities and local contexts;
- Achieve faster and deeper emissions cuts in the near term, thereby minimising the cumulative emissions to the atmosphere between now and 2050; and
- Accelerate the development of new technologies (such as blast furnace carbon capture) that will be essential to decarbonising much larger steel sectors in China and India.

With a strong carbon price and carbon border adjustment mechanism, the EU can lead the creation of a market for decarbonised steel. These supply-side drivers must be supported by policies to grow demand for decarbonised steel, such as public procurement, compliance standards for embedded carbon in end-use sectors, and greater harmonisation of green steel standards.\textsuperscript{22} However, decarbonising primary steel production will fundamentally require an abundance of clean energy and new infrastructure to transport and store hydrogen and CO\textsubscript{2}, which will also rely on appropriate policy support and coordination. Hydrogen and carbon capture and storage can provide complementary solutions in the transition to net-zero steel production, and the choice of optimum pathway will depend on regional context and decisions at the facility level. To support the development of these long-term strategies, it is critical that policymakers help ensure a variety of options to decarbonise steel are made available.

\textsuperscript{21} Mission Possible Partnership (2021) \textit{Making net zero steel possible}

\textsuperscript{22} CATF (2023) \textit{Building demand for low-carbon materials}