Achieving CO_2-free steelmaking: pathways and challenges

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Highlights

- Scenarios for CO_2 mitigation pathways for crude steel production are defined.
- Circular economy enhances material efficiency.
- Modification of existing steelmaking processes by smart carbon usage.
- Potential reduction of CO_2 emission by 90 % with carbon direct avoidance technologies.

1. Introduction

Steel, renowned for its high performance, has become a vital material of modern life thanks to its diverse properties. As a result, global crude steel production has doubled over the past two decades, reaching approximately 1.9 billion tons in 2024. However, the production of iron and steel consumes significant amounts of fossil fuels. In 2024, on average, every tonne of steel produced emitted 2.18 tonnes of CO_2 (SCOPE 1, 2, and 3) and accounted for 7 to 9% of the world's human-induced CO_2 emissions. The steel industry aims globally to reduce its emissions by focusing on three levers: (1) material efficiency, including digitalization and AI; (2) maximizing the availability and use of scrap; and (3) deploying groundbreaking technologies. [1, 2].

2. Pathways to CO_2-free steelmaking

All industrialized countries and regions have defined transformation scenarios to convert their steel production to CO_2 neutrality. A holistic approach is pursued in the EU, and the pathways to decarbonize steelmaking until 2050 are shown in Figure 1. The circular economy (CE) focuses on increased recovery of materials from residues and on steel scrap recycling. With smart carbon usage (SCU), CO_2 emissions should be reduced by modifying existing blast furnace and basic oxygen (BF-BOF) routes for crude steel production (process integration, PI) and utilizing captured CO_2 as a raw material to produce valuable products such as fuels or basic chemicals (carbon capture and usage, CCUS). Carbon direct avoidance (CDA) is about replacing current fossil fuels with renewables to avoid direct CO_2 emissions from steelmaking, mainly from virgin iron ore. This path is divided into electricity and hydrogen-based metallurgy.

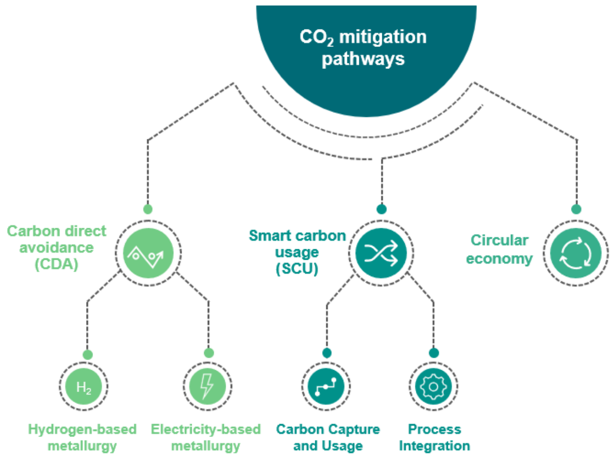

Figure 1. CO_2 mitigation pathways in the EU [3]

In the CDA path, electricity can be used directly to produce metallic iron from iron ores through high- and low-temperature electrolysis, powered by renewable electricity. The hydrogen-based crude steel production routes as an alternative to the current fossil-based route are presented in Figure 2. Two principal process routes can be identified: the H-DR and H-SR routes. The characteristic of the H-DR technologies is that iron ore is reduced with hydrogen in shaft furnaces or fluidized beds to DRI. This DRI is converted to crude steel in subsequent process steps using electric energy. The outline of H-SR technologies is that iron ore is converted to crude steel in a single process step. A pre-heating and pre-reduction stage is an integral part of these technologies. With CDA technologies, CO_2 emissions can be reduced by 90% compared to the current dominant fossil-based BF-BOF route.

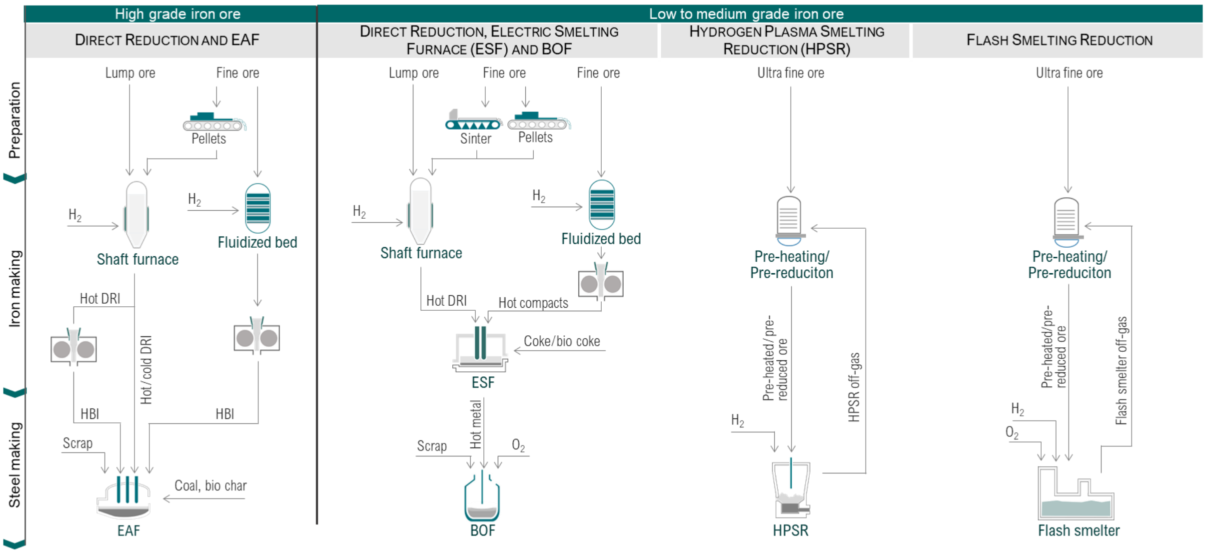

Figure 2. Hydrogen-based crude steel production routes

3. Challenges for the transformation

Achieving CO_2-free steel production faces significant technical hurdles, including the limited readiness of CDA technologies and large-scale CCUS, as well as constraints on the quality of DR-grade iron ore and scrap. The transformation requires huge amounts of reliable, low-carbon electricity and affordable green hydrogen, as well as extensive upgrades to electricity grids, storage facilities, and local infrastructure. The high cost of replacing or retrofitting blast furnaces, combined with fluctuating electricity and hydrogen prices, creates financing and operational risks. Market and political uncertainties, such as inconsistent CO_2 pricing, unclear green premiums, and the need for robust certification, further complicate investment decisions. Supply chain bottlenecks, workforce retraining needs, water availability, land use, and the timeframes for approval procedures can also slow implementation.

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Keywords

"Circular economy", "Smart carbon usage", "Carbon direct avoidance", "Hydrogen-based metallurgy"