The Future of Low-Carbon Steel: Technological Trends and Industrial Transformation

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Introduction

Global steel production has shown a consistent upward trend over the decades, reflecting industrial growth worldwide. The only notable exception is the temporary dip during the COVID-19 pandemic (2020–2021), when production briefly stagnated or declined due to supply chain disruptions and reduced demand. Importantly, steel is 100% recyclable, which provides a strong advantage when considering CO_2 emissions and opportunities for a low-carbon circular economy. From current world production of steel of about 1.9bnt/year, available model estimates world production in 2050 in the range 2.5-2.5bnt/year. Global and European efforts to decarbonize the steel industry are accelerating, driven by national and regional climate commitments that target net-zero emissions between 2050 and 2060 in most major economies. Governments and steelmakers are converging on a mix of strategies: ambitious climate policies, incentives for “green” production routes such as electric arc furnaces, green hydrogen–based direct reduction, expanded steel recycling, and-where feasible-the deployment of carbon capture, utilization, and storage (CCUS).

Yet the transition remains technically complex and economically demanding. Transforming an industry built on coal-based blast furnaces requires massive infrastructural upgrades, secure access to renewable electricity and affordable green hydrogen, and in many cases the full conversion or retirement of existing assets. Although low-carbon steelmaking is gaining traction, it still represents a small fraction of global output. The real impact on worldwide emissions will depend on how quickly these emerging technologies can scale and how effectively countries align industrial policy, energy systems, and investment flows with long-term climate goals.

year	**World steel production (Mt)**	**∆ respect previous year (Mt)**
1950	189	–
1960	347	+158
1970	595	+248
1980	717	+122
1990	770	+53
2000	850	+80
2005	1 148	+298
2010	1 435	+287
2015	1 627	+192
2016	1 634	+7
2017	1 738	+104
2018	1 831	+93
2019	1 879	+48
2020*	1 883	+4
2021	1 963	+80
2022	1 889	–74
2023	1 888.2	–0.8
2024	1 882.6	–5.6

*COVID

CO_2 Emission Target to net Zero

The steel industry is a major source of CO_2 emissions, approximately 1 ton of BF-based steel generates about 2.3 tons of CO_2 (source: World Steel Association), and many countries are increasingly subjecting it to carbon-pricing mechanisms, such as Emissions Trading Systems (ETS) or carbon taxes. These mechanisms assign a price to CO_2 emissions, incentivizing producers to adopt low-carbon technologies. In the 2025 policy-mapping report by The Climate Club, the column "CO_2 pricing / ETS in place" refers to explicit carbon-pricing instruments applicable to heavy industry, including steel. However, the presence of an ETS does not automatically guarantee strong emission reductions. Many systems grant free allowances to "emissions-intensive, trade-exposed" sectors such as steel, which can significantly weaken the economic incentive to decarbonize. The 2025 Climate Club report highlights this as a key limitation in achieving meaningful emission reductions.

In addition, for steel imported into the European Union, the Carbon Border Adjustment Mechanism (CBAM) is being implemented to prevent the import of high-carbon steel from regions without comparable carbon pricing. While CBAM is a step toward ensuring fair competition and incentivizing global decarbonization, accurately verifying the embedded CO_2 content of imported steel remains challenging, due to differences in production methods, data availability, and reporting standards. Finally, the "Steel production mix" (BF-BOF vs EAF) reported in the Climate Club 2025 mapping provides an important indicator of a country's readiness to decarbonize: electric arc furnaces (EAF) using scrap steel are generally much less carbon-intensive than traditional blast furnace-basic oxygen furnace (BF BOF) routes. The mix thus informs both policy and market considerations in carbon-constrained environments.

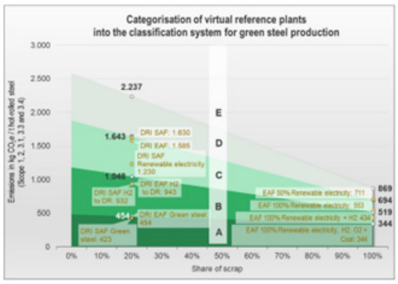
Country / Area	**Net-Zero (or equivalent) target for national / steel sector**	**Steel production mix (latest, BF-BOF vs EAF, %)**	**CO_2-pricing / Carbon-quota / ETS in place? (or status)**
EU-27 (European Union)	2050	~ 56.3 % BF-BOF / 43.7 % EAF	Yes - covered by EU Emissions Trading System (ETS)
Germany	2045	~ 70.2 % BF-BOF / 29.8 % EAF	Yes (via EU ETS)
France	2050	~ 67.4 % BF-BOF / 32.6 % EAF	Yes (EU ETS)
Italy	2050 (aligned to EU)	~ 16.0 % BF-BOF / 84.0 % EAF - among highest EAF share	Yes (EU ETS)
United Kingdom	2050	~ 80.9 % BF-BOF / 19.1 % EAF	Yes (UK ETS / carbon-pricing regime)
United States	2050 (industrial decarb. commitments)	~ 31.0 % BF-BOF / 69.0 % EAF	Partial - ETS exist in some states (e.g. California, Washington)
Canada	2050	~ 53.9 % BF-BOF / 46.1 % EAF	Yes - carbon-pricing / ETS in place
Australia	2050	~ 73.5 % BF-BOF / 26.5 % EAF	Yes - mapping indicates a carbon-pricing instrument applies to industry/steel sector)
China	2060 national target (The Climate Club)	~ 90.5 % BF-BOF / 9.5 % EAF (coal-heavy)	Partial / Emerging - pilot ETS in some provinces (as of 2025)
South Korea	2050	~ 68.5 % BF-BOF / 31.5 % EAF	Yes - ETS / carbon-pricing mechanism applies

Country / Area	Net-Zero (or equivalent) target for national / steel sector	Steel production mix (latest, BF-BOF vs EAF, %)	CO_2-pricing / Carbon-quota / ETS in place? (or status)
India	2070 (general net-zero target)	~ 45.8 % BF-BOF / 54.2 % EAF	No (yet) - no mature carbon-pricing / ETS for steel currently in force.
Brazil	2050	~ 75.1 % BF-BOF / 23.8 % EAF	No explicit instrument listed for steel / heavy-industry carbon pricing.
Indonesia	2060	~ 70.1 % BF-BOF / 29.9 % EAF	No - no explicit carbon-pricing / ETS for steel per mapping.
Türkiye	2053	~ 28.5 % BF-BOF / 71.5 % EAF	No (yet) - mapping shows no carbon-pricing instrument currently in force for steel.
United Arab Emirates (UAE)	2050 (national strategic target) - steel major (emsteel.com)	~ 31.0 % BF-BOF / 69.0 % EAF	No formal ETS publicly listed yet, but major producer EMSTEEL has announced a net-zero-by-2050 strategy; UAE is reportedly working on emissions legislation allowing credits / carbon-credit trading for large emitters. (emsteel.com)

Table 1 Decarbonization targets and steel production mix

With the term "Green Steel" it is intended a steel produced with low (or even zero" carbon footprint. Even if there is not yet a unique definition at European and International level[1], the green steel market and the adoption of "green technologies" are expected to grow rapidly in the next years.

[1] Regarding the definition of Green Steel, at European level a proposal has been raised by the German steel producers, but the definition of a standard and also of a labelling for green steel is not yet agreed among Member States. L'unione Europea non ha ancora adottato una definizione ufficiale di green Steel. This proposal suggest to use a label indicating the carbon footprint (expressed as kg CO_2/ton of finished steel, and a ranking based on letters (from A to E) similarly labelling of households. The letters are attributed by a classification system with five categories: the first ambition level, D, requires emission intensity beyond today's state-of-the-art production processes; the highest level, A, is for near zero emission steel, produced exclusively with renewable energy.2 For the intermediate levels, the thresholds values/limits are defined in a technology-open manner and are set such as to require considerable CO_2 emissions reduction efforts to reach the next level. A central element of this proposal is to account for the use of steel scrap by means of a so-called "sliding scale" . This means that the CO_2 intensity of a ton of steel is set in relation to the share of steel scrap used in the production process. This is to reflect the limited availability of steel scrap worldwide as well as the lack of a clear threshold to distinguish between primary and secondary steel production. Figure below clarify the attribution of the category. India is the unique member Staes that adopted an own definition of Green Steel. According to this definition, Green Steel: Steel is produced with CO_2 equivalent emission intensity of less than 2.2 tonnes of CO_2e per tonne of finished steel. Star Rating System (based on greenness): The threshold limit for star ratings will be reviewed every three years. The current threshold is: five-star green-rated steel: Emission intensity lower than 1.6 tonnes; four-star green-rated steel: Emission intensity between 1.6 and 2.0 tonnes; three-star green-rated steel: Emission intensity between 2.0 and 2.2 tonnes.



DRI=Direct Reduced Iron, SAF=Submerged Arc Furnace, DR=Direct Reduction, EAF=Electric Arc Furnace

Steel Decarbonization Technologies

Several technological routes are being developed to decarbonize the steel sector. The traditional blast furnace-basic oxygen furnace (BF-BOF) route can be partially decarbonized through improved energy efficiency, use of low-carbon reductants, reforming and recirculation of BF and cokeoven off gases, CO_2 capture and storage (CCS) applied to the blast furnace, hot stoves, and other high-emitting units. CCS represents one of the main options to mitigate emissions from integrated steel plants that continue to rely on ore-based primary steelmaking.

A parallel and increasingly relevant pathway is the adoption of Direct Reduction (DRI/DRP) technology, which can operate using natural gas, hydrogen, or blends of the two. DRI plants are typically paired with Electric Arc Furnaces (EAFs), enabling a significant reduction in direct CO_2 emissions, especially when hydrogen is introduced or when the upstream energy supply is low-carbon. DRI systems can also be combined with CCS, particularly when natural gas is used as the reductant.

At the international level, the main decarbonization strategies being deployed combine DRI plants using flexible feedstocks (NG, H_2-ready, or hydrogen-based) with EAF steelmaking, complemented by CCS and the production of low-CO_2 energy carriers, such as renewable hydrogen or hydrogen produced with carbon capture.

The current project pipeline-such as Salzgitter, Boden, ThyssenKrupp, Gravithy, Dillingen, Adria (Danieli-Metinvest) and Tata Steel IJmuiden-reflects this trend, with multiple installations planned between 2026 and 2030 using Midrex or Energiron technology and progressively integrating low carbon hydrogen.

Beyond these dominant routes, additional emerging options include biogenic reductants, electrification of heat processes, and advanced concepts such as electrochemical or plasma-based iron ore reduction, which represent longer-term possibilities for deeper decarbonization. While these technologies are at earlier stages of development, they form part of the broader landscape of future decarbonization measures.

Overall, the international approach is converging on the deployment of DRI-based steelmaking with multiple feed alternatives, integration with existing assets, and the progressive introduction of CCS and low-CO_2 hydrogen as complementary technologies to reduce emissions across both the BF-BOF and DRI-EAF routes.

Picture below shows the technological analysis carried out in a research project funded by European Union (GreenSteel for Europe, grant agreement NUMBER 882151).

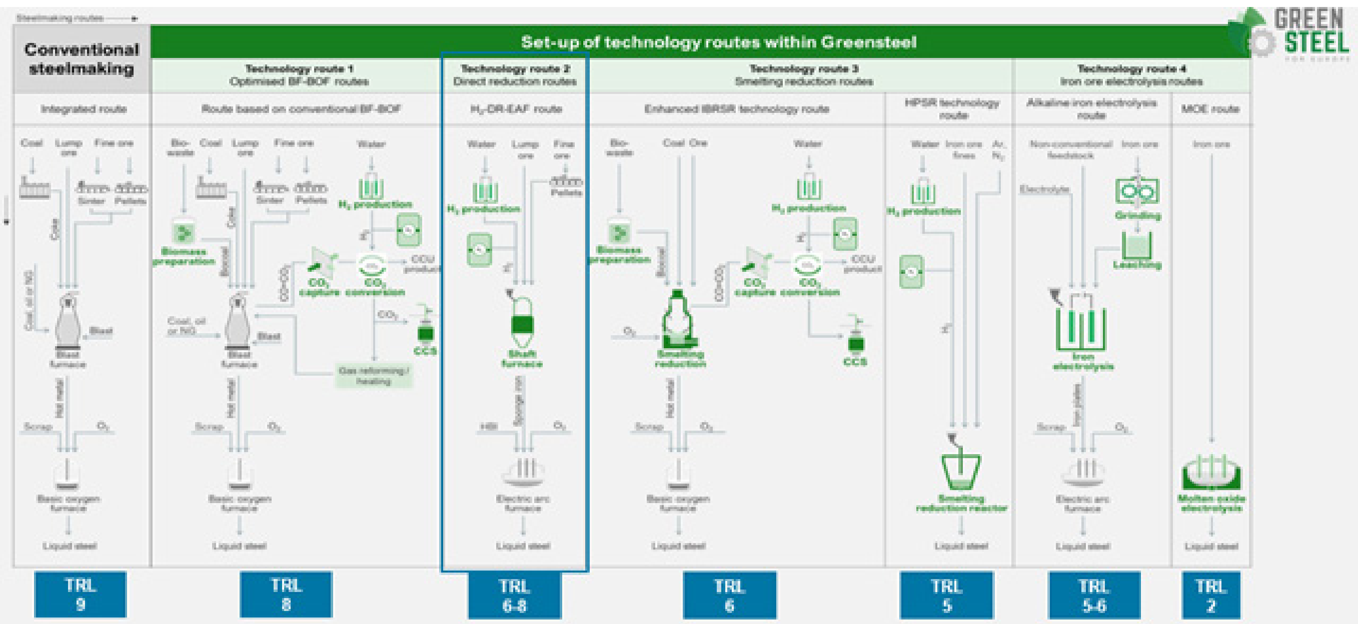


Figure 1 Classification of Technolgoies according to research project funded by European Union (GreenSteel for Europe, grant agreement NUMBER 882151)

BF + CCS as a Decarbonization Pathway - Discursive Explanation

One of the key options under consideration for decarbonizing the steel sector is the application of carbon capture and storage (CCS) to the conventional blast furnace–basic oxygen furnace (BF–BOF) production route. This pathway seeks to substantially reduce emissions from integrated steelmaking without requiring immediate replacement of the existing production infrastructure. In essence, CCS allows the BF–BOF configuration to remain operational while capturing a large portion of the CO_2 emitted during primary steel production, particularly from the blast furnace gas, the hot stoves, and other high-emission process units.

The main appeal of BF + CCS lies in its compatibility with the current industrial landscape. Many regions rely on large integrated steel plants that supply essential volumes to automotive, construction, and mechanical industries, and retiring or replacing these assets in the short term would be both economically and logistically challenging. CCS makes it possible to achieve meaningful reductions in direct emissions while maintaining production stability and avoiding the need for immediate large-scale hydrogen supply, which remains limited by infrastructure and cost constraints.

Moreover, the core technologies for CO_2 capture, compression, transport, and geological storage are already known and have been demonstrated in other industrial sectors, making them relatively mature solutions that can be adapted to steelmaking.

Nevertheless, the BF + CCS pathway also presents significant limitations. Although CO_2 capture can significantly reduce emissions, the overall reduction achieved depends on the number of flue gas streams treated and on the capture efficiency of each unit. Some emissions sources are more difficult to treat and may require extensive pre-conditioning of the gas streams, meaning that full decarbonization is rarely achievable.

The capture process is energy-intensive, adding a substantial energy penalty that must be supplied through low-carbon electricity or heat to avoid offsetting part of the emissions savings. At the same time, CCS adds considerable capital and operating costs related to the installation and operation of capture plants, compression systems, pipelines or shipping infrastructure, and long-term storage monitoring. These aspects underline the importance of regulatory support, carbon pricing, and regional infrastructure planning in determining whether BF + CCS can be economically viable.

Another factor that heavily influences the feasibility of BF + CCS is the availability of suitable CO_2 transport and storage infrastructure. Regions with access to geological storage sites or established CO_2 networks are significantly better positioned to adopt this solution. Conversely, in areas where transport routes and storage locations are not yet available, large-scale deployment becomes much more uncertain and may introduce long delays. Public acceptance, permitting processes, and long-term storage liability also add layers of complexity that must be addressed for projects to proceed.

Despite these challenges, BF + CCS can play a meaningful role in national or regional decarbonization strategies, particularly during the transition phase while newer technologies mature. It offers a way to reduce emissions from existing assets and can serve as a bridge solution while the industry gradually scales up alternative pathways such as Direct Reduction using natural gas, hydrogen, or blends, combined with Electric Arc Furnaces.

Over time, this hybrid approach can provide flexibility: CCS reduces emissions from the existing BF–BOF route, while incremental deployment of DRI–EAF systems and low-carbon hydrogen allow steelmakers to diversify and progressively shift the production mix toward lower-carbon technologies.

In practical terms, the effectiveness of BF + CCS depends on integrated planning that considers the energy system, CO_2 logistics, regulatory frameworks, and market incentives. It is not a zero-emissions pathway, since residual emissions remains and the process still depends on coal as a reductant. However, when conditions are favorable-particularly in regions with suitable storage basins and supportive policy environments-it can enable substantial reductions in the carbon footprint of integrated steelmaking.

In this sense, BF + CCS should be viewed as part of a broader transition strategy: a pragmatic and technically feasible medium-term measure that can complement the longer-term shift toward hydrogen-based DRI and other emerging low-carbon technologies.

Gas-Fed DRP + CCS

The Direct Reduced Iron (DRP) process produces Direct Reduced Iron (DRI), also known as sponge iron, obtained from iron ore at significantly lower temperatures compared to traditional blast furnaces (BOF). This lower-temperature process already offers energy advantages and flexibility in terms of feedstock.

When the reduction is carried out using hydrogen (H_2) instead of carbon, the direct CO_2 emissions are drastically reduced, with water being the primary by-product in the ideal H_2-DRI scenario. This makes hydrogen-based DRI one of the most promising pathways toward near-zero carbon steel. Even when using a gas-fed DRP process with natural gas, the integration of Carbon Capture and Storage (CCS) can significantly mitigate CO_2 emissions, allowing existing production infrastructures to transition toward low-carbon steel.

The combination of H_2-DRI and Electric Arc Furnace (EAF) production is widely considered one of the most viable routes for producing “almost zero-carbon” steel. It offers the flexibility to gradually replace traditional blast furnace operations, while leveraging renewable hydrogen and carbon capture technologies to achieve a substantial reduction in the steel sector’s carbon footprint.

The coupling with EAF melting step allows to further mitigate the CO_2 emissions of the whole production chain with proper blending with scrap. The utilization of improved scrap sorting technologies allows to use relevant percentages in the melting mix, further reducing the CO_2 emissions from production route.

In summary, the gas-fed DRP + CCS pathway, and especially hydrogen-based DRI, represent key technologies in the global effort to decarbonize steel production, balancing technical feasibility, scalability, and environmental impact.

H2- DRP

The use of hydrogen for direct reduced iron (DRP) naturally raises the critical issue of low-CO_2 hydrogen production, which is a delicate topic both technically and energetically.

To understand the renewable energy demand associated with producing green hydrogen for a DRP plant, consider the following example:

- 1 ton of steel produced via DRP requires approximately 55 kg of hydrogen, which in turn requires around 3 MWh of electricity to be produced from water electrolysis
- For a production of 2 million tons of steel, the total energy demand for green hydrogen would be about 6 TWh

For reference, the annual electricity production of an average European country, such as Italy, is approximately 300 TWh.

Therefore, producing the hydrogen required for 2 million tons of steel would represent roughly 2% of the country’s annual electricity production. In terms of renewable energy capacity, this would correspond to:

- About 4.8 GWp of solar photovoltaic capacity (with 1250 hours of radiation), or
- About 2.28 GWp of wind power capacity

These figures help illustrate the scale of the energy investment required to make hydrogen-fed DRP a viable solution for producing green steel.

Category	Solar PV Only	Wind Only	Mixed Solar + Wind
Energy target	6 TWh/yr	6 TWh/yr	6 TWh/yr (3 + 3)
Installed capacity required	≈ 4.8 GWp	≈ 2.28 GW	≈ 2.4 GWp solar + 1.14 GW wind
Capacity factor	~15%	~30%	Solar ~15% + Wind ~30%

Table 2 Renewable energy demand to produce Hydrogen for annual production of 2Mt of steel

The production of blue hydrogen, primarily via Steam Methane Reforming (SMR) with Carbon

Country	Location	Company	Associated project (s)	Technology	Expected commissioning	Plant capacity (Mt/y DRI)
DE	Salzgitter	Salzgitter	SALCOS	Energiron	2026	2.1
SE	Boden	Stegra	Stegra (previ-ously H2Green-Steel)	Midrex	2027	2.1
DE	Duisburg	ThyssenKrupp	tkH2STEEL	Midrex	2027	2.5
FR	Fos-sur-Mer	Gravithy	Gravithy	Midrex	2029	2.0
DE	Dillingen	Rogesa	POWER4STEEL	Midrex	2029	2.0
NL	IJmuiden	Tata Steel	HeraCless	Energiron	2030	2.5
FI	Inkoo	Blastr Green Steel	Blastr Green Steel	Midrex	2030	2.5
ES	Gijón	ArcelorMittal			On hold	2.3
SE	Norbotten	LKAB				
IT	Piombino	Danieli Metinvest	ADRIA	Energiron	2029	2.5

Table 3 Current state of European installations of production plants based on direct reduction

Capture and Storage (CCS), has a significant energy demand inherent in the process and the operation of the CCS technology. The CCS process adds approximately 16 kWh of energy demand per kilogram of hydrogen produced. This results in a total energy demand of around 71 kWh/kg H_2 for blue hydrogen, compared to about 55 kWh/kg H_2 for grey hydrogen (SMR without CCS). Anyhow the utilization of blue hydrogen can be considered an important transitory option.

DRI as the Preferred Green Steel Technology in Europe

The European Union has identified Direct Reduced Iron (DRI) as a cornerstone technology for the decarbonization of the steel sector. The DRI process, particularly when combined with hydrogen (H_2-DRI) and electric arc furnace (EAF) production, is considered one of the most promising pathways toward near-zero carbon steel. This choice reflects Europe's strategic focus on scalable, technologically mature solutions that can significantly reduce CO_2 emissions while leveraging renewable energy sources.

There are ten ongoing projects foreseen the installation of DRI green steel plants. This illustrate the region's commitment to industrial decarbonization. These facilities not only integrate hydrogen reduction and, in some cases, CCS technologies, but they also demonstrate the feasibility of producing steel with dramatically reduced carbon footprints. The European approach emphasizes policy support, innovation, and renewable energy integration, ensuring that DRI-based steel production can scale efficiently while meeting climate targets. Table below reports the detail on the ongoing installations.

The DRI route-particularly hydrogen-based DRI-is central to Europe's green steel strategy. With multiple installations already underway or planned, Europe is setting the standard for industrial decarbonization, combining technology, renewable energy, and strategic policy to transform the steel sector.

Currently in Europe there are only two DRI plants under operation and there are pilot plants (Salcos in Germany and HYBRIT in Sweeden, both based on Energiron technology). Starting from beginning of 2026 the open platform managed by Rina will be in operation. This platform, integrates a pilot DRI production plant (able to work from 100% natural gas up to 100% hydrogen), an EAF to perform melting tests able to work in a flexible manner with any percentages of scrap and DRI and equipped with hydrogen burner and innovative lances to inject secondary carbon carriers to replace pulverised coal injection.

HYDRA experimental platform includes also the erection of advanced labs for analysis and qualification of materials in hydrogen containing atmosphere and utilization of the combustion station to tests innovative burnes up to 3MW. HYDRA project is an IPCEI project, funded by the Italian minister MIMIT under the frame of NextGenEU

HYDRA Direct Reduction Pilot Plant in the Rina premises in Castel Romano - Rome

Decarbonization Roadmap Considerations

When planning the decarbonization of steel production under a carbon pricing regime, several pathways can be considered, each with its advantages and challenges.

One option is to maintain a conventional Blast Oxygen Furnace (BOF) and implement Carbon Capture and Storage (CCS). This can serve as a temporary "bridge solution," allowing the plant to reduce emissions while other technologies are developed. The main advantage is that it leverages existing infrastructure, but it has limitations in terms of the ultimate reduction of CO_2 emissions and involves additional operational and capital costs associated with CCS.

A more transformative approach is the adoption of Direct Reduced Iron (DRI) technology, particularly when powered by hydrogen. This pathway can significantly decarbonize steel production, potentially achieving near-zero carbon emissions. However, the energy demand for hydrogen is substantial. For instance, a DRP plant producing 2 million tons of steel annually would require approximately 4 GW of solar photovoltaic capacity to supply green hydrogen. The high capital expenditure (CAPEX) and operational expenditure (OPEX) make this a costly solution. One practical strategy is to start with a natural gas-fed DRP supplemented by a small hydrogen fraction, gradually increasing the hydrogen share as availability grows and costs decline.

An intermediate solution is also possible: pairing a BOF with a DRP fed by methane (CH_4), with the potential to switch to green hydrogen in the future. In this scenario, the BOF can continue production with reduced emissions by receiving partially decarbonized DRI from the DRP, and an integrated carbon capture system can further reduce the CO_2 footprint. Once the BOF reaches the end of its operational life, the DRP plant can continue operating independently, already configured for hydrogen, maintaining production while further lowering emissions.

In summary, the decarbonization roadmap can involve multiple stages: temporary solutions with CCS, gradual introduction of hydrogen in DRP, and hybrid strategies combining DRP and BOF to optimize emissions reductions, capital deployment, and operational feasibility. Each pathway requires careful planning to balance technological maturity, energy availability, and economic considerations.

- GWorldwide, DRI-based green steel installations are expanding rapidly. Several countries, particularly in the Middle East and Asia, are investing in hydrogen-ready DRI facilities to meet both domestic and export demands for low-carbon steel. While Europe is leading in terms of policy-driven adoption, the global trend shows growing interest in DRI as a key technology for green steel
- European Perspective: In Europe

Role of CO_2 Pricing and CBAM

The presence of carbon pricing mechanisms, such as the EU Emissions Trading System (ETS), can progressively make DRI adoption more economically attractive. As the cost of emitting CO_2 rises, the financial benefits of producing low-carbon steel via DRI become more significant, particularly for European producers subject to strict ETS rules.

For producers outside Europe, the introduction of the Carbon Border Adjustment Mechanism (CBAM) further strengthens the business case for low-carbon steel. Imported steel is effectively penalized if its carbon footprint exceeds certain thresholds, meaning that overseas producers may find it advantageous to invest in DRI or other decarbonization technologies to remain competitive in the European market.

In summary, the decarbonization roadmap can involve multiple stages: temporary solutions with CCS, gradual introduction of hydrogen in DRP, hybrid strategies combining DRP and BOF, and the strategic influence of carbon pricing and CBAM. Together, these factors create both regulatory pressure and economic incentives that accelerate the transition toward green steel, balancing technological feasibility, energy requirements, and long-term competitiveness.

Conclusions

The decarbonization of the steel sector is a complex challenge that requires a combination of technological innovation, energy planning, and strategic policy incentives. Direct Reduced Iron (DRI) combined with Electric Arc Furnace (EAF) production is emerging as one of the most promising pathways toward near-zero carbon steel.

Blast furnace revamping can be applied as temporary alternative and it is reasonably applicable in case of plants with relatively low age (less than twenty years).

While the transition involves high energy requirements, capital expenditure, and operational considerations, staged approaches-such as starting with natural gas-fed DRP and gradually introducing hydrogen-offer feasible routes toward full decarbonization. Carbon pricing mechanisms and instruments such as the EU Emissions Trading System (ETS) and the Carbon Border Adjustment Mechanism (CBAM) further reinforce the economic case for low-carbon steel production, both within Europe and for global producers targeting European markets.

In this context, the HYDRA Project by RINA represents a crucial step forward. With a production capacity of 10,000 tons per year, HYDRA is designed to test the complete DRP + EAF process, enabling the simulation of various operational conditions and different technology combinations. The project is of a scale sufficient to reproduce real process conditions, providing a unique technical and economic demonstrator.

HYDRA also serves as a platform for training, procedure development, and workforce formation, ensuring that personnel are equipped with the skills and knowledge required to operate next-generation green steel facilities. It also enables targeted techno-economic assessments, helping evaluate how hydrogen-based technologies can be integrated into different industrial contexts and providing evidence-based insights for investment and deployment decisions.

By bridging the gap between laboratory research and full-scale industrial implementation, the HYDRA Project contributes significantly to the practical advancement of sustainable steel production.

In conclusion, initiatives like HYDRA are essential to accelerating the transition toward green steel, providing not only technological validation but also operational, economic, and human-capital insights necessary to scale low-carbon steel production effectively.

Decalogue of 10 Priorities

1.Deploy Hydrogen-Based Direct Reduction (H_2-DRI/DRP) with EAF
Hydrogen-based DRI combined with Electric Arc Furnace (EAF) production is one of the most promising pathways toward near-zero carbon steel. It significantly reduces direct CO_2 emissions, with water as the main by-product.
Motivation: Key technology for deep decarbonization; scalable and increasingly mature.

2.Integrate Carbon Capture, Utilization & Storage (CCUS) in existing BF–BOF plants
CCS can serve as a bridge solution, capturing CO_2 emissions from blast furnaces while hydrogen infrastructure and low-carbon energy capacity scale up.
Motivation: Reduces emissions without immediate replacement of existing assets; technically mature.

3.Implement a Gradual Transition: Pair DRP with Existing BOF
Operate a gas-fed DRP plant alongside an existing BF–BOF. Partially decarbonized DRI can feed the BOF, reducing emissions. Once the BOF reaches end-of-life, the DRP can operate independently, fully hydrogen-ready.
Motivation: Smooth transition strategy; leverages existing infrastructure while preparing for full H_2 adoption; avoids stranded assets.

4.Expand Steel Recycling and Scrap-Based EAF Usage
Using scrap steel in EAFs significantly lowers CO_2 emissions and reduces demand for primary iron.
Motivation: Mature technology; immediate environmental benefits; supports circular economy.

5.Gradual Introduction of Green Hydrogen in Transitional DRP Plants
Begin with natural gas-fed DRP supplemented by a small hydrogen fraction, gradually increasing hydrogen share as supply grows.
Motivation: Enables cost-effective, staged decarbonization; mitigates high CAPEX and energy demands.

6.Develop Low-Carbon Energy Supply for Hydrogen Production
Green hydrogen requires large amounts of renewable electricity; securing reliable, affordable renewable energy is critical.
Motivation: Ensures scalability of H_2-DRI and long-term decarbonization.

7.Leverage Carbon Pricing and Regulatory Mechanisms (ETS, CBAM)
Carbon pricing incentivizes low-carbon steel production, while CBAM ensures imported steel meets emissions standards.
Motivation: Aligns economic incentives with climate goals; strengthens global competitiveness of green steel.

8.Invest in Transport and Storage Infrastructure for Hydrogen and Captured CO_2
Hydrogen pipelines, ammonia shipping, and CO_2 storage networks are essential for integrating low-carbon steel technologies at scale.
Motivation: Enables practical deployment of H_2-DRI and CCS across industrial regions.

9.Support Technological Innovation and Pilot Demonstrators
Platforms like HYDRA allow full-process testing, techno-economic assessments, and integration of emerging technologies under real operational conditions.
Motivation: Provides technical validation and evidence-based guidance for scaling up.

10.Train Workforce and Develop Procedures for Next-Generation Steel Plants
Skilled personnel are essential to operate H_2-DRI/EAF and hybrid systems efficiently.
Motivation: Ensures operational reliability and safe adoption of new technologies.

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