Technology Ready Reckoner Low Emission Ironmaking

Suitability to India

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Acknowledgments

TERI acknowledges the support received from Sustainability, Equity and Diversity (SED) Fund for preparing this document.

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Suggested citation

Hall, W 2025. Low emission ironmaking technologies – suitability to India, The Energy and Resources Institute. New Delhi

Published by

The Energy and Resources Institute (TERI) Darbari Seth Block, IHC Complex, Lodhi Road New Delhi – 110003

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1.0 Introduction

In order to decarbonise, the steel sector will require new low emission technologies, all of which are at different stages of development, with different characteristics that make them more or less suited to the Indian context.

The majority of emissions in the iron and steel sector are in the ironmaking process, with well-established technologies available for low emission steelmaking (electric arc / induction furnaces).

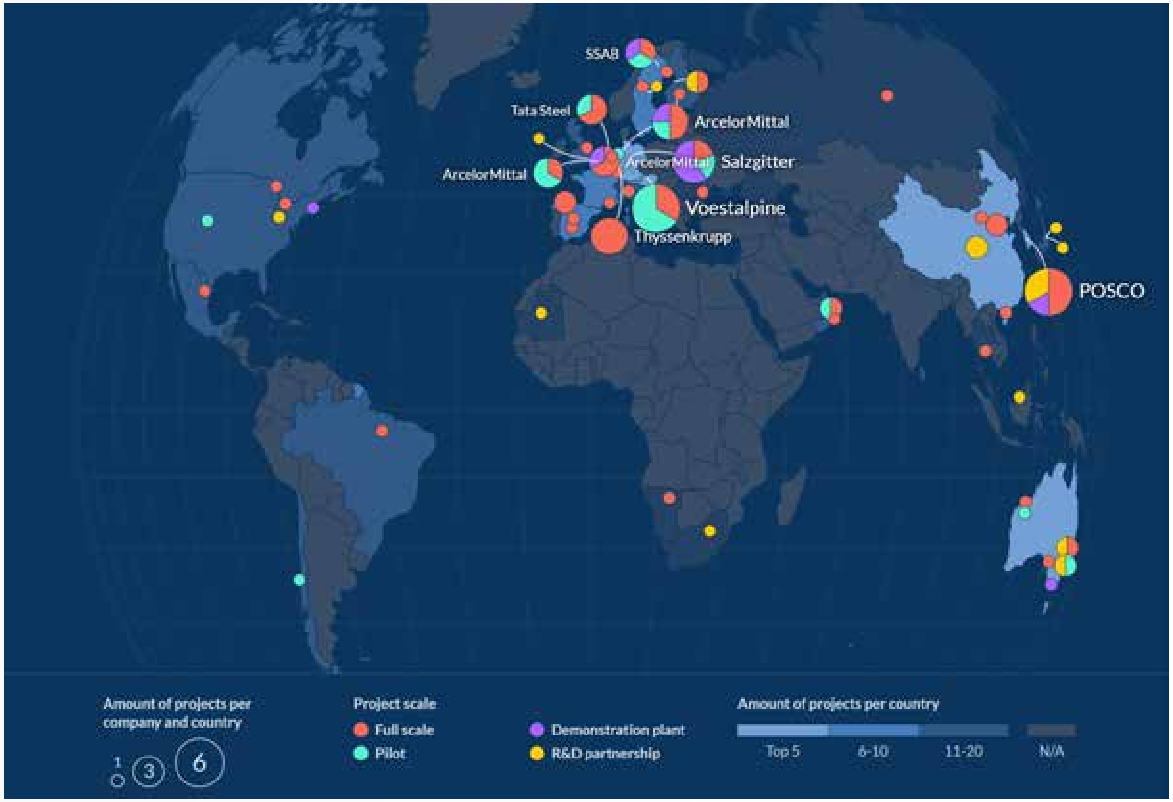
This document will provide an overview of the latest developments in key low emission ironmaking technologies, assessing their potential suitability to the Indian iron and steel sector.

Emissions from ironmaking vs. steelmaking processes (e.g., BF-BOF route)

Source: B. Tikadar et al. 2025

2.0 Low emission steel projects around the world

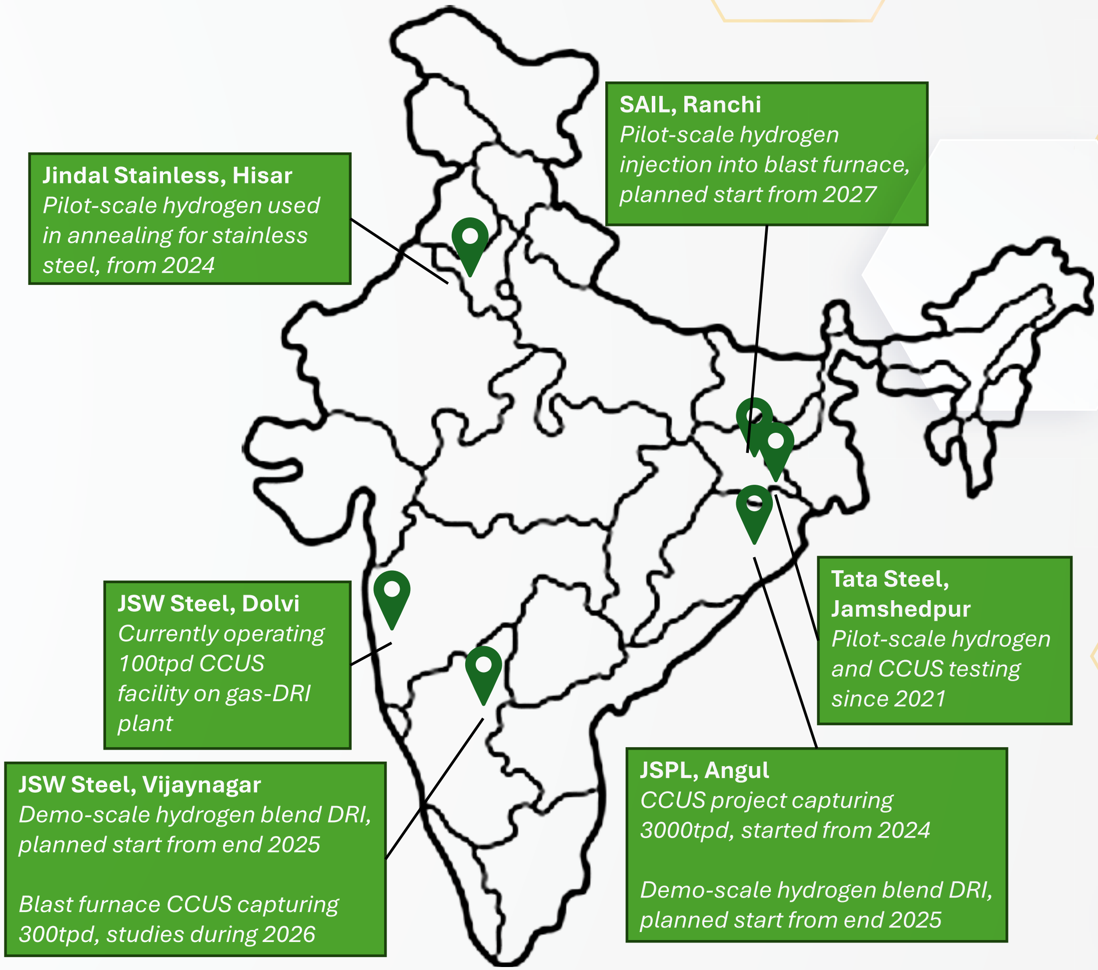
- There are a large and growing number of low emission steel projects around the world.
- Europe is currently dominating the new project pipeline, although announcements are now spreading into new regions, especially the Middle East, China and Australia.



Source: Green Steel Tracker (LeadIT, 2024)

3.0 Low emission steel projects in India

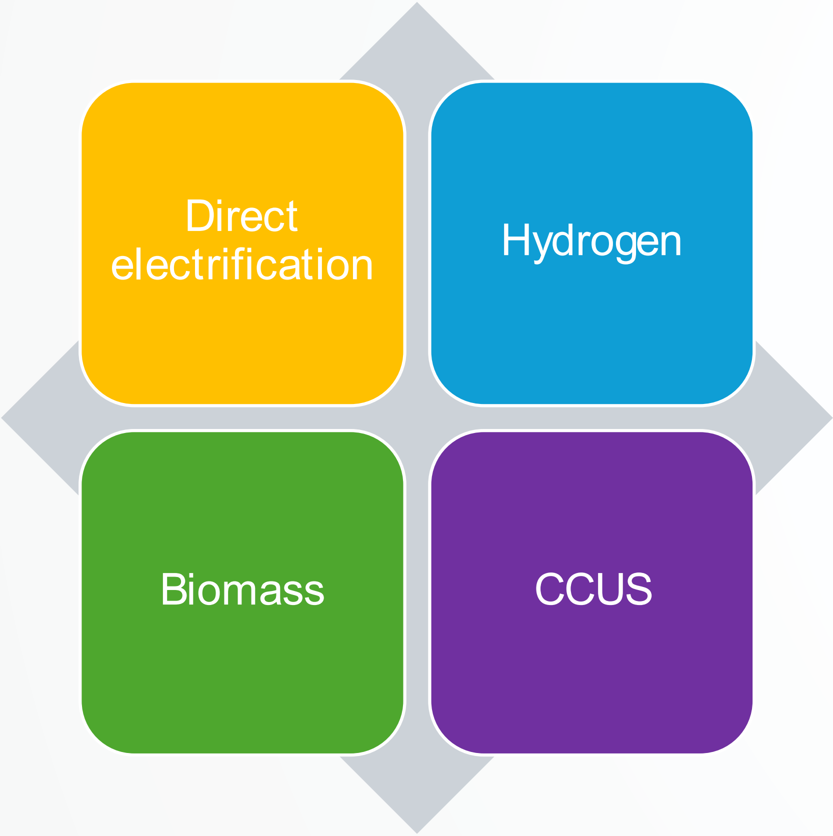
- There are several Low emission steel projects coming up in India, which are at various scales of implementation.
- In 2025, the Ministry of Steel awarded funding to three R&D projects, with additional privately funded activities also being pursued by the majors.
- From existing announcements, there is a growing trend towards H_2-DRI, supported by wider policy announcements on the hydrogen economy in India.



4.0 Technology groups

Technologies that directly use low carbon electricity to process iron ore

Technologies that use low carbon hydrogen or hydrogen plasma to process iron ore



Use of biomass to replace fossil fuels in the iron and steel making processes

Use of carbon capture, usage and storage technologies to mitigate emissions from iron and steel making processes

	Ironmaking technology	Reductant	Ore and ore processing	Ironmaking	Steelmaking
Existing process routes	Blast furnace	Coal	All fines → Sinter → All lump / pellet →	Blast furnace →	Basic oxygen furnace
	Shaft furnace	NG	HG fines → Pellet → HG lump →	Shaft furnace →	Electric arc / induction furnace
	Rotary kiln	Coal	All lump / pellet →	Rotary kiln →	Electric arc / induction furnace
Direct electrification	Molten oxide electrolysis	Elec	All fines →	Molten oxide electrolysis →	Electric arc / induction furnace
	Low temp electrolysis	Elec	All fines →	Low temperature electrolysis →	Electric arc / induction furnace
Hydrogen	Shaft furnace	H2	HG fines → Pellet → HG lump →	Shaft furnace →	Electric arc / induction furnace
	Fluidised bed	H2	HG fines →	Fluid bed →	Electric arc / induction furnace
	Rotary kiln	H2	All lump / pellet →	Rotary kiln → ESF →	Electric arc / induction furnace
	Plasma Smelting reduction	H2	All fines →	Plasma reactor →	Electric Arc Furnace
Biomass	Biomass reduction	Biomass	LG/MG fines → Briquette →	Microwave furnace → ESF →	Basic oxygen furnace
	Biochar furnace	Biomass	All fines → Sinter → All lump / pellet →	Blast furnace →	Basic oxygen furnace
CCUS	Blast furnace	Coal	All fines → Sinter → All lump / pellet →	Blast furnace →	Basic oxygen furnace
	Shaft furnace	NG	HG fines → Pellet → HG lump →	Shaft furnace →	Electric arc / induction furnace
	Smelting reduction	Coal	All fines → Sinter → All lump / pellet →	Smelting reduction furnace →	Basic oxygen furnace

Source: Adapted from Finding Better Ways to Progress Steel Decarbonisation (Rio Tinto, 2024); HG = High Grade; LG = Low Grade; MG = Medium Grade; NG = Natural gas; ESF = Electric Smelter Furnace

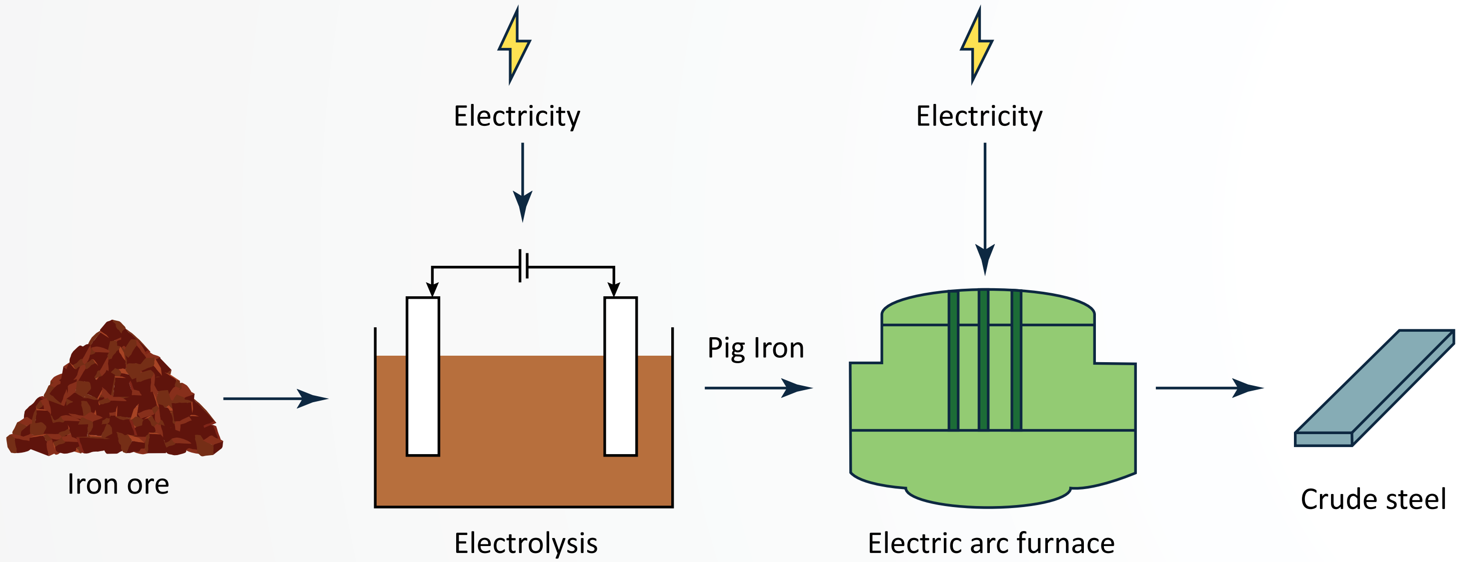
5.0 Technology readiness levels (TRL)

Concept	1	Initial idea
	2	Application formulated
	3	Concept needs validation
Small prototype	4	Early prototype
Large prototype	5	Large prototype
	6	Full prototype at scale
Demonstration	7	Pre-commercial demonstration
	8	First-of-a-kind commercial
Early adoption	9	Commercial operation in relevant environment
	10	Integration needed at scale
Mature	11	Proof of stability reached

Source: ETP Clean Energy Technology Guide (IEA, 2025)

6.0 Technology deep-dives

6.1 Molten oxide electrolysis



Source: Adapted from Low-carbon technologies for the global steel transformation (Agora Industry, 2024)

Technology description:

Molten oxide electrolysis is an electro-metallurgical process used to produce liquid metal directly from oxide feedstocks. Electrons are the reducing agents, and the main product is pure metal along with oxygen, which can be fed directly into an electric arc furnace. The steelmaking process requires high temperatures of up to 2000 °C. The high temperatures require a constant rate of operation to minimize energy loss, meaning a continuous supply of zero carbon electricity is required in order to reach low emissions.

Cost increase estimate:	Emissions reduction potential:	Leading projects globally:	Technology readiness level:
+25-50% (2050)	100%	Boston Metal, Brazil and USA	5 (large prototype)

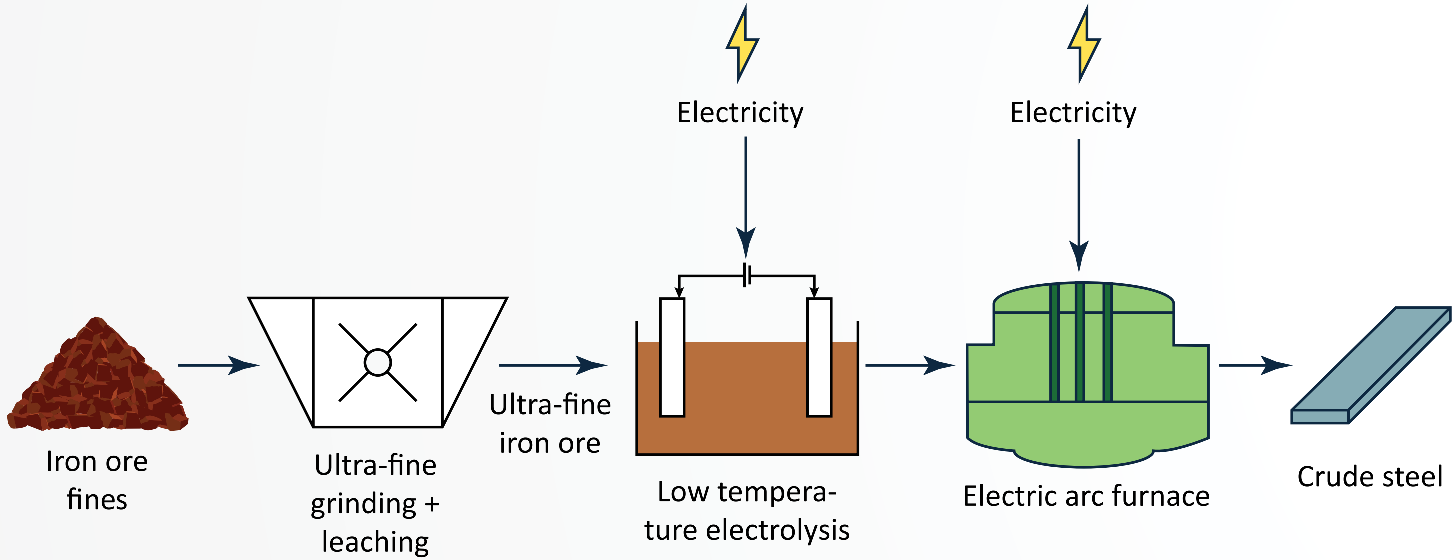
Suitability to India

MEDIUM

This technology is still at a relatively early stage, with early testing underway in the USA and Brazil. As a result, it will not be ready for deployment in India until the mid 2030s at the earliest, before which India will need to deploy many new low emission plants to avoid new blast furnaces. Moreover, the continuous supply of zero-carbon electricity may be more challenging versus other low emission ironmaking technologies, which can operate with more flexibility. Lastly the high cost estimates will be challenging for Indian policymakers and consumers, although India's relatively low cost renewable electricity could make India one of the more competitive markets for this technology.

Source: Low-carbon technologies for the global steel transformation (Agora Industry, 2024); ETP Clean Energy Technology Guide (IEA, 2025); MOE Green Steel Cell (Boston Metal, 2025)

6.2 Low temperature electrolysis



Source: Adapted from Low-carbon technologies for the global steel transformation (Agora Industry, 2024)

Technology description:

This electrolytic steelmaking process uses renewable electricity to transform iron oxides into pure metals. Low temperature electrolysis (<110°C) is one of the two main types of such electrolysis, generally involving extraction from an aqueous solution, with far lower temperatures versus molten oxide electrolysis. This results in a lower energy expenditure in the ironmaking process itself, although the pure metal will need to be heated ahead of being processed into steel via an electric arc furnace.

Cost increase estimate:	Emissions reduction potential:	Leading projects globally:	Technology readiness level:
+30-70% (2050)	>99%	• Electra, USA • Fortescue Future Industries, Australia	4-5 (early-large prototype)

Suitability to India

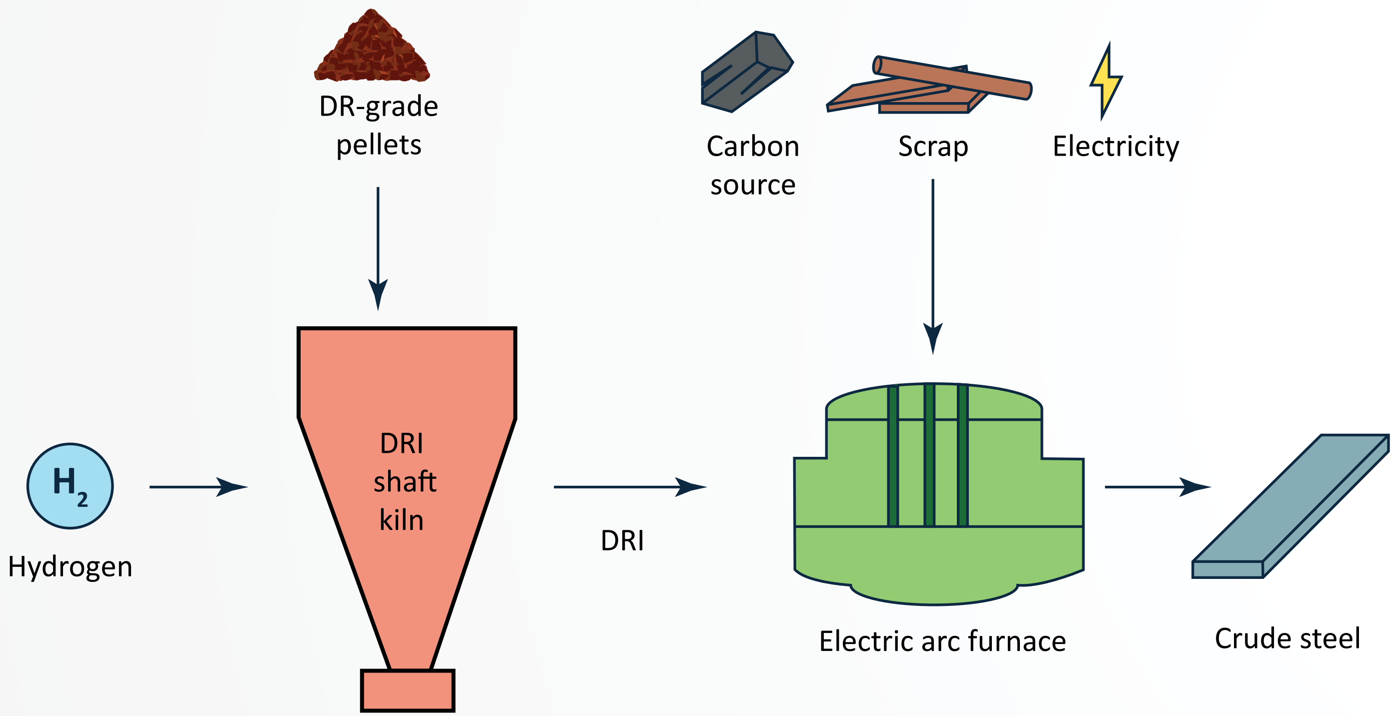
MEDIUM

This technology is still at a relatively early stage, with early testing underway in the USA and Australia. As a result, it will not be ready for deployment in India until the mid 2030s at the earliest, before which India will need to deploy many new low emission plants to avoid new blast furnaces.

Given the low energy inputs for the ironmaking process, with energy only needed ahead of steelmaking, this could be run more flexibly, allowing for integration with renewable electricity, although further details are needed.

Source: Low-carbon technologies for the global steel transformation (Agora Industry, 2024); ETP Clean Energy Technology Guide (IEA, 2025); Our technology (Electra, 2025)

6.3 Hydrogen shaft furnace



Source: Adapted from Low-carbon technologies for the global steel transformation (Agora Industry, 2024)

Technology description:

A hydrogen DRI shaft furnace can use up to 100% hydrogen as an iron ore reductant, whereby using electrolytic or 'green' hydrogen can result in significant emissions reductions. The hydrogen can also be blended in with varying levels of natural gas or syngas, depending on technology specification. This technology route requires the use of high-grade iron ore (>67% Fe) formed into pellets. There is some flexibility with the operation of the furnace (between 80–100%), although greater flexibility can be built in via hydrogen or electricity storage. Direct reduced iron can then be processed in an electric arc furnace or a basic oxygen furnace.

Cost increase estimate:

+40-60% (2030)

Emissions reduction potential:

>99%

Leading projects globally:

- Stegra, SSAB, Sweden
- Blastr, Finland
- HBIS, China
- SALCOS, Germany

Technology readiness level:

6

(full prototype at scale)

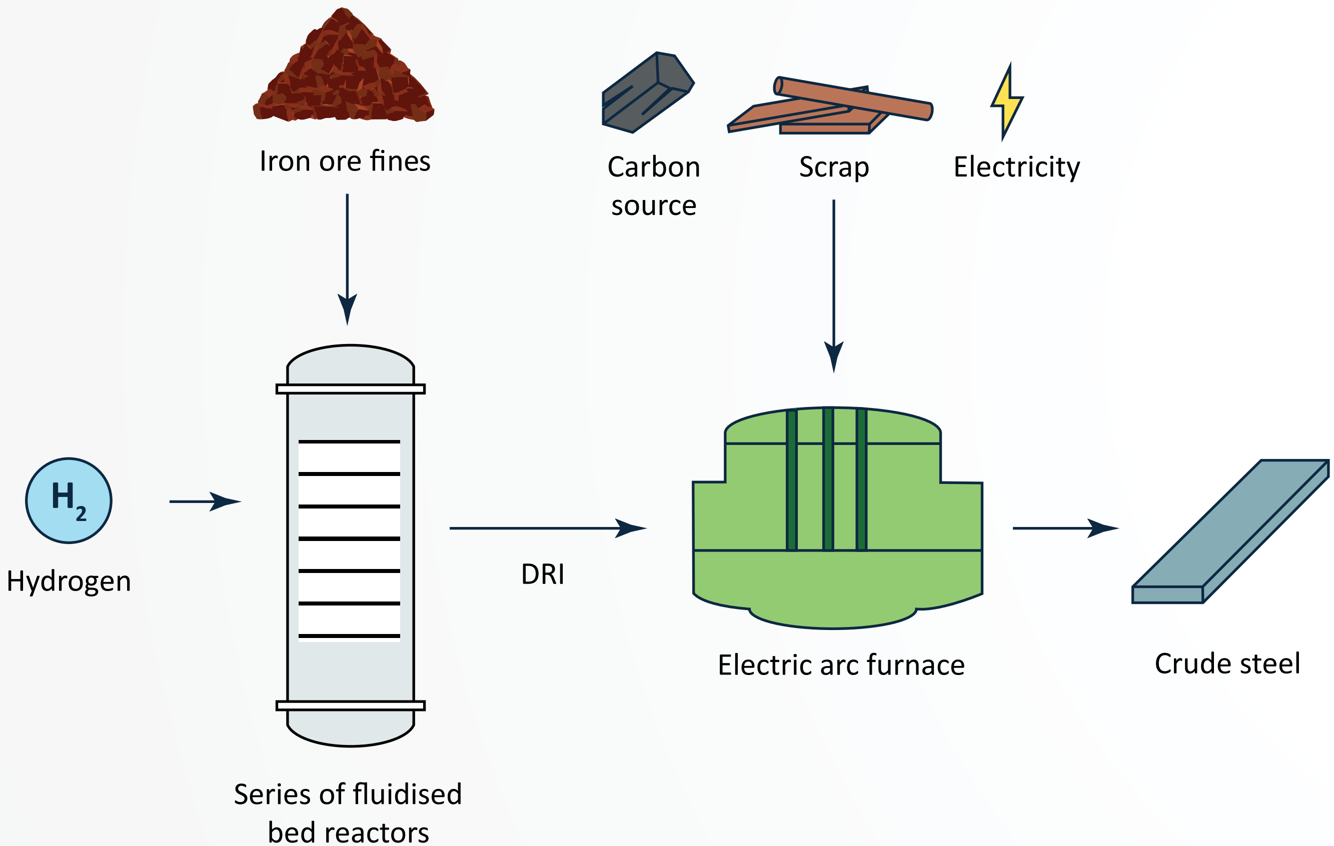
Suitability to India

HIGH

This technology is widely considered to be the leading option for very low emission ironmaking, with by the far the largest number of project announcements around the world. India could be well-placed to deploy this technology, benefitting from low-cost renewable electricity and a rapidly growing hydrogen technology supply chain, including several domestic electrolyser manufacturers, who are expected to be globally competitive. Several Indian companies are already looking to deploy this technology, collaborating closely with major international technology providers, Midrex and Tenova. One of the main challenges for India will be the sourcing of high-quality Direct Reduced (DR) pellets, given domestic iron ore quality is lower than 67% Fe. Otherwise, steelmakers will need to achieve sufficient beneficiation of domestic DR pellets, without adding too much cost.

Source: Low-carbon technologies for the global steel transformation (Agora Industry, 2024); ETP Clean Energy Technology Guide (IEA, 2025); Uses of DRI (Midrex, 2024)

6.4 Hydrogen fluidised bed



Source: Adapted from Low-carbon technologies for the global steel transformation (Agora Industry, 2024)

Technology description:

Similar to the shaft furnace, this process achieves emission reduction through the use of low emission or 'green' hydrogen. The main difference being that iron ore fines are suspended in a bed of gas (hydrogen) within a reactor, avoiding the pelletisation step and potentially allowing for the use of lower quality iron ore.

Cost increase estimate:	Emissions reduction potential:	Leading projects globally:	Technology readiness level:
Not known	>99%	• HyREX, POSCO, South Korea • HYFOR, Primetals, Austria • Circored, Metso, Trinidad	4 (early prototype)

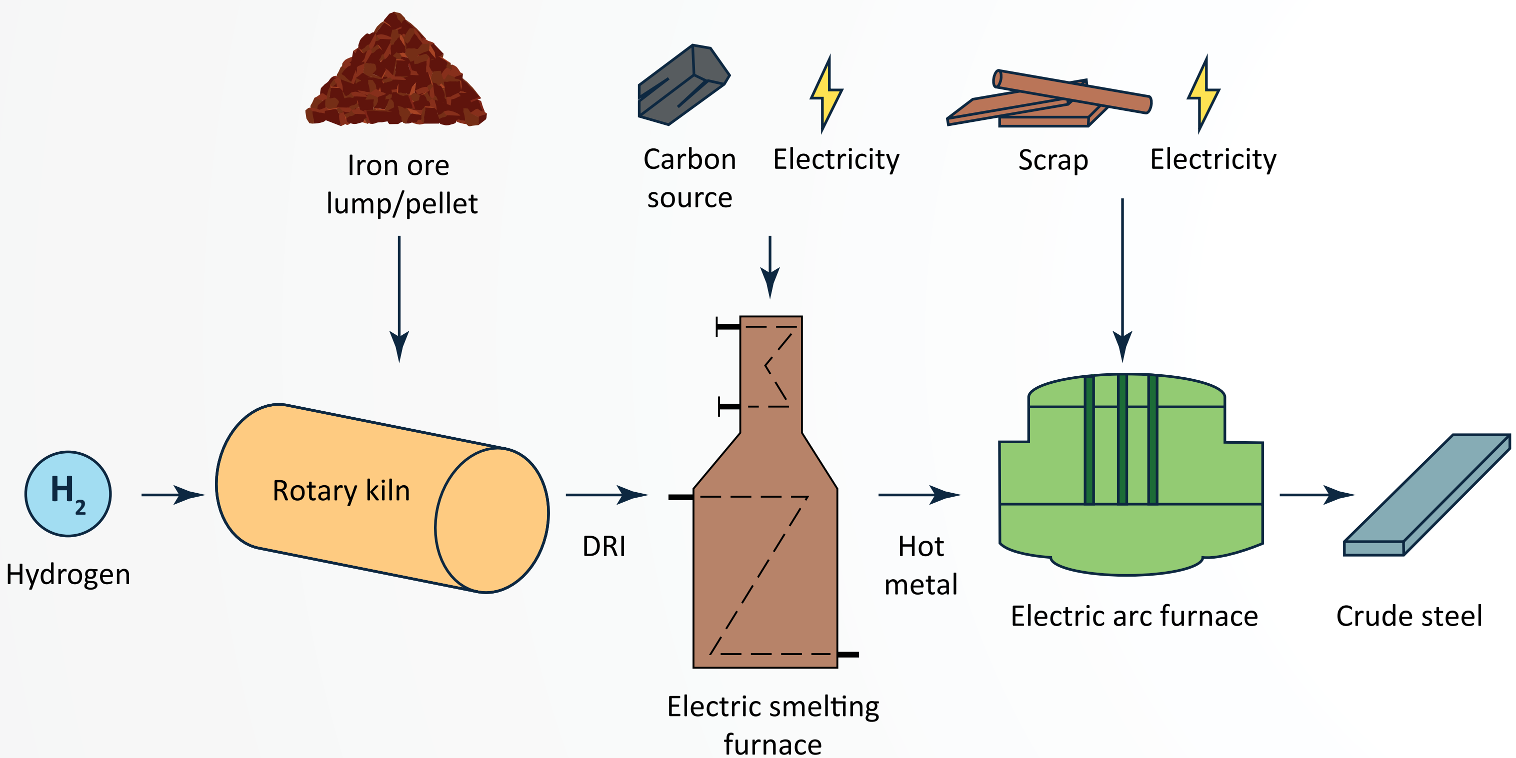
Suitability to India

HIGH

Compared with the shaft furnace, the ability of the fluidised bed to use lower quality iron ores means that it could be a good fit for India, given the domestic ore qualities. Moreover, the presence of POSCO in India as of 2024, who is one of the leading providers for this technology, could accelerate the learning and its deployment in India. That said, it is still at a relatively early stage of development, so steelmakers will have to wait until at least the mid 2030s before the technology is commercially available.

Source: Low-carbon technologies for the global steel transformation (Agora Industry, 2024); ETP Clean Energy Technology Guide (IEA, 2025); Circored (Metso, 2021);

6.5 Hydrogen rotary kiln



Source: Adapted from Low-carbon technologies for the global steel transformation (Agora Industry, 2024)

Technology description:

A rotary kiln is a smaller-scale production facility (50–800 tpd) compared with typical commercial-scale blast furnace or shaft furnace, mostly using natural gas or coal in existing applications. These are a horizontal shaft, tilted at a slight angle to enable raw material and gas to combine as the kiln rotates. The technology was originally developed in the USA, although today, they are mostly found in India, using coal. A low emission option would use hydrogen in place of coal. The smaller-scale requires less capex, at the expense of some economies of scale.

Cost increase estimate:	Emissions reduction potential:	Leading projects globally:	Technology readiness level:
Not known	100%	Hylron, Namibia	5 (large prototype)

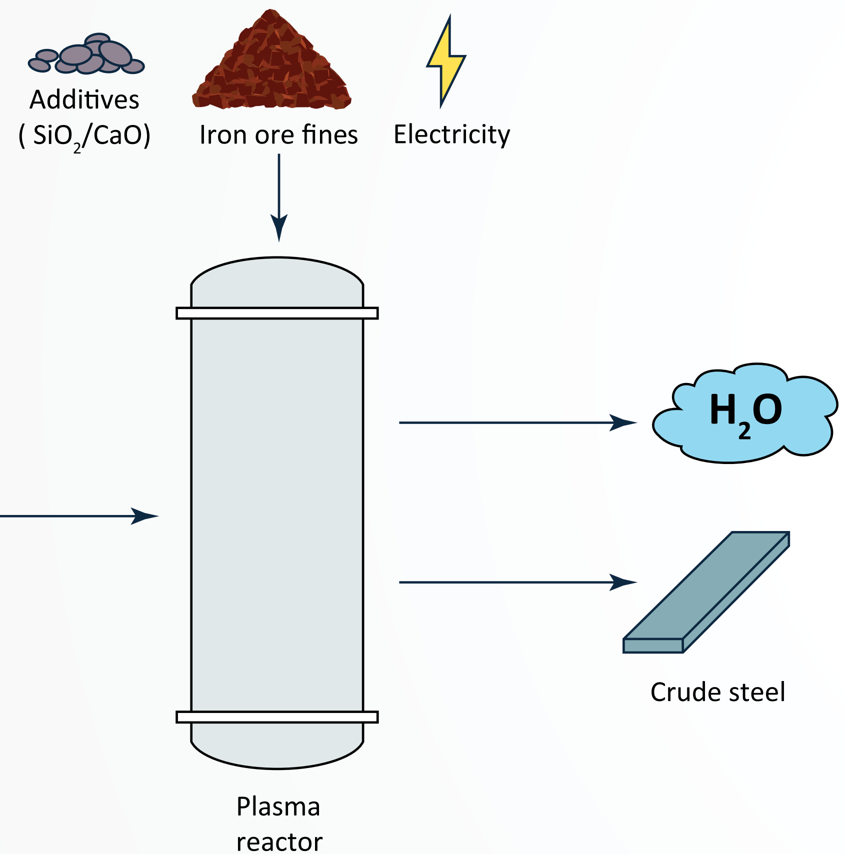
Suitability to India

HIGH

The hydrogen rotary kiln is potentially well suited to the small and medium scale steel producers in India, who today, use the coal-based rotary kiln. The main challenge with switching over to a hydrogen equivalent will be the cost and availability of low emission hydrogen. Though hydrogen transport and storage infrastructure would benefit significantly from economies of scale if focused at singular, large industrial clusters, versus the highly distributed nature of today's rotary kilns across India. The lower capex requirements would be attractive to smaller-scale steel companies in India, who may be less able to finance larger, more capital-intensive projects.

Source: Technology & Product (Hylron, 2024)

6.6 Hydrogen plasma smelting reduction



Source: Adapted from Low-carbon technologies for the global steel transformation (Agora Industry, 2024)

Technology description:

Smelting reduction based on hydrogen plasma is the process of using hydrogen in a plasma state to reduce iron oxides. This can be done through the generation of a hydrogen plasma arc between a hollow graphite electrode and liquid iron oxide. The main benefit over other reduction processes, is that plasma smelting reduction melts iron ores and reduces them in an electric arc furnace (EAF), all in one go. This avoids the energy penalty of processing direct reduced iron in an EAF.

Cost increase estimate:	Emissions reduction potential:	Leading projects globally:	Technology readiness level:
Not known	100%	SuSteel, Austria	4 (early prototype)

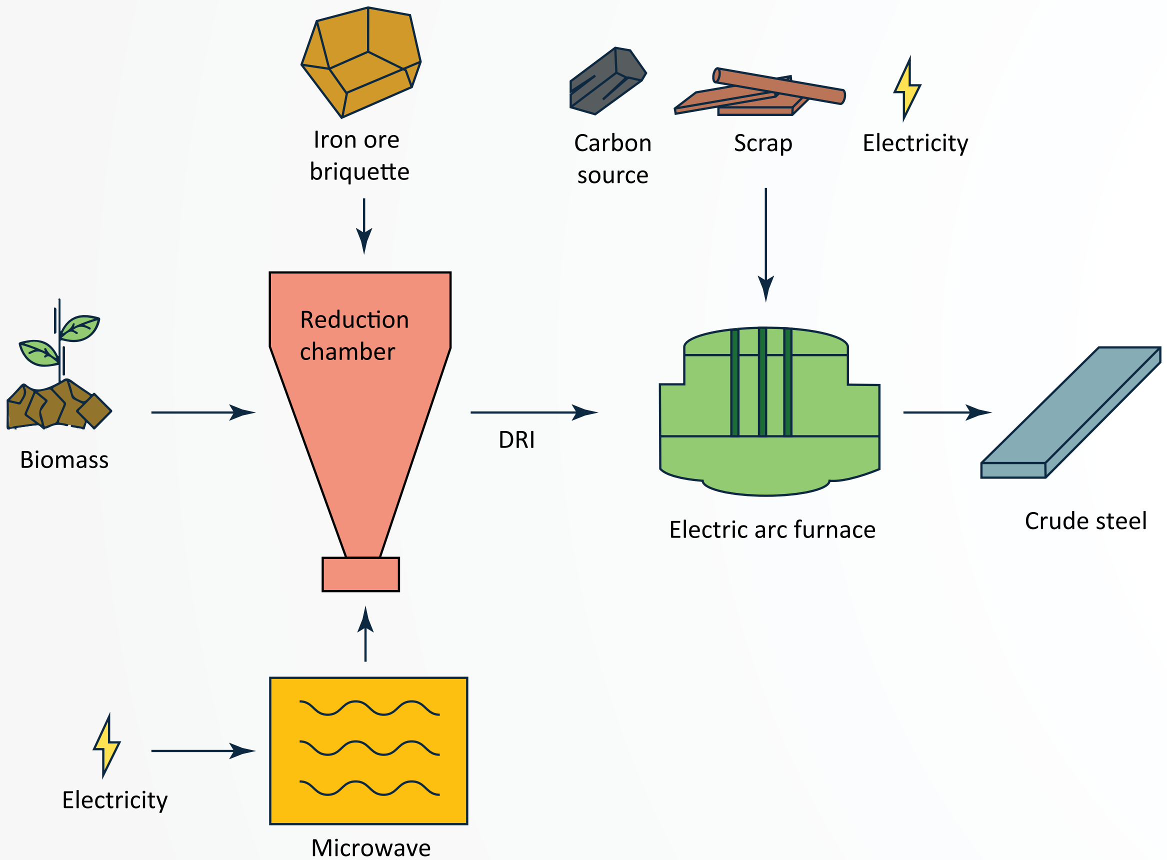
Suitability to India

HIGH

Hydrogen plasma smelting reduction is still at a relatively early stage in its development, with only a single prototype-scale project underway in Austria. The potential of the technology to reduce energy consumption and lower capital costs in low emission iron and steelmaking are high but further testing is needed to prove the process.

Source: ETP Clean Energy Technology Guide (IEA, 2025); SuSteel (K1-Met, 2021)

6.7 Biomass reduction



Source: Adapted from Low-carbon technologies for the global steel transformation (Agora Industry, 2024)

Technology description:

This process uses raw biomass and microwave energy instead of coal to convert iron ore into metallic iron. When combined with the use of renewable electricity and sustainably sourced biomass, this technology has the potential to reduce carbon emissions by up to 95% compared with the current blast furnace method. It is still in a relatively early stage of development, with development being led by the mining company, RioTinto.

Cost increase estimate:	Emissions reduction potential:	Leading projects globally:	Technology readiness level:
Not known	<95%	• BioIron, RioTinto, Australia • FerroSilva, Sweden (bio syngas)	4 (early prototype)

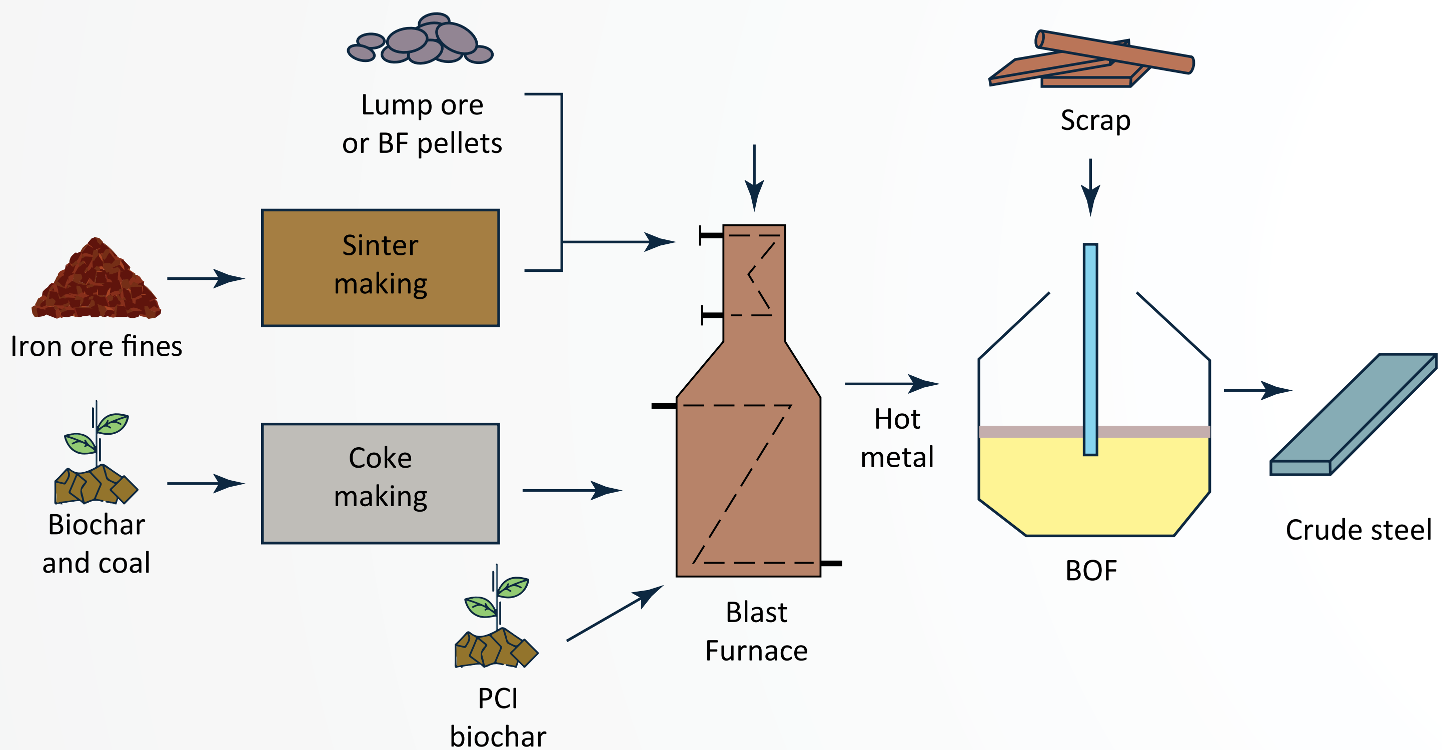
Suitability to India

MEDIUM

This technology is still at a relatively early stage and is unlikely to scale in time to provide large quantities of steel for the Indian market until the late 2030s. Moreover, sustainably sourced biomass is a limited resource, which should be prioritised for use in sectors where there are limited alternatives for decarbonisation, such as aviation or chemicals. Whilst India has substantial forestry and agriculture sectors, including bamboo harvesting, establishing biomass supply chains for use in, e.g. transportation, have been challenging.

Source: Greening the Steel Sector in India Roadmap and Action Plan (MoS, 2024); BioIron (RioTinto, 2023)

6.8 Biochar blast furnace



Source: Adapted from Low-carbon technologies for the global steel transformation (Agora Industry, 2024)

Technology description:

Biomass use in blast furnaces is already used commercially in Brazil (approx. 11% of steel production), acting as a reductant. Not all types of biomass are suitable for direct injection, and some types require small-scale, less efficient blast furnaces due to the lower compressive strength of charcoal compared to coke. To overcome this, it is possible to convert biomass into a coal-like material through torrefaction or pyrolysis. This 'bio-char' has characteristics more similar to coal and can be used in standard blast furnaces, for PCI, cokemaking and sintering, to replace a portion of coal.

Cost increase estimate:	Emissions reduction potential:	Leading projects globally:	Technology readiness level:
Not known	<25% (for PCI replacement, coking coal replacement not known)	• Arcelor Mittal, Canada and Belgium • SSAB, Finland	9 (commercial operation in relevant environment)

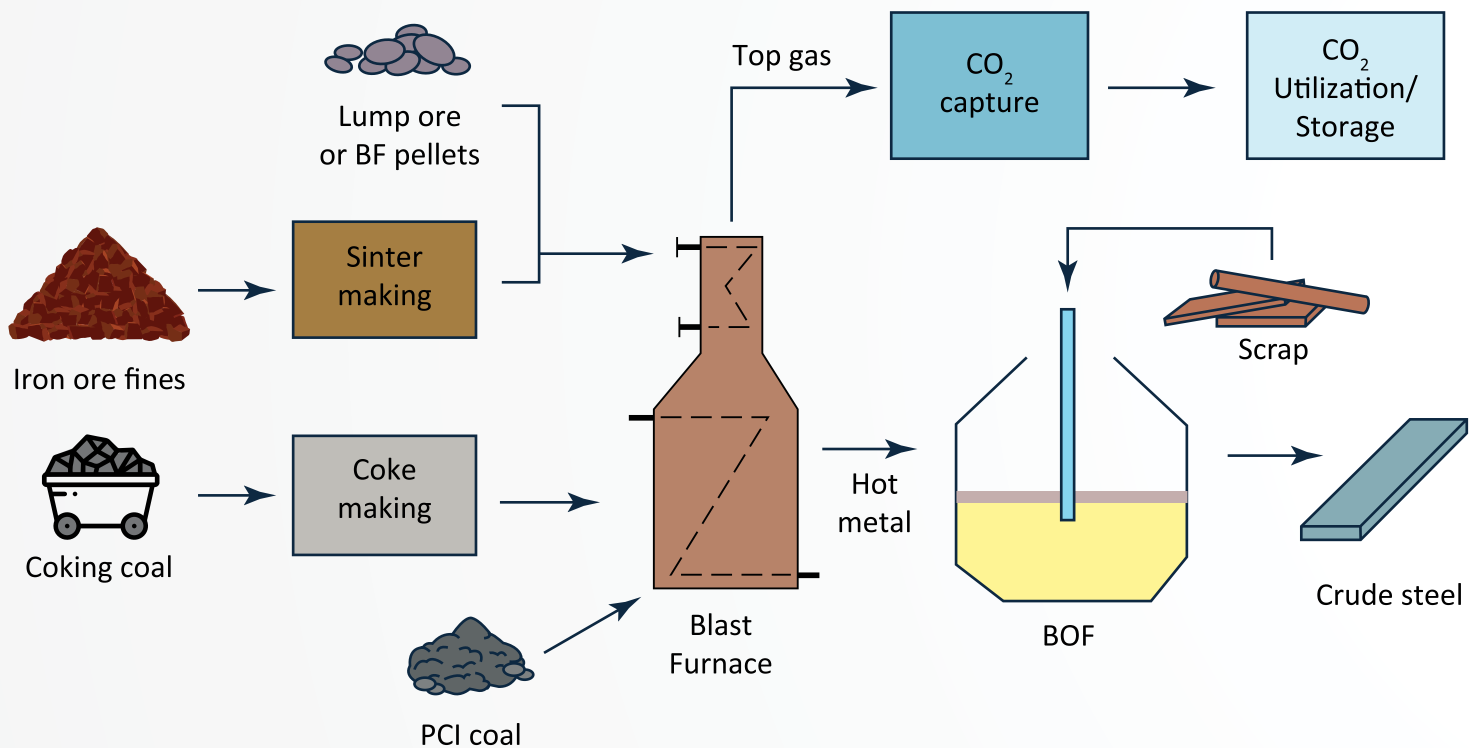
Suitability to India

MEDIUM

Whilst this technology has proved possible in varying forms in Brazil and now more advanced biomass processing solutions in Europe and North America, the main limitations will be on biomass type and availability. Again, this should be prioritised for use in sectors where there are limited alternatives for decarbonisation, such as aviation or chemicals. Whilst India has substantial forestry and agriculture sectors, including bamboo harvesting, establishing biomass supply chains for use in, e.g. transportation, have been challenging. There may be a possibility to use some small quantities to replace pulverised coal injection (PCI) in the near- to medium-term to limit emissions, although this solution is limited in its emission reduction potential.

Source: Greening the Steel Sector in India Roadmap and Action Plan (MoS, 2024); ETP Clean Energy Technology Guide (IEA, 2025)

6.9 Blast furnace with CCUS



Source: Adapted from Low-carbon technologies for the global steel transformation (Agora Industry, 2024)

Technology description:

Capturing CO_2 from blast furnace flue gases, either with subsequent transportation for storage and or hydrogen enrichment (which involves capturing process gases and recirculating them after reheating (to 900 °C) into the blast furnace as a reducing agent to lower requirements for coke and other fuels) can reduce emissions from a blast furnace by up to around 60%. CO and H_2 from coke oven gas and basic oxygen furnace gas the easiest to recover, with capture from additional flues becoming exponentially more expensive.

Cost increase estimate:	Emissions reduction potential:	Leading projects globally:	Technology readiness level:
+30-50%	<60% (capturing CO_2 from coke oven, BF and BOF)	• Course50, Japan • Arcelor Mittal, France and Belgium • HBIS and BHP, China	5 (large prototype)

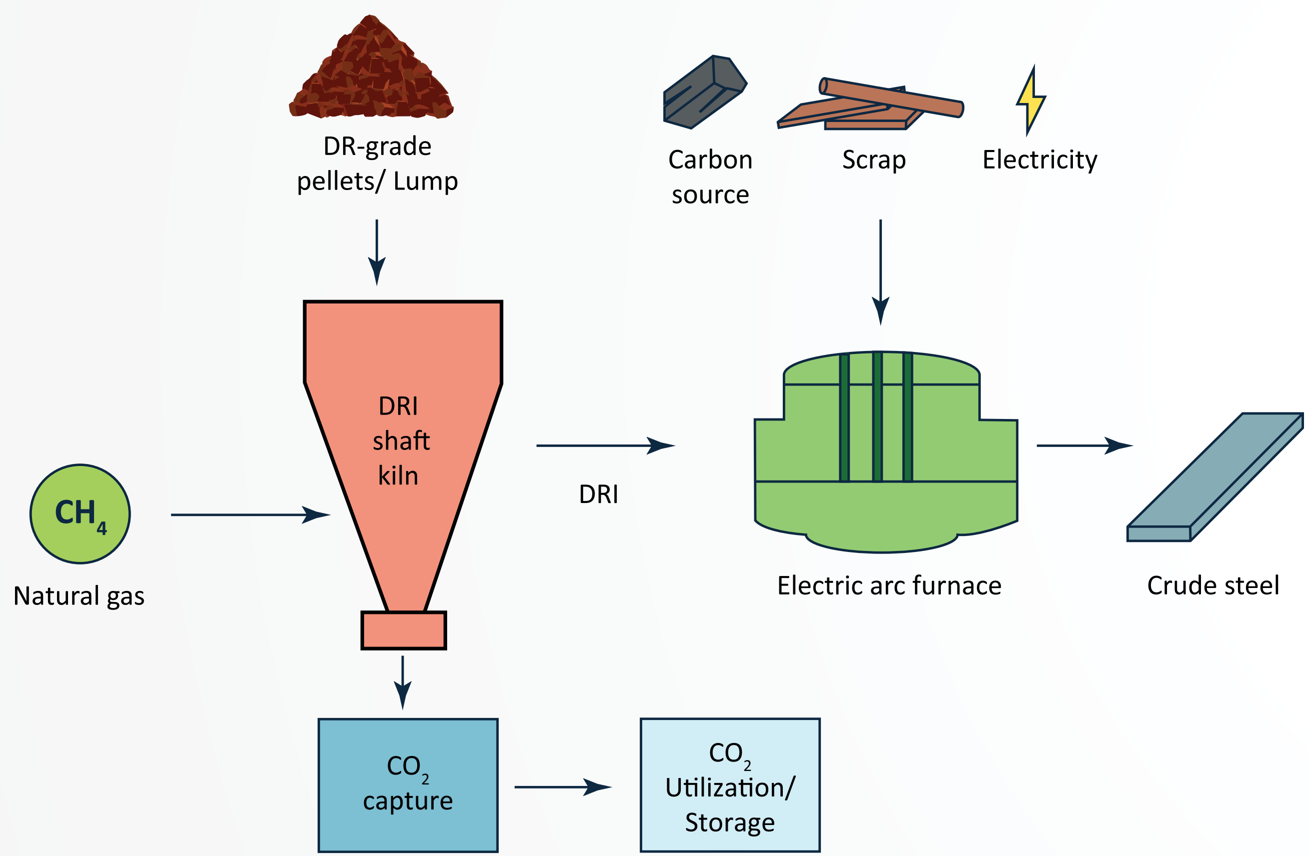
Suitability to India

MEDIUM

Given India's large number of blast furnaces that are currently operating, as well as the very large number in the pipeline, developing Carbon Capture, Utilization and Storage (CCUS) infrastructure that could serve these plants would be vital to slow the increase in emissions. However, building out the required infrastructure would be very costly, particularly given India's low availability of CO_2 storage sites.

Source: Low-carbon technologies for the global steel transformation (Agora Industry, 2024); ETP Clean Energy Technology Guide (IEA, 2025)

6.10 Natural gas shaft furnace with CCUS



Source: Adapted from Low-carbon technologies for the global steel transformation (Agora Industry, 2024)

Technology description:

This process involves gas-based DRI plants equipped with chemical absorption-based CO_2 capture, a common process operation based on the reaction between CO_2 and a chemical solvent (e.g. amine-based). The CO_2 is released at temperatures typically in the range 120 °C to 150 °C and the solvent is regenerated for further operation.

Cost increase estimate:	Emissions reduction potential:	Leading projects globally:	Technology readiness level:
+30-50% (2030)	<90%	Al Reyadh CCUS facility, ADNOC, Saudi Arabia	9 (commercial operation in relevant environment)

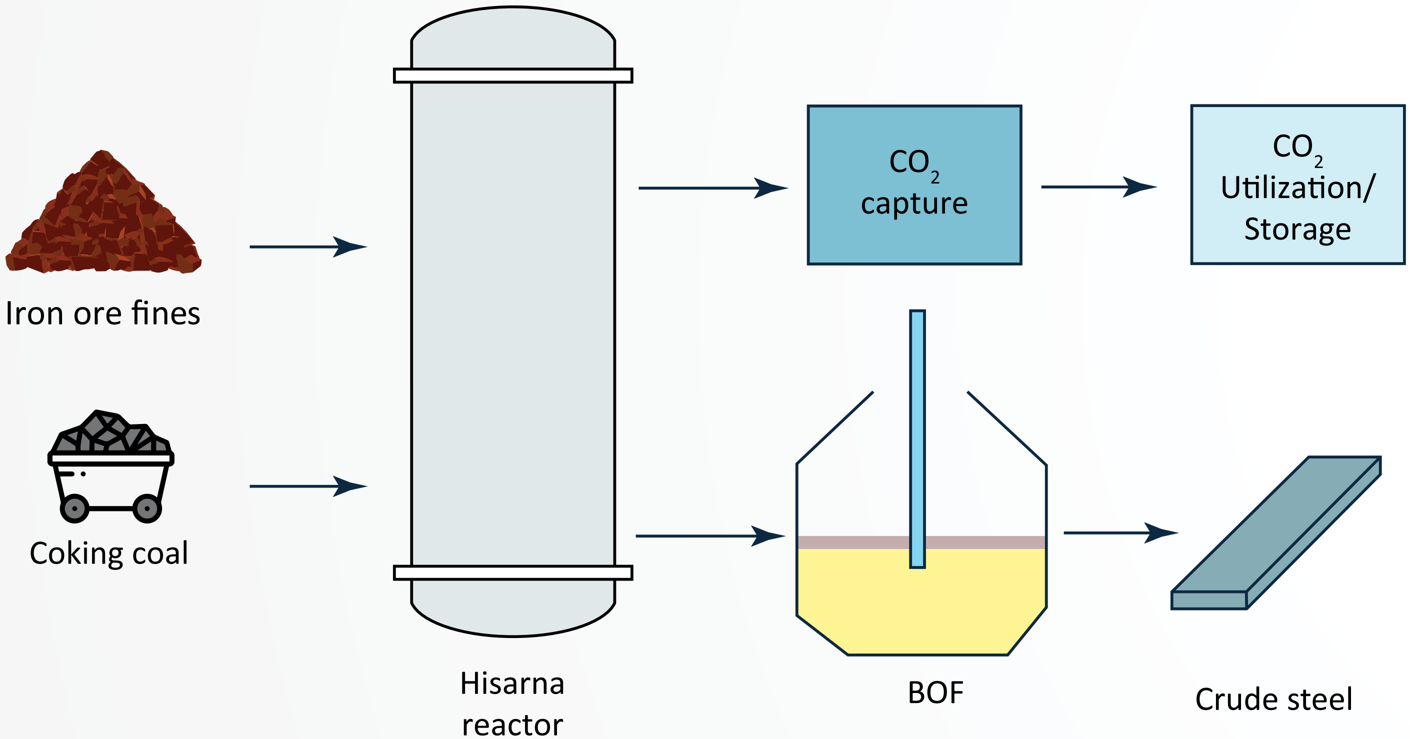
Suitability to India

LOW

Whilst this process is well-understood, with the longest running project of any low emission technology, the requirement of both natural gas and CO_2 infrastructure make this poorly suited to Indian conditions. Only in a small number of cases, where steel companies have existing access to competitively priced natural gas, alongside CO_2 storage options (largely found in the northeast), would this prove viable.

Source: Low-carbon technologies for the global steel transformation (Agora Industry, 2024); ETP Clean Energy Technology Guide (IEA, 2025)

6.11 Smelting reduction with CCUS



Source: Adapted from Low-carbon technologies for the global steel transformation (Agora Industry, 2024)

Technology description:

This technology involves an oxygen-rich smelting reduction process, consisting of a reactor in which iron ore is injected at the top and powder coal at the bottom. The use of pure oxygen makes this process well suited to integrating CCUS, as it generates a high concentration of CO_2 offgas and emissions are delivered in a single stack compared to a standard steel mill plant with multiple emission points.

Cost increase estimate:	Emissions reduction potential:	Leading projects globally:	Technology readiness level:
+20-40% (2030)	<95%	Hisarna, Tata Steel, Netherlands and India	7 (pre-commercial demonstration)

Suitability to India

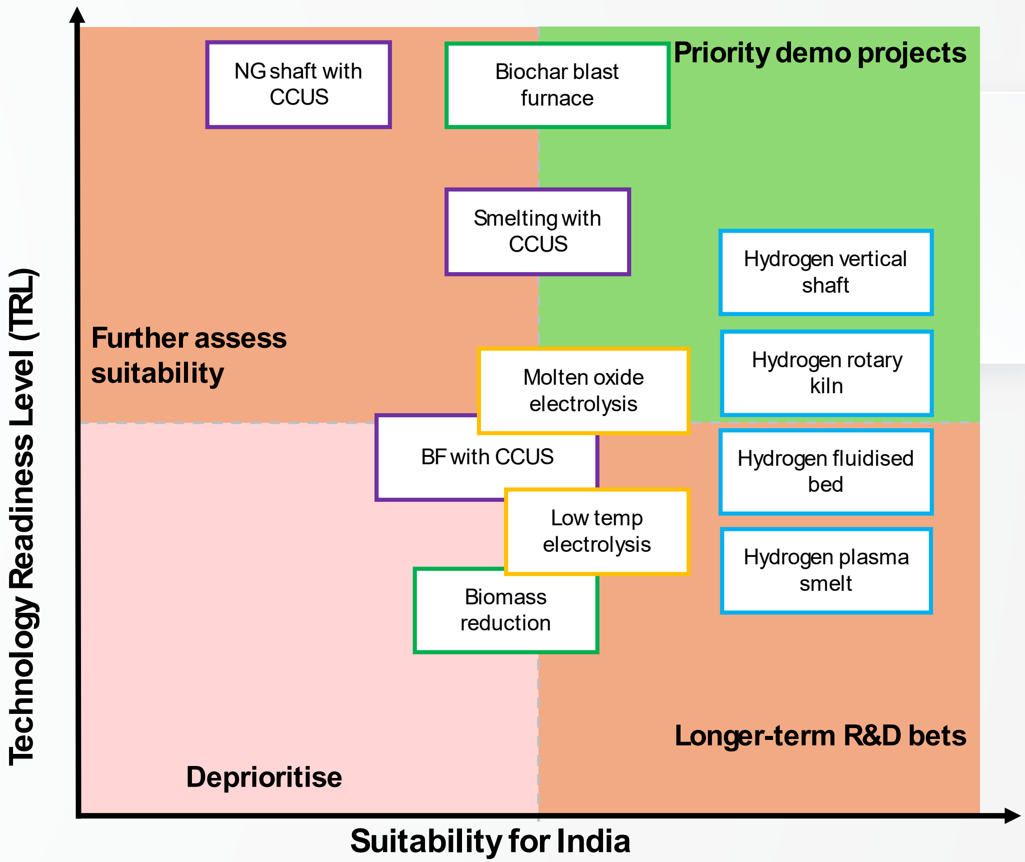
MEDIUM

Tata Steel is the leading company testing and developing this technology, with some testing in the Netherlands and, more recently, in Jamshedpur, India. As a result, there are fewer challenges with technology access versus other low emission ironmaking routes, although plans for further testing and development of this technology have slowed, with no recent announcements. As with other CCUS-dependant routes, the main barrier to the large-scale deployment of this technology is the cost and availability of CO_2 transport and storage infrastructure. Early analysis in India suggests that the market for CCU is small relative to the potential emissions and CO_2 storage options are limited.

Source: Low-carbon technologies for the global steel transformation (Agora Industry, 2024); ETP Clean Energy Technology Guide (IEA, 2025)

7.0 Recommendations

- Government and the private sector should prioritise large-scale demonstrations of those technologies which are most suitable to India and higher up the TRL scale, such as hydrogen vertical shafts and hydrogen rotary kilns.
- Longer-term R&D bets might include hydrogen fluidised bed and hydrogen plasma smelting reduction, alongside high and low temperature electrolysis, biomass reduction and BF with CCUS.
- Biochar blast furnace and smelting reduction with CCUS may need further assessments on their suitability, in particular around biomass and carbon storage availability.



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