Hydrogen Rotary Kilns for Ironmaking in India

A novel solution for decarbonizing small-scale ironmaking

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Executive Summary

The iron and steel sector in India needs to decarbonize as the nation sets out to achieve economy-wide net zero emissions by 2070. This includes small-scale sponge iron production facilities, which largely rely on coal-based rotary kilns, as their production process, where relatively little progress on emissions reduction has been made to date.

There are a number of low emission ironmaking technologies being explored by companies and governments around the world, which broadly fall into one of four technology groups: hydrogen, biomass, carbon capture use and or storage (CCUS) and direct electrification.

Based on an initial assessment of 11 low emission ironmaking technologies, the hydrogen rotary kiln appears to be the most suitable alternative for the small-scale sponge iron sector in India.

Learning from the ongoing research and initial pilot projects in Europe and Africa, this paper sets out the anticipated advantages of adopting the hydrogen rotary kiln technology over other low emission alternatives, such as the hydrogen vertical shaft furnace. They are listed as follows:

Low capital investment: Rotary kilns are relatively cheaper to manufacture and install, with nearly 340 coal-based rotary kilns operational in India.

Flexibility of iron ore inputs: Hydrogen rotary kilns can use non-agglomerated iron ore, i.e., lumps or fines, lowering the cost of production.

Low reaction temperature: This reduces operation and maintenance costs, leading to multiple other benefits, such as operational flexibility.

Increased metallization rate: Using pure hydrogen increases the metallization rate, increasing the product value as well as reducing operating costs.

Flexibility of operation: The reactor is expected to be able to operate between 20–100% of its capacity, improving integration with variable renewable electricity supply.

Modelling the cost of producing direct reduced iron (DRI) via a hydrogen rotary kiln shows that it has the potential to produce DRI at lower costs of production than from other low emission ironmaking technologies (e.g., hydrogen vertical shaft furnace) and could be close to competitive with coal-based DRI.

It will be important to validate these anticipated advantages through the sustained operation of pilot and demonstration plants, including testing in Indian conditions.

To further develop the hydrogen rotary kiln for the Indian market, we recommend the following steps:

- Deploy pilot and demonstration-scale plants in India
- Build awareness and expertise in the technology
- Secure offtake agreements
- Establish an ambitious carbon price through the CCTS
- Support scale-up with concessional finance
- Unblock renewable electricity and hydrogen infrastructure
- Foster industrial clusters to lower costs

Background

India's iron and steel sector remains one of the most emission-intensive sectors within the Indian economy and is set to expand considerably in the coming decades. As shown in Figure 1, steelmaking is split into three broad technologies—basic oxygen furnace (BOF), electric arc furnace (EAF) and electric induction furnace (EIF). According to the Joint Plant Committee (JPC), small-scale, coal-based rotary kilns form around one-third of all ironmaking in India (42 Mt in 2023–24), increasing by 17% on the previous year (Figure 2). Typically paired with an EIF, this route is the most emission-intensive way of producing steel in India, ranging between 2.7 to 3.1 tCO_2 per tonne of crude steel (tcs) versus an all-India average of 2.54 tCO_2/tcs.[1] This is driven by the use of thermal coal in the heating and reduction process, which is less efficient than alternative production routes, such as the blast furnace.

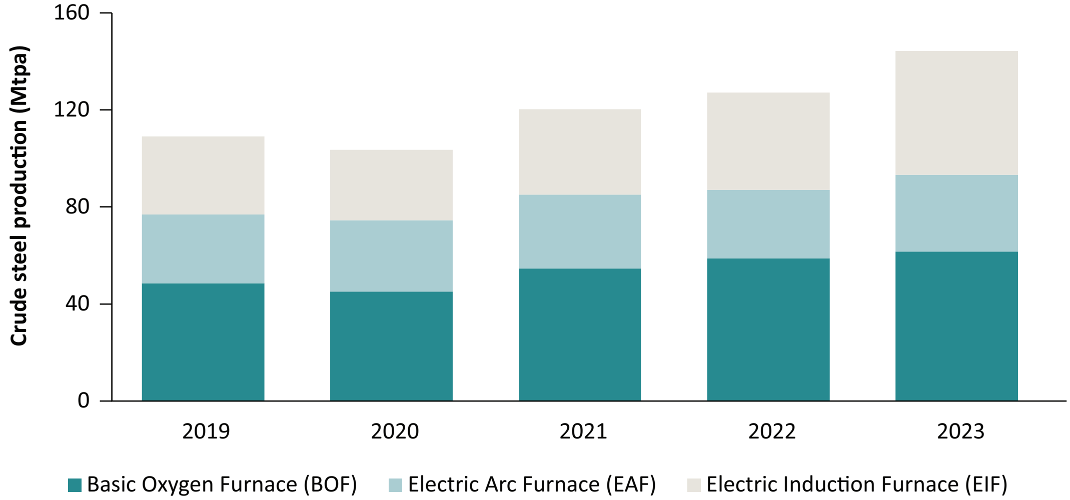

Figure 1: Crude steel production by steelmaking process in India, 2019–2023

Source: Annual Statistics 2023-24 (JPC, 2024); Electric arc furnace route primarily uses hot metal (BF BOF), gas-based DRI, a small share of coal-based DRI, and scrap. Electric induction furnaces primarily use coal-based DRI and scrap. See Greening Steel Sector in India Roadmap and Action Plan for further information.

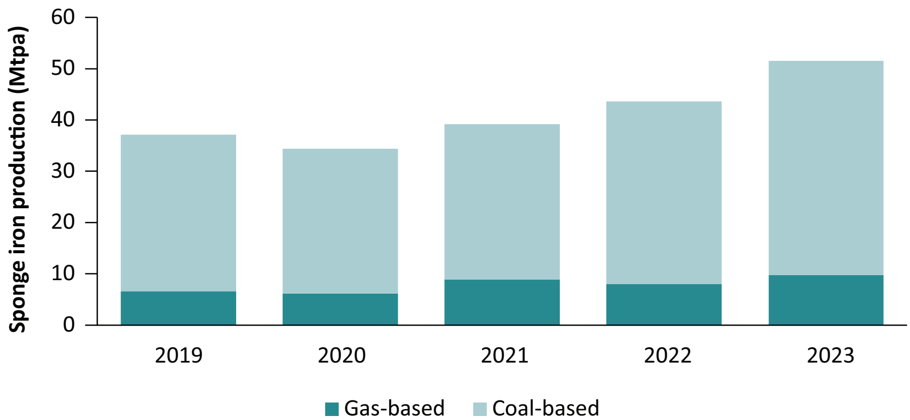

Figure 2: Sponge iron production in India, 2019–2023

Source: Annual Statistics 2023-24 (JPC, 2024); Gas-based mostly refers to vertical shaft furnaces using natural gas and coal-based mostly refers to horizontal rotary kilns using thermal coal.

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1 BF BOF is 2.2–2.6 tCO_2/tcs; natural gas-based DRI EAF is 1.4–1.6; scrap-based steelmaking via an EAF is 0.55–0.65. See Greening Steel Sector in India Roadmap and Action Plan for further information.

Whilst emission intensive, these small-scale facilities are a vital part of the local economy, providing employment in typically less wealthy, although resource rich, parts of the country, such as Odisha, Chhattisgarh, West Bengal, and Jharkhand (Figure 3).[2] Their unique role in the Indian steel sector has continued to grow due to their lower capital costs, greater flexibility on feedstock and co-location near iron ore and coal reserves, although many are now switching to higher quality, imported coal to improve operational efficiency.[3] There have been attempts to gradually improve the energy efficiency of these plants, such as via Waste Heat Recovery (WHR) systems for larger plants (200 tpd and above) but as yet, there have been limited discussions on how to achieve deep decarbonization, to help future-proof these facilities on India's pathway to net zero by 2070.

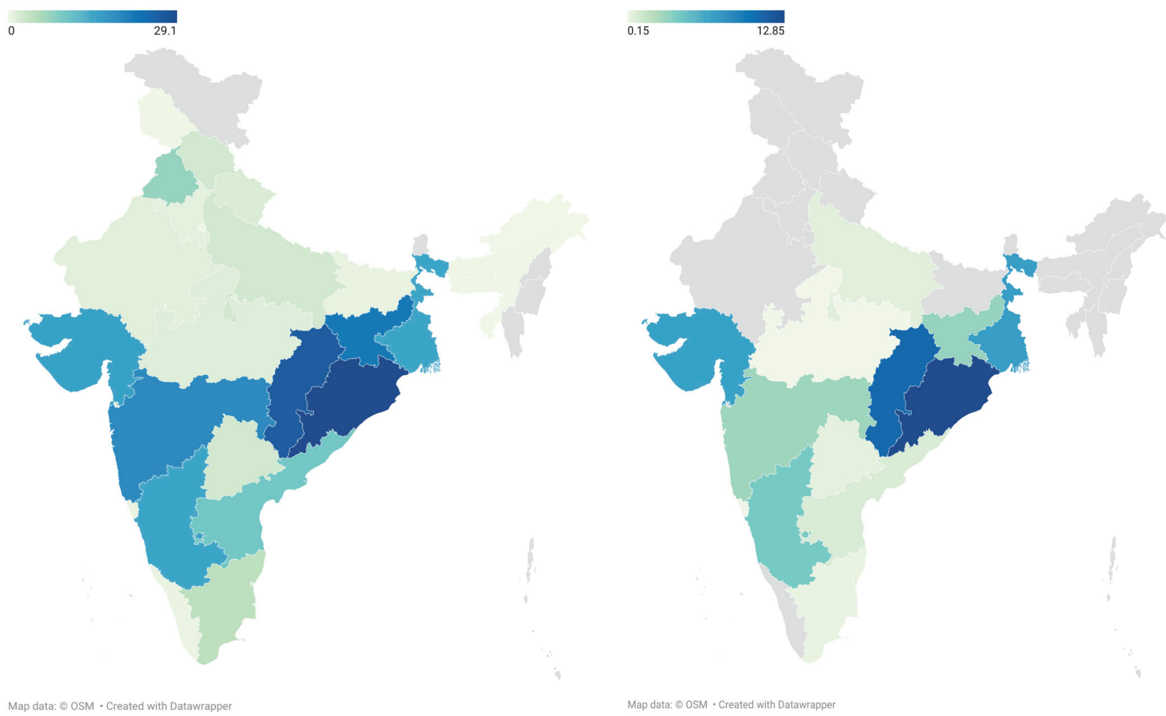

Figure 3: State-wise concentration of steel production capacity (left) and sponge iron production capacity (right) in India, 2023

Source: Annual Statistics 2023-24 (JPC, 2024)

In terms of achieving emission reductions, solutions targeting larger facilities have typically received greater focus, such as carbon capture, usage and storage (CCUS) on blast furnaces, as well as vertical hydrogen shafts at commercial scales of 1 million tonnes per annum (Mtpa) and above. This is in contrast with the scale of coal-based direct reduction kilns, which range from 50 tonnes per day (tpd) up to 900 tpd, equivalent to around 15,000 to 3,00,000 tonnes per annum (tpa).

There are several challenges that these small-scale producers face in adopting lower emission ironmaking technologies, including access to low-cost finance, access to latest technologies, technical capabilities pertaining to renewable electricity and hydrogen infrastructure and the scarcity

2 GDP per capita in Odisha is INR 190,439, Chhattisgarh is INR 184,833, West Bengal is INR 181,786 and Jharkhand is INR 128,252, versus an all-India average of INR 234,859, all 2025 prices (MoSPI, 2025).

3 https://www.ceew.in/publications/how-can-india-decarbonise-coal-based-direct-reduced-iron-plants-in-steel-production

of high-quality iron ore. These factors make it difficult for small-scale players to develop a transition strategy for their facilities, necessitating a need for tailored technology solutions that can meet the specific needs of these companies, the market and the local communities in which they operate.

Low Emission Ironmaking Technologies

There are a range of different ironmaking technologies that are being developed around the world that are able to achieve a substantial reduction in their emissions. Broadly speaking, these can be split into four technology groups—direct electrification, hydrogen, biomass, and CCUS. TERI recently reviewed 11 of these technologies and their potential suitability to India (Figure 4), helping to narrow down which of these may be most applicable to the small-scale iron and steel industry.

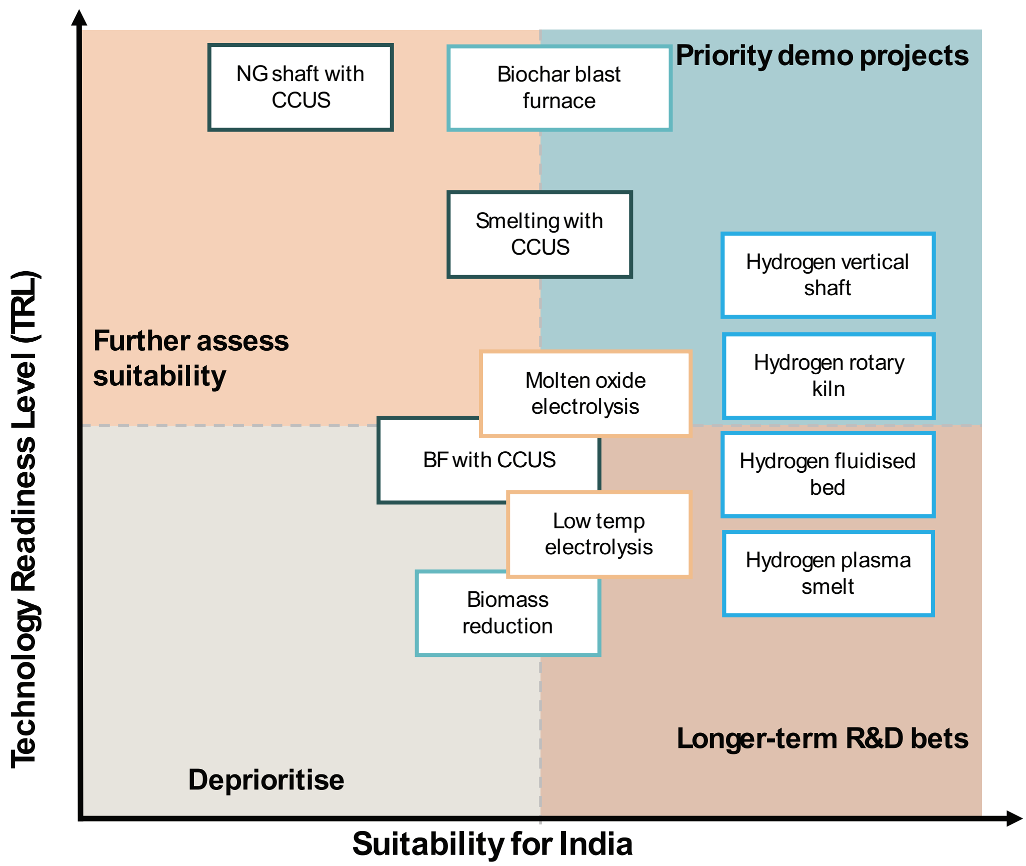

Figure 4: Technology Readiness Level (TRL) and suitability for India assessment of key low emission ironmaking technologies

Source: Low emission ironmaking technologies – suitability to India (TERI, 2025)

This assessment identifies several promising technologies for India, including various hydrogen reduction routes, such as the hydrogen vertical shaft and the hydrogen rotary kiln. These are promising given their relatively high TRL, meaning they could be deployed in the next five years, along with their use of green hydrogen, which is expected to be cost-competitive in India, given low-cost renewable electricity and electrolysers.

The gas-based vertical shaft technology is already being supported by several major Indian steel companies, with green hydrogen blending projects announced for the late 2020s.[4,5] Whilst technology providers, such as Midrex and Tenova are already supplying 1 Mtpa gas-based vertical shafts and larger, these often represent too large a capital investment for small-scale players, at around $345 million or INR 3000 crore per Mt for the vertical shaft alone.[6] Moreover, these require direct reduction grade pellets, with an iron content of 67% or higher, necessitating expensive and energy-intensive beneficiation and pelletization of low-grade Indian iron ores.

The rotary kiln on the other hand looks more promising for small-scale players in India. This uses a very similar horizontal rotary kiln technology that is currently ubiquitous in the industry, with modifications to make it gas-tight as compared to the existing coal-based kilns. Based on initial pilot projects, it is expected that such kilns have relatively low capital costs and can be deployed at a much smaller scale, making it much more suitable to the smaller companies that tend to dominate the sponge iron industry in India. Unlike the hydrogen vertical shaft, the rotary kiln is also flexible to a range of iron ore inputs, being able to take lower grade lumps and fines, which are more widely available in India. Lastly, it also has a greater flexibility in operations, able to cycle between 20% and 100% of its capacity, helping to lower the costs of integration with variable renewable electricity supply. The technology is not yet commercially available but early projects in Namibia, as well as R&D activities in the UK, Germany and the US, indicate that several countries and companies are looking at its potential.[7,8,9,10]

Other hydrogen technologies that could be a part of the solution in future years include hydrogen fluidized bed (HyREX) or hydrogen plasma smelting reduction (HYFOR), although both are not directly applicable to small-scale ironmaking.[11,12] In parallel, a suite of direct electrification technologies, such as molten oxide (or high-temperature) electrolysis (MOE) and low temperature electrolysis are being developed, but are currently at low technology readiness levels. Whilst both are promising, they should be considered as longer-term R&D bets, given there are key unknowns around the economics of their operations, such as electricity consumption, flexibility of production, catalyst degradation rates and iron ore suitability.

The use of biomass to displace fossil fuels has been explored across many end-use sectors for decades, including in India. The biochar-based blast furnaces constitute about 11% of steel production in Brazil, with many smaller-scale units operating across the country. Alternative methods of reduction using biomass to replace coal in microwave-assisted, electrically-heated reduction chambers are also being explored by companies like Rio Tinto, who have invested $143 million in such a facility in Australia.[13] The main challenge for India, and other countries looking to expand the role of biomass in the energy

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4 https://energy.economictimes.indiatimes.com/news/renewable/jindal-steel-doubles-down-on-green-hydrogen-production-in-india/113388848

5 https://www.iamrenew.com/green-energy/jsw-energy-will-build-indias-largest-commercial-scale-green-hydrogen-project/

6 https://www.diw.de/documents/publikationen/73/diw_01.c.901039.de/dp2082.pdf

7 https://hyiron.com/

8 https://www.mpiuk.com/research-project-h2dri.htm

9 https://fuelcellsworks.com/news/lingen-opens-pilot-plant-for-green-iron-production-using-hydrogen

10 https://arpa-e.energy.gov/programs-and-initiatives/search-all-projects/zero-emission-process-direct-reduction-iron-hydrogen-plasma-rotary-kiln-reactor

11 https://www.posco.co.kr/homepage/docs/eng7/jsp/hyrex/

12 https://www.mhi.com/technology/review/sites/g/files/jwhtju2326/files/tr/pdf/e592/e592070.pdf

13 https://www.riotinto.com/en/news/releases/2024/rio-tinto-to-develop-bioiron-rd-facility-in-western-australia-to-test-low-carbon-steelmaking

system, is the availability of a sustainable supply at an appropriate price and competition with other end-use sectors. The iron and steel sector alone is highly energy-intensive and would consume a considerable quantity of biomass, even if only a portion of the sector uses this as a fuel. Already, the power sector in India is unable to meet their biomass blending targets due to supply shortages, with other sectors including aviation, road transport, cement and petrochemicals, all looking to further increase its use in the coming years.[14,15,16,17,18]

CCUS is also being explored by Indian steel companies, mainly via the smelting reduction (or HIsarna) route, or via the gas-based routes (including both natural gas and coal gasification). Adding CCUS to existing blast furnaces is also being developed elsewhere around the world, most notably in Japan under the Course50 programme, although emissions reduction is limited to approximately 60%.[19] The most advanced project in India is Jindal Steel's coal gasification direct reduction facility in Angul, where the company is inviting companies to co-locate new manufacturing facilities nearby, in order to off-take CO_2.[20] These could be food and drink suppliers or businesses in the fertilizer (urea), chemical or pharmaceutical industry, which require a pure stream of CO_2 in their production process.

Whilst this is a promising initiative, there is a limited market for the use of CO_2 in India, and emissions from the iron and steel sector far exceed this demand. Moreover, CO_2 use does not remove the emissions but recycles them, which may be a useful interim step on the pathway to net zero but is ultimately limited relative to other technology routes. It is possible to achieve >90% CO_2 reduction if the emissions are stored but further work is required to identify suitable storage sites across India, with current known sites (Maharashtra and Gujarat) being far away from existing iron and steel production hubs.

This assessment highlights the challenges that small-scale iron and steel producers face when identifying a technology that can help achieve deep emission reductions, with several being too costly, or at a nascent stage of development. Nevertheless, based on this assessment, the hydrogen rotary kiln is considered the most suitable for the small-scale iron and steel industry, given its low capital costs, modular scale, flexibility to iron ore inputs and flexibility of operation, all warranting further consideration of this technology in India.

14 https://www.bioenergy-news.com/news/indias-biomass-supply-falls-drastically-short-of-government-mandate/

15 https://www.iamrenew.com/green-energy/trualt-to-build-one-of-the-biggest-saf-plants-in-india-md-vijay-nirani/

16 https://iocl.com/pages/satat-overview

17 https://www.dalmiabharat.com/sustainability/

18 https://energy.economictimes.indiatimes.com/news/renewable/indian-oil-to-convert-50-per-cent-of-its-refineries-hydrogen-use-to-green-by-2050-says-dir-rd-ssv-ramakumar/101408808

19 https://www.greins.jp/course50/en/

20 https://www.indianchemicalnews.com/sustainability/lite/jspl-angul-invites-eoi-for-offtake-of-3600-tpd-of-captured-co2-26666

Hydrogen Rotary Kiln: A Tailored Technology Solution

Technology Details

Figure 5 depicts a conceptual process flow diagram of a rotary kiln for emission free direct reduced iron production using hydrogen as the reducing agent. First, iron ore feedstock in the form of iron ore concentrates or coarse fines are processed based on their size and suitability. Iron ore feedstock is then stored within the production system boundary to ensure continuous operation of the plant. The iron ore is then pre-heated in an electrically heated rotary kiln, increasing the temperature of the iron ore before feeding it into the rotary kiln for the reduction process. A heat recovery heat exchanger is used to extract heat from the exhaust stream of the reduction rotary furnace.

The hydrogen rotary kiln is a gastight, horizontal kiln, using hydrogen as the reducing agent, very similar to coal-based kilns used by the industry today. This kiln is a counter flow reactor, where hydrogen is fed from the output end and the pre-heated iron ore enters from the feed end. The endothermic reaction is carried out by providing thermal energy from electrical heaters installed on the surface of the rotary kiln. The electrical heaters can be embedded in a refractory layer on the outside of the kiln to prevent heat losses from the surface of the kiln.

Based on initial testing in the UK under the Materials Processing Institute (MPI)'s H2DRI project, iron ore, in the form of concentrates, coarse fines or lumps, undergoes peak reduction between 600–800°C.[21] This is a lower temperature as compared to a coal-based rotary kiln (900–1,000°C) because of the superior reduction kinetics of hydrogen.[22] Moreover, the same study shows that the use of pure hydrogen as a reductant results in a faster reduction process and higher metallization rate (>95%) relative to the existing coal-based reduction due to faster kinetics, improving the rate of output. In existing coal-based rotary kilns iron ore and coal are fired together for 8–10 hours to achieve an average metallization rate of 89–90%. Impurities from the coal are often added to the DRI, lowering its commercial value.

The overall reduction process is as follows:

$Fe_2O_2(s) + 3\ H_2(g) \rightarrow 2\ Fe(s) + 3\ H_2O(g)\ \Delta H° = +99.5\ kJ/mol$

It is expected that both the lower operation temperature and the use of hydrogen can allow a more flexible operation of the plant, as is the current setup in the HyIron project in Namibia, which uses a hydrogen rotary kiln supplied solely by hydrogen from solar plus batteries.[23] Based on authors' interaction with the equipment suppliers, vertical shaft furnaces tend to be less flexible, with an operating range of 80–100% of its capacity. This lack of flexibility requires larger investments in electricity and hydrogen infrastructure upstream of the plant, especially where the steel plant is not reliant (or only partially reliant) on an electricity or hydrogen grid. This includes renewable electricity generation, electrolysers, electricity and hydrogen storage infrastructure, and water supply and purification, which would have to be 'oversized' to ensure that the plant achieves a suitably high utilization rate.

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21 https://assets.publishing.service.gov.uk/media/649ac838b4d6ef000c038f67/Materials_Processing_Institute_-_Hydrogen_Direct_Reduction_of_Iron_pilot_furnace_and_steelmaking__H2DRI_pilot__-_IFS_Feasibility_Report.pdf

22 https://www.sciencedirect.com/science/article/abs/pii/S0360319920324411

23 https://hyiron.com/oshivela/

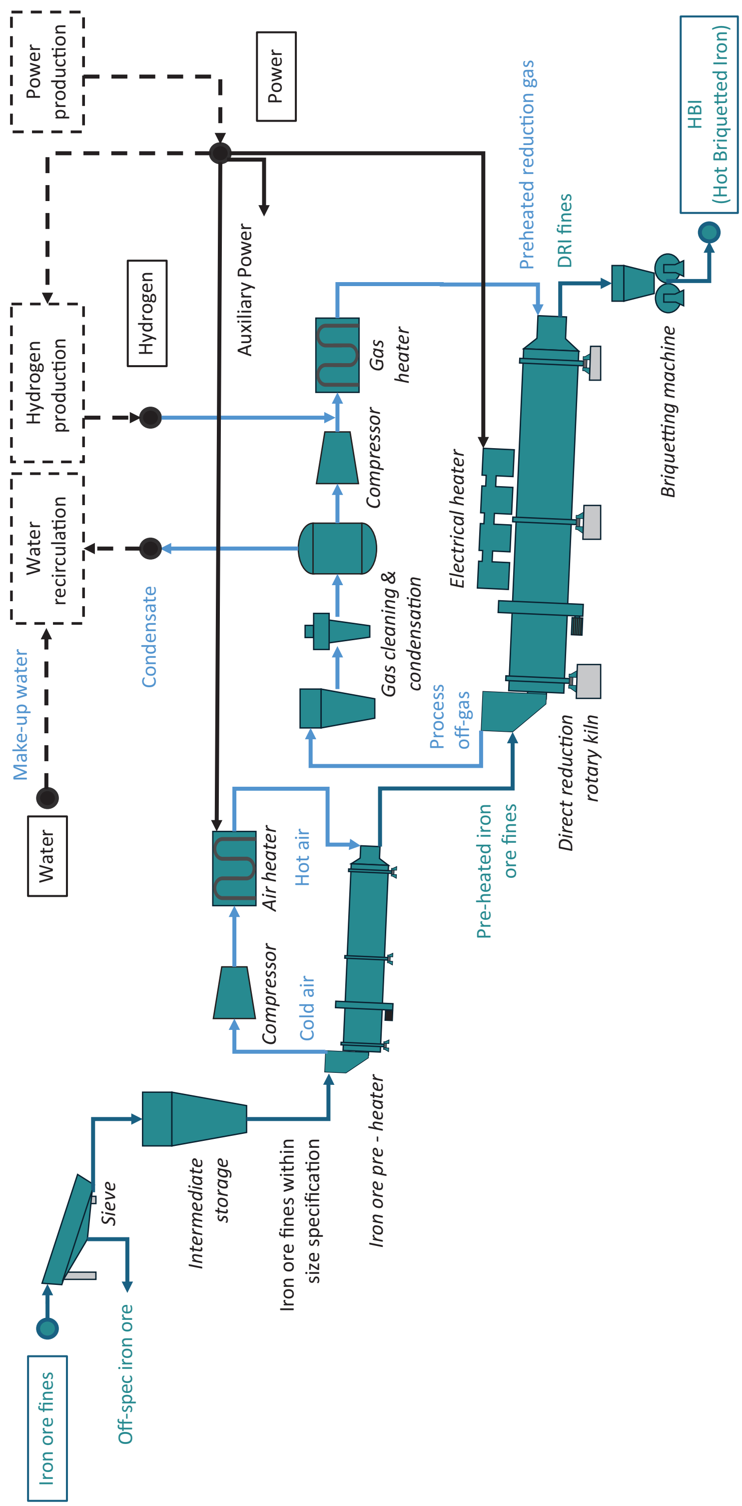

Figure 5: Process flow diagram for a hydrogen rotary kiln

Source: Author

Lower reactor temperature also reduces accretion formation on the surface of the kiln. Accretion refers to the deposition or build-up of low-melting oxide compounds on the internal surface of the reduction zone in the rotary kilns. Accretion formation is a key challenge for the current coal-based rotary kilns, caused by the high temperature of operation. Accretion results in the formation of a slag layer, which increases over time with use, affecting the metalizing reactions. This ultimately results in reduced working volumes and unscheduled kiln shutdowns as the accretion cannot be removed during operation.

During reduction, hematite is first converted to magnetite (Fe_3O_4) or wüstite (FeO) before complete reduction to iron. However, the net reaction enthalpy for the complete reduction of hematite to iron remains +99.5 kJ/mol. Solid metallic iron (Fe) is obtained as the primary product. Water vapor (H_2O) is generated as a byproduct, which can be condensed and recycled for further hydrogen production in a closed-loop system.

Electricity and Green Hydrogen Supply

A hydrogen-based rotary kiln would rely on green hydrogen, generated by renewable electricity, as the chemical feedstock/reducing agent. India is home to some of the lowest priced renewables in the world, supported by subsidy programmes from state and central governments. With the potential to significantly grow both wind and solar generating capacity in the coming years, in part to meet the 2030 target of 500 GW, it can be expected that costs will continue to fall, supporting lower cost green hydrogen production. This has been proven through the latest SECI tenders for round-the-clock (RTC) power, coming in at just over ₹5/kWh (or $56/MWh) in June 2025.[24]

This has been borne out in recent tenders for green ammonia in India, which have achieved some of the lowest known prices in the world. These are underpinned by the Strategic Interventions for Green Hydrogen Transition (SIGHT) programme, which provides support for both electrolyser manufacturing facilities, as well as the final delivered cost of green hydrogen, which is paid by off-takers.[25] The combination of this subsidy, plus India's capabilities in delivering large-scale renewable energy projects, promises to deliver green ammonia at prices between $575–744/tonne. These prices indicate a green hydrogen price between $3.27–4.23/kg. Whilst these projects are still at an early stage, they signal encouraging momentum towards cost reduction in the green hydrogen supply chain.

Emissions and Pollution Reduction

This process can be emission free, if the hydrogen is produced using renewable electricity and electrolysis. During the transition to such a technology, it may be necessary to use grid power to supply at least some of the electricity, resulting in some indirect emissions from the Indian electricity grid, which has an emission intensity of around 727 gCO_2/kWh as of 2024.

Direct emissions at the site would be close to zero, drastically reducing CO_2 and other pollutants. Existing coal-based direct reduction facilities are the most emission-intensive route in operation, ranging between 2.7 and 3.1 tCO_2/tcs, resulting in this technology delivering a significant saving.

Equally important as a reduction in CO_2 emissions is the reduction in air pollution that can result from switching to green hydrogen. Pollution from coal-based rotary kilns is responsible for a large amount of negative health impacts across India, including respiratory diseases, reduction in agricultural output and hazardous working conditions.

24 https://www.seci.co.in/uploads/tenders/bidders/bidder_6850f89eb023a2_03406162.pdf

25 https://mnre.gov.in/en/national-green-hydrogen-mission/

Cost of Production

For a hydrogen-based rotary kiln to be adopted in India, its cost of production should be close to competitive with both the existing coal-based routes of production, as well as alternative future low emission routes of production. Based on a levelized cost analysis, this paper illustrates the potentially attractive economics of a hydrogen rotary kiln, highlighting how its lower capex and flexibility can help reduce costs of production as compared to competing technologies.

Figure 6 highlights how the costs of DRI from a hydrogen-based rotary kiln compares with the same from a hydrogen vertical shaft furnace. At hydrogen prices seen in the green ammonia tenders in India, of around \$3.5/kg, DRI from a hydrogen rotary kiln would be close to competitive with DRI made using coal-based rotary kilns. The higher capex, energy consumption, use of high-grade pellets and lack of flexibility from a vertical shaft mean that it struggles to reduce costs far enough, as compared to coal DRI.

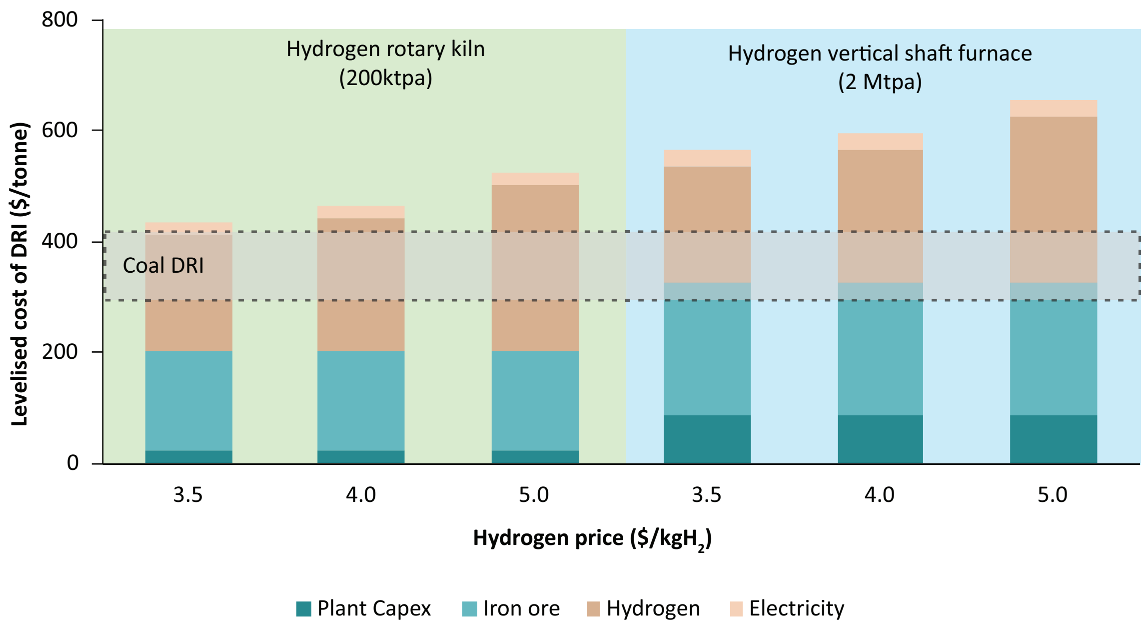

Figure 6: Levelized cost of DRI production

Source: Authors' analysis

Note: Levelized cost of production comparison of the rotary kiln furnace and a vertical shaft furnace operating under similar conditions. It is assumed that the cost of electricity is \$50/MWh and the weighted average cost of capital is 8%. Higher iron ore costs for the vertical shaft are driven by the use of pellets, versus non-agglomerated form of the rotary kiln.

By testing different input assumptions, we can see the impact of increasing the flexibility of operation for procuring DRI from a hydrogen-based rotary kiln. Increased flexibility allows the production process to take advantage of lower cost renewable electricity, ramping up when prices are low and ramping back down when the prices are high.

Assuming even lower capex, achieved through learning-by-doing, once several of these kilns have been built, this process route can achieve even lower costs. It is worth noting that the most competitive grid setup in all cases is a combination of both grid and off-grid electricity supply, with the project able to benefit from the lower costs of an off-grid system, whilst guaranteeing a minimum level of operation from the grid connection. This hybrid setup ensures access to lower cost electricity, whilst reducing storage requirements, which can be costly at large scales.

The possibility of 'grid banking' for green hydrogen projects in India, which allows allows producers to store excess renewable energy in the power grid and draw it later for electrolysis, providing additional flexibility and reducing on-site storage needs, further improves the economics of such projects in India.

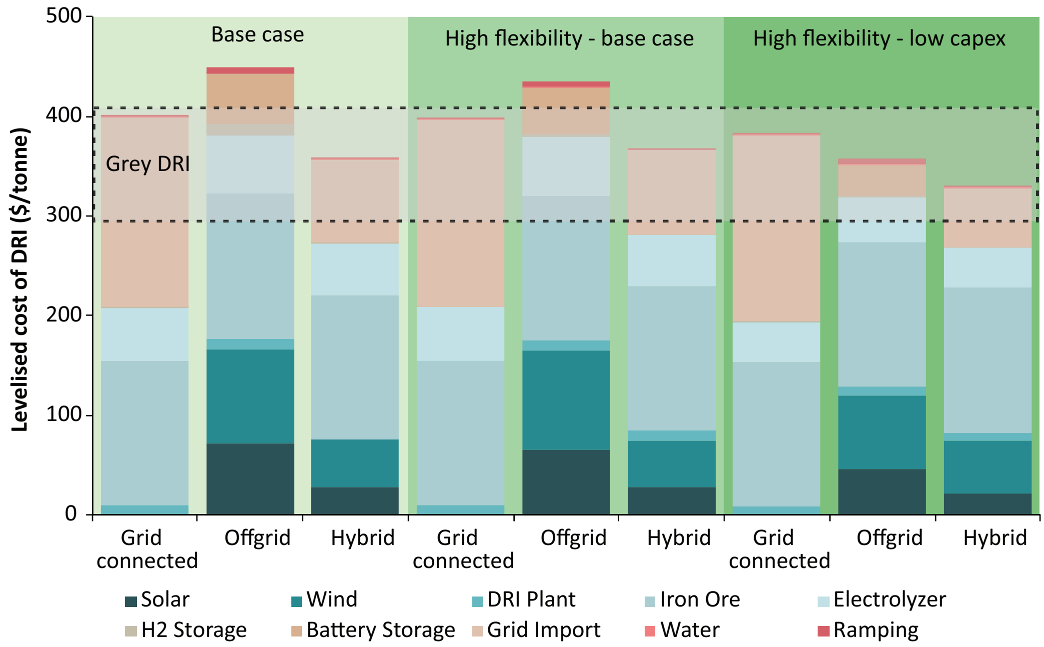

Figure 7: Levelized cost of DRI production for a hydrogen rotary kiln (200,000 tpa) under different scenarios

Source: Authors' analysis

Note: Solar and wind refer to off-grid generation capacity versus grid-connected capacity. Grid import includes both electricity unit costs and grid connection charges. Hybrid refers to a mix of grid connected and off-grid capacity. Ramping refers to costs associated with the increased maintenance of equipment due to frequent cycling.

A Future Scenario for the Adoption of Hydrogen Rotary Kilns in India

India is by far the largest market for rotary kilns in the steel sector, with over 42 Mt of production capacity currently in operation. There is significant technical expertise with regard to this technology and a broad understanding of its operation, particularly among SMEs. That said, there is a reason why larger BF-BOF routes dominate capacity expansion around the world—the economies of scale and flexibility on input and degree of control over the quality of outputs makes it a highly competitive production route despite high emissions. As India accelerates its shift to net zero, BF-BOFs are likely to be replaced by alternative technologies that can be competitive within a new paradigm of zero (or near-zero) emissions.

As mentioned above, the main option being considered by steel companies looking to make the shift are gas-based vertical DRI shafts, in many cases initially using natural gas before blending to 100% low emission hydrogen. CCUS is also being considered by some steel companies, although its emission reduction potential is more limited. Whilst it is likely that both these routes will form an important part of India's steel production mix by 2070, it is also likely that smaller rotary kilns will continue to play a role, as they do today.

The main reasons that will continue to drive the uptake of smaller hydrogen rotary kilns are in many cases similar to the reasons why their coal-based equivalents continue to grow. This includes their lower capex, allowing a broader range of actors to enter the market, who can respond to surging demand for steel, or shortages of scrap, much faster than larger facilities. For the hydrogen rotary kiln, this also can be built out in tandem with renewable electricity generation and distribution infrastructure, where time taken for planning, permitting and construction can be a major delay on larger projects. The ability to more readily co-locate smaller facilities near to the iron ore resources and renewable electricity generation will reduce transport and logistics costs, similar to how these plants operate today.

Recommendations

Deploy a Large-scale Demonstration Plant in India

Companies and research institutions in India should work together to accelerate the testing and scale-up of this technology, to ensure it can be deployed quickly and cost-effectively. This includes further lab and pilot-scale testing to fine-tune a setup that can work best in Indian conditions, before moving to a demonstration plant before 2030. For reference, a similar project in Namibia, producing 15,000 tpa of DRI (approx. 50 tpd), costs €30 million or ₹310 crore, including all renewable electricity and hydrogen infrastructure.[26] This was partly financed by the German government and private equity.

Build Awareness and Expertise in the Technology

India is home to the most mature rotary kiln industry in the world, with deep expertise in the technology's development and operation. However, this experience is currently focused on the use of coal, with a relatively limited understanding of building and operating renewables and hydrogen infrastructure, as well as the use of a rotary kiln using hydrogen. As a result, efforts should be taken to brief the industry on the potential of this technology, illustrating the ideal use cases. This could take the form of workshops and engagement with individual steel companies.

Secure Off-take Agreements

It is expected that producing green iron using a hydrogen rotary kiln will be approximately 10–15% more expensive than coal-based DRI route for the initial plants (Figure 6), requiring a portion of the green premium to be covered by offtake agreements. As with successful examples of early green ammonia projects, similar green iron projects should target overseas off-takers, particularly in developed countries that are willing to absorb the green premium.

Beyond agreeing to pay a portion of the green premium, it may be possible to secure additional co-benefits between importing and exporting countries and companies, including licensing and co-developing the hydrogen rotary kiln technology. Also, off-takers may be willing to invest directly in the project in India, providing low-cost finance, ultimately lowering the final cost of green iron.

Domestic off-take markets will also start to scale, supported initially by the Ministry of Steel's Green Public Procurement Policy, although the emissions intensity of steel required under this policy are

26 https://hyiron.com/oshivela/

far higher than what would be achieved by a hydrogen rotary kiln. As a result, government should explore a more transformative component to their procurement policy, which also incentivizes a smaller portion of truly net-zero compliant steel, alongside incremental emission reductions.

Establish an Ambitious Carbon Price

India is in the process of implementing its own emissions trading system, known as the Carbon Credit Trading Scheme (CCTS). The CCTS will cover majority of iron and steel plants, including all rotary kilns above 200 tpd. Whilst it is expected that the carbon price under the CCTS will start relatively low, it will nonetheless provide additional support for producing green iron and steel, relative to the conventional, high emission routes. Moreover, revenues from the CCTS should be used to accelerate the switch to hydrogen among rotary kiln players.

Support Scale-up with Concessional Finance

The cost of capital for smaller-scale industrial producers in India remains relatively high, with loans often provided by state-level banks or Small Industries Development Bank of India (SIDBI). For capital-intensive facilities, such as those for iron and steel, concessional lending rates, from public or private financiers can have a major impact on the commercial viability of a project. Such sources of finance include Bureau of Energy Efficiency's (BEE) Assistance in Deploying Energy Efficiency Technologies in Industries & Establishments (ADEETIE) scheme, which is designed to help MSMEs adopt energy-efficient technologies, through interest rate subvention, as well as broader technical assistance.[27]

Unblock Renewable Electricity Infrastructure

There already exists some level of support in using India's electricity infrastructure for projects related to green hydrogen, including the omission of inter-state transmission charges, to help incentivize new projects. Beyond this, it may be necessary to further support within-state infrastructure, via accelerated permitting of new generation sites. For some larger steel companies, which also have electricity companies under their wider corporate umbrella, for example, Tata Steel and Tata Power or JSW Steel and JSW Energy, they may look to build and own the entire energy and material supply chain for producing green iron. However, for smaller iron and steel companies, such as those currently using rotary kilns, it may be more suitable to partner with a well-established renewable energy company, which can use their expertise to build low-cost infrastructure, as needed. This can also benefit renewable energy companies, that can rely on the guaranteed off-take from a single, large user.

Foster Industrial Clusters to Lower Costs

Alongside support for renewable electricity infrastructure, it would be beneficial to cluster hydrogen and DRI production units around the same location to reduce transportation and handling costs for hydrogen. With multiple potential off-takers across different industrial sectors, this could help derisk investments, as demand would be more resilient to sectoral fluctuations.

27 https://adeetie.beeindia.gov.in/

Conclusion

Developing the hydrogen rotary kiln for ironmaking in India represents one of the promising pathways for accelerating the decarbonization of the iron and steel sector. This will require concerted collaboration between government, steel companies, energy companies, financiers and civil society, both domestically and internationally. In doing so, India can deliver a tailor-made solution that will leverage the success of its hydrogen sector, as well as its renewable resources, ensuring Indian steel remains competitive in the long-term.

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