Evaluating Net-zero for the Indian Steel Industry

Marginal Abatement Cost Curves of Carbon Mitigation Technologies

Sabarish Elango, Kartheek Nitturu, Deepak Yadav, Pratheek Sripathy, Rishabh Patidar, and Hemant Mallya

Report | October 2023

Suggested citation: Elango, Sabarish, Kartheek Nitturu, Deepak Yadav, Pratheek Sripathy, Rishabh Patidar, and Hemant Mallya. 2023. *Evaluating Net-zero for the Indian Steel Industry: Marginal Abatement Cost Curves of Carbon Mitigation Technologies*. New Delhi: Council on Energy, Environment and Water.

Cover images: iStock.

Peer reviewers: Deependra Kashiva, Executive Director, Sponge Iron Manufacturers' Association (SIMA); Ratna Prasad, CEO, Hospet Steels; Sujan Hazra, Principal Researcher, Tata Steel Ltd; and Dr Aman Malik, Programme Lead, CEEW.

Publication team: Kartikeya Jain (CEEW); Alina Sen (CEEW); The Clean Copy; Aspire Design; and Friends Digital Color Solutions.

Acknowledgment: The authors of the report would like to express their appreciation to Ellan Anbarasu, Head – Corporate Sustainability, Tata Steel Ltd; Dr Mukesh Kumar, Senior Advisor, Jindal Steel and Power Ltd; Vaibhav Pokharna, Senior Lead, Sustainability, ArcelorMittal Nippon Steel India for providing inputs at various stages of the report analysis, and to bp for supporting this study.

Organisation: The Council on Energy, Environment and Water (CEEW) is one of Asia's leading not-for-profit policy research institutions and among the world's top climate think tanks. The Council uses data, integrated analysis, and strategic outreach to explain — and change — the use, reuse, and misuse of resources. The Council addresses pressing global challenges through an integrated and internationally focused approach. It prides itself on the independence of its high-quality research, develops partnerships with public and private institutions, and engages with the wider public. CEEW has a footprint in over 20 Indian states and has repeatedly featured among the world's best managed and independent think tanks. Follow us on X (formerly Twitter) @CEEWIndia for the latest updates.

COUNCIL ON ENERGY, ENVIRONMENT AND WATER (CEEW)
ISID Campus, 4 Vasant Kunj Institutional Area
New Delhi – 110070, India
+91 11 4073 3300
info@ceew.in | ceew.in | @CEEWIndia | ceewindia

Evaluating Net-zero for the Indian Steel Industry

Marginal Abatement Cost Curves of Carbon Mitigation Technologies

Sabarish Elango, Kartheek Nitturu, Deepak Yadav, Pratheek Sripathy, Rishabh Patidar, and Hemant Mallya

Report
October 2023
ceew.in

About CEEW

The Council on Energy, Environment and Water (CEEW) is one of Asia's leading not-for-profit policy research institutions and among the world's top climate think tanks. The Council uses **data, integrated analysis, and strategic outreach to explain — and change — the use, reuse, and misuse of resources.** The Council addresses pressing global challenges through an integrated and internationally focused approach. It prides itself on the independence of its high-quality research, develops partnerships with public and private institutions, and engages with the wider public. CEEW is a strategic/ knowledge partner to 11 ministries for India's G20 presidency.

The Council's illustrious Board comprises Mr Jamshyd Godrej (Chairperson), Dr Anil Kakodkar, Mr S. Ramadorai, Mr Montek Singh Ahluwalia, Dr Naushad Forbes, and Dr Janmejaya Sinha. The 250-strong executive team is led by Dr Arunabha Ghosh. CEEW was certified a **Great Place To Work**® in 2020 and 2021. It has also repeatedly featured among the world's best managed and independent think tanks.

In over 13 years of operations, The Council has engaged in over 450 research projects, published 380+ peer-reviewed books, policy reports and papers, created 190+ databases or improved access to data, advised governments around the world 1400+ times, promoted bilateral and multilateral initiatives on 130+ occasions, and organised 540 seminars and conferences. In July 2019, Minister Dharmendra Pradhan and Dr Fatih Birol (IEA) launched the CEEW Centre for Energy Finance. In August 2020, Powering Livelihoods — a CEEW and Villgro initiative for rural start-ups — was launched by Minister Piyush Goyal, Dr Rajiv Kumar (then NITI Aayog), and H.E. Ms Damilola Ogunbiyi (SEforAll).

The Council's major contributions include: Informing India's net-zero goals; work for the PMO on accelerated targets for renewables, power sector reforms, environmental clearances, Swachh Bharat; pathbreaking work for India's G20 presidency, the Paris Agreement, the HFC deal, the aviation emissions agreement, and international climate technology cooperation; the first independent evaluation of the National Solar Mission; India's first report on global governance, submitted to the National Security Advisor; support to the National Green Hydrogen and Green Steel Missions; the 584-page National Water Resources Framework Study for India's 12th Five Year Plan; irrigation reform for Bihar; the birth of the Clean Energy Access Network; the concept and strategy for the International Solar Alliance (ISA); the Common Risk Mitigation Mechanism (CRMM); India's largest multidimensional energy access survey (ACCESS); critical minerals for Make in India; India's climate geoengineering governance; analysing energy transition in emerging economies, including Indonesia, South Africa, Sri Lanka, and Viet Nam. CEEW published Jobs, Growth and Sustainability: A New Social Contract for India's Recovery, the first economic recovery report by a think tank during the COVID-19 pandemic.

The Council's current initiatives include: State-level modelling for energy and climate policies; consumer-centric smart metering transition and wholesale power market reforms; modelling carbon markets; piloting business models for solar rooftop adoption; fleet electrification and developing low-emission zones across cities; assessing green jobs potential at the state-level, circular economy of solar supply chains and wastewater; assessing carbon pricing mechanisms and India's carbon capture, usage and storage (CCUS) potential; developing a first-of-its-kind Climate Risk Atlas for India; sustainable cooling solutions; developing state-specific dairy sector roadmaps; supporting India's electric vehicle and battery ambitions; and enhancing global action for clean air via a global commission 'Our Common Air'.

The Council has a footprint in over 20 Indian states, working extensively with 15 state governments and grassroots NGOs. Some of these engagements include supporting power sector reforms in Uttar Pradesh, Rajasthan, and Haryana; energy policy in Rajasthan, Jharkhand, and Uttarakhand; driving low-carbon transitions in Bihar, Maharashtra, and Tamil Nadu; promoting sustainable livelihoods in Odisha, Bihar, and Uttar Pradesh; advancing industrial sustainability in Tamil Nadu, Uttar Pradesh, and Gujarat; evaluating community-based natural farming in Andhra Pradesh; and supporting groundwater management, e-auto adoption and examining crop residue burning in Punjab.

Contents

The BF-BOF route contributes the most to the total steel production and emissions

Image: iStock

Executive summary

The Indian steel industry is currently the second largest in the world and has immense growth potential. India's steel capacity is projected to double from 154 Mtpa in 2021–22 to 300 Mtpa by 2030 (JPC 2022a, Ministry of Steel 2017). In 2018–19, the steel industry accounted for 12 per cent of India's total CO_2 emissions (GHG Platform India, n.d.) – a sizable share that necessitates the use of comprehensive decarbonisation measures if India is to achieve its 2070 net-zero emissions goal. Considering that the steel industry employs several manufacturing technologies and routes, there is a need for a consolidated estimate of the emissions from each route, the decarbonisation measures available for each route, their abatement potential, and the abatement costs. Our study aims to provide options for the steel industry to effectively work towards achieving net-zero targets. The study considers four major steelmaking pathways:

- Blast furnace-basic oxygen furnace (BF-BOF) route
- Coal-based direct reduction of iron-induction furnace (coal DRI-IF) route
- Coal-based direct reduction of iron-electric arc furnace (coal DRI-EAF) route
- Gas-based direct reduction of iron-electric arc furnace (gas DRI-EAF) route

For each pathway, we estimated the baseline emissions for the year 2021–22. We then calculated the costs and emission reductions possible with various technologies under four categories:

- **Energy efficiency (EE):** Measures and technologies that reduce the energy consumed per unit of product output.
- **Renewable energy (RE):** Switching from coal-based captive power generation to renewable energy sources such as solar and wind power.
- **Alternative fuels (AF):** Switching to cleaner process fuels such as biomass and green hydrogen.
- **Carbon management:** Adopting carbon capture technologies to capture those emissions that cannot be mitigated through other measures.

The study provides options for existing steel plants to achieve net-zero emissions

A. Key findings

The Indian industry emits 2.36 tonnes of CO_2 per tonne of crude steel

Our assessment indicates that the Indian steel industry emitted 297 million tonnes of CO_2 ($MtCO_2$) in 2021–22 while producing 120.3 million tonnes of crude steel. Table ES1 shows the emission estimates for various steelmaking routes along with the respective shares of the inputs. The BF-BOF route accounted for the highest cumulative emissions, not only because it holds the largest share in steelmaking but also because of its emission-intensive process. Although the coal DRI-IF route exhibits a relatively low emission intensity of 2.30 tonnes of CO_2/tcs due to the higher usage of scrap (39 per cent, including primarily scrap-based, standalone IF plants), it ranks second in terms of emissions due to its substantial steel production volume. In comparison, the coal DRI-EAF and gas DRI-EAF routes have lower absolute emissions, primarily because their shares in the overall production are relatively smaller. Our assessment indicates that the average emission intensity of steel in India amounts to approximately 2.36 tCO_2/tcs.

Table ES1 Baseline emissions from the Indian steel industry totalled ~297 $MtCO_2$ in 2021–22

Pathway	Production in 2021–22 (Mtcs)	Production share (%)	Total emissions ($MtCO_2$)	Emission intensity (tCO_2/tcs)	Hot metal share (%)	DRI share (%)	Scrap share (%)
BF-BOF	57.6	48	185.82	2.46	91	0	9
Coal DRI-IF	34.6	29	79.71	2.30	0	61	39
Coal DRI-EAF	15.0	12	15.46	2.51	61	26	13
Gas DRI-EAF	13.1	11	15.72	1.91	29	58	13
Total	**120.3**	**100**	**296.72**	**2.36**			

Source: JPC (2022a); JPC (2022b); Authors' analysis

Note 1: Figures may not tally due to rounding.

Note 2: The emission intensity of a given route was calculated by considering both the iron produced by plants employing that route and the allocated emissions of iron from other plants.

*includes emissions from pig iron sold directly.

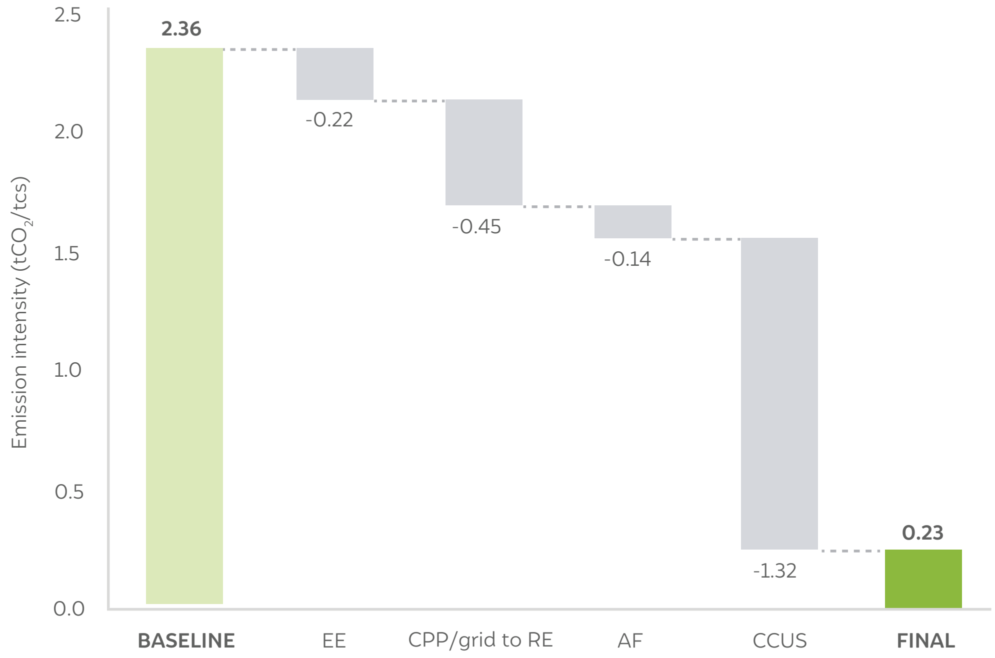
Note 3: The emission intensity of coal DRI-IF is lower than that of BF-BOF and coal DRI-EAF because we have grouped integrated plants, which consume only about 15 per cent scrap, and standalone IF plants, which can consume as much as 80 per cent scrap, under the same overall route. With 15 per cent scrap, the emission intensity of integrated DRI-IF plants can be higher than 3 tCO_2/tcs.

Carbon capture, utilisation, and storage is critical for decarbonising the steel industry

Due to process- and technology-specific constraints and operating conditions, the decarbonisation trajectory of each steelmaking pathway will be unique. The role of EE, RE, AF, and carbon management for decarbonising the Indian steel industry is shown in Figure ES1.

Assuming an initial weighted average emission intensity for steel produced across processes, we estimate that EE contributes to 9 per cent of the total reduction, followed by a nearly 19 per cent reduction through round-the-clock (RTC) renewable energy. The use of alternative fuels, such as natural gas and biomass pellets, has a limited effect on the overall reduction of emissions (at 6 per cent). In contrast, carbon capture, utilisation, and storage (CCUS) have the potential to abate 56 per cent of the emissions generated from the steel sector.

Figure ES1 CCUS will play a significant role in the decarbonisation of the Indian steel industry

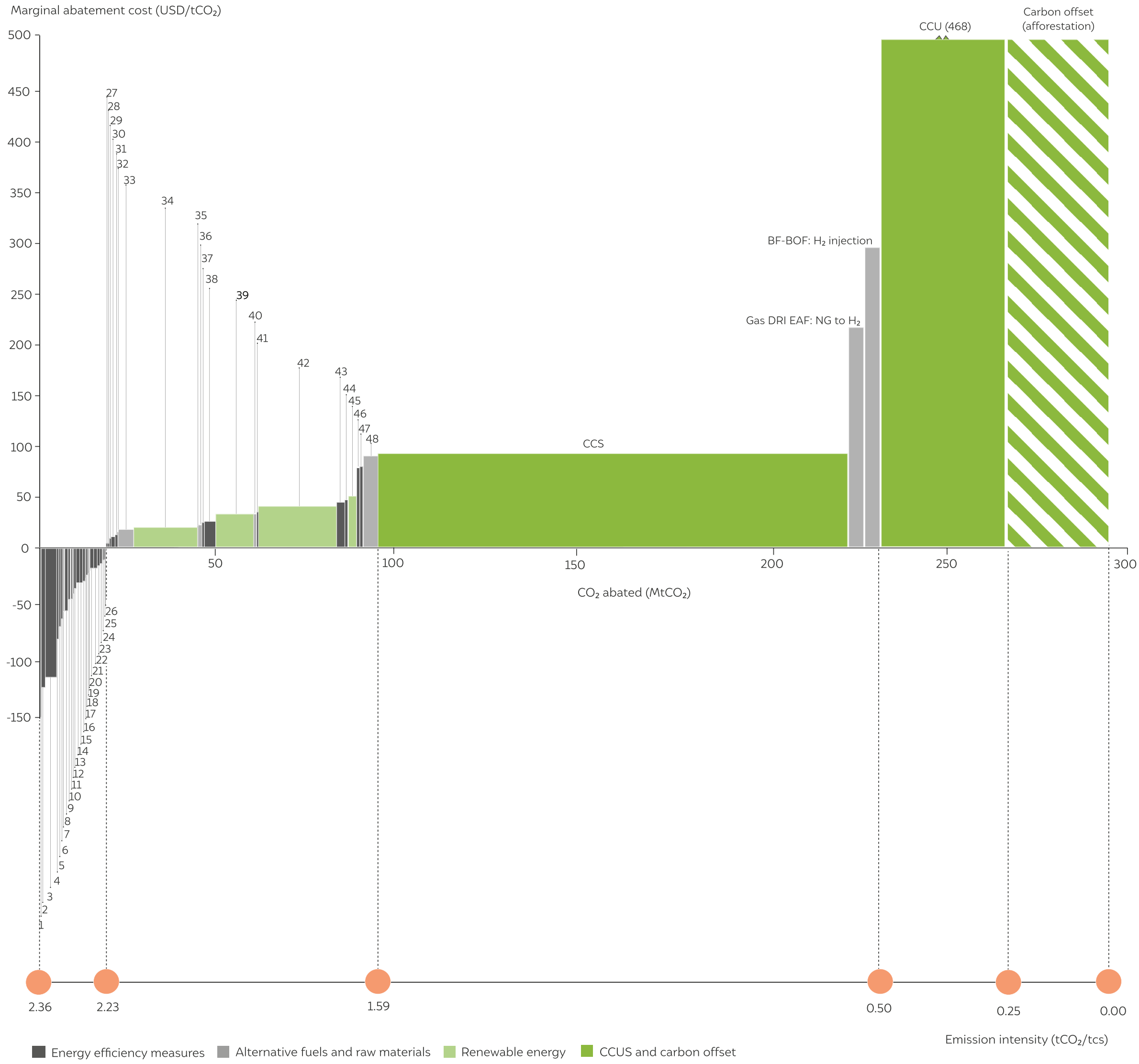


Source: Authors' analysis

Figure ES2 shows the consolidated marginal abatement cost (MAC) curve for the Indian steel industry. The X-axis represents the total emissions of the steel industry in 2021–22, which was 297 $MtCO_2$. Approximately 7 per cent of the average emissions per tonne of crude steel (tcs) can be reduced through mitigation measures that have a net negative annualised mitigation cost. However, the remaining emissions can only be reduced by employing technologies that have a positive annualised mitigation cost, suggesting that manufacturers who adopt these measures will face an increase in their steel production cost.

By implementing other EE measures (that have a positive cost of mitigation), switching to renewable power, and using alternative fuel options, we can reduce emissions by 28 per cent, which is equivalent to 92 $MtCO_2$. For abating the remaining emissions, carbon management techniques or expensive alternative fuels, such as green hydrogen injection, need to be considered to achieve net-zero emissions. We expect the cost of hydrogen-based steel to decline more aggressively than the cost of measures such as CCUS. In such a scenario, hydrogen-based steelmaking would become a predominant production pathway, specifically for new capacity deployment. It should, however, be noted that in accordance with plant-specific conditions, location, and the availability of alternative fuels, the order of adopting various carbon mitigation technologies might vary.

Figure ES2 **A majority share of abatement measures have a positive mitigation cost**



Legend

1. Coal DRI-EAF: Bottom stirring in EAF
2. BF-BOF: Increasing PCI rate
3. BF-BOF: COG use in DRI production
4. Coal DRI-EAF: Higher power EAF transformer
5. Coal DRI-EAF: Optimised EAF power control
6. BF-BOF: Increasing sintering burner efficiency
7. Coal DRI-EAF: Efficient dedusting system for EAF
8. BF-BOF: Energy monitoring system
9. BF-BOF: Hot stove: Sensible heat recovery
10. Coal DRI-EAF: Oxyfuel burner in EAF
11. Gas DRI-EAF: Bottom stirring in EAF
12. Gas DRI-EAF: EAF gas WHR power
13. Coal DRI-EAF: EAF charge preheating
17. Gas DRI-EAF: EAF charge preheating
18. Coal DRI-EAF: Eccentric tapping of EAF
19. Coal DRI-IF: Efficient kiln blowers
20. BF-BOF: Variable speed drives
21. Coal DRI-IF: Kiln flue gas WHR power
22. BF-BOF: Cogeneration (excluding COG)
23. BF-BOF: Preventive maintenance
24. Gas DRI-EAF: Optimised EAF power control
25. Gas DRI-EAF: Higher power EAF transformer
26. Gas DRI-EAF: Efficient dedusting system for EAF
27. Gas DRI-EAF: Oxyfuel burner in EAF
28. Gas DRI-EAF: Scrap pretreatment system for EAF
29. Coal DRI-EAF: Scrap pretreatment system for EAF
33. Coal DRI-IF: Use of higher-quality imported coal
34. Coal DRI-IF: Coal-based CPP/grid to RE
35. Coal DRI-EAF: Efficient kiln blowers
36. BF-BOF: Biomass injection in BF
37. BF-BOF: Coal moisture control
38. BF-BOF: Coke dry quenching
39. Gas DRI-EAF: Coal-based CPP to RE
40. Coal DRI-EAF: Use of higher-quality imported coal
41. Coal DRI-EAF: DRI char WHR power
42. BF-BOF: Coal-based CPP to RE
43. BF-BOF: Top-pressure recovery turbine
44. Coal DRI-IF: DRI char WHR power
45. Coal DRI-EAF: Coal-based CPP/grid to RE

Source: Authors' illustration

Achieving net-zero in the steel industry needs significant investments

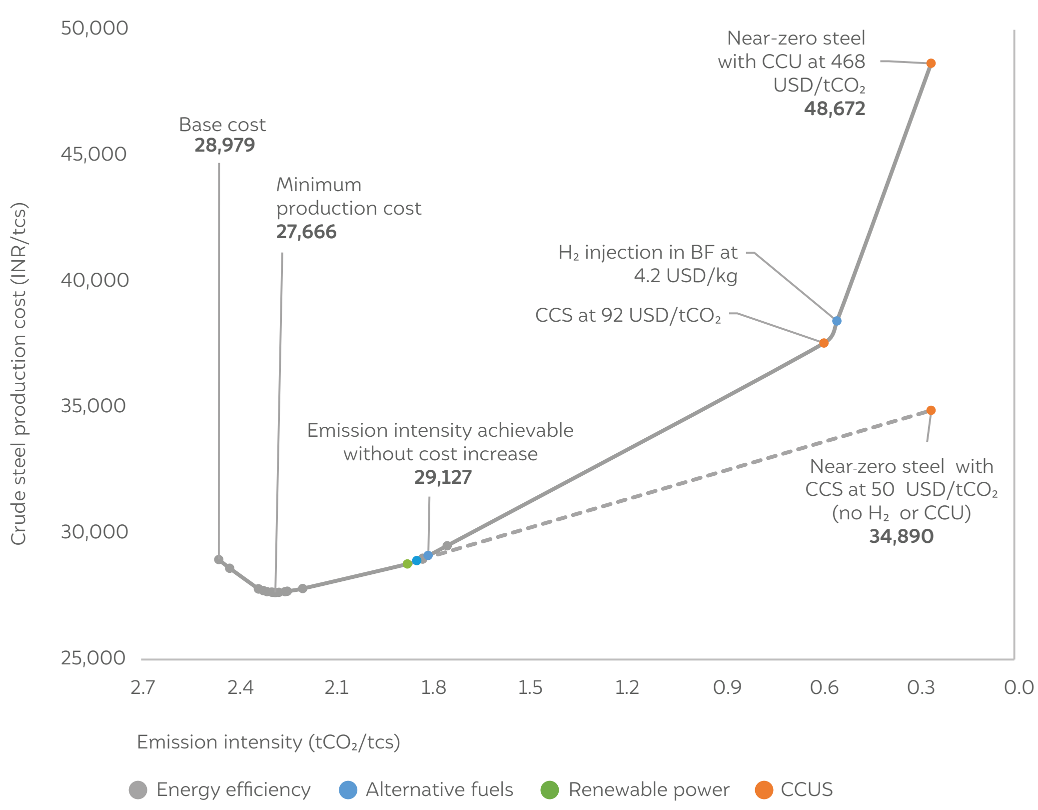
Our analysis indicates that the present capacity of the steel industry will need a total capital expenditure (CAPEX) of more than USD 283 billion (INR 21.2 lakh crore) (in 2022 value), of which the BF-BOF route alone has a 61 per cent share. The annual operational expenditure (OPEX) for these measures will amount to USD 8.8 billion (INR 66,715 crore) per annum to achieve net-zero emissions. However, if the cost of green hydrogen decreases to USD 1/kg, then the total CAPEX requirement for achieving net zero in the steel industry decreases to USD 182 billion (INR 13.6 lakh crore) due to a significant decrease in the cost of CCU Deploying EE measures alone will cost around USD 9.5 billion (INR 76,317 crore), of which the BF-BOF route holds a share of more than 87 per cent.

The CCUS cost greatly influences the price premium of near net-zero steel

The cost of producing steel will increase with the tightening of emission intensity limits. For the BF-BOF process, Figure ES3 shows that the cost of producing steel can be reduced by 5 per cent while achieving a 7 per cent reduction in emission intensity, primarily due to the deployment of EE measures. At the lowest production cost, the emission intensity of steel is 2.28 tCO_2/tcs. If the emission intensity of steel has to be reduced below this, then the cost of producing steel will increase. However, our analysis shows that the BF-BOF process could achieve an emission intensity of 1.84 tCO_2/tcs without any increase in the production cost. If COG is not used for producing DRI but is used in reheating furnaces and captive power plants, then the production cost breaks even at 1.94 tCO_2/tcs. The monetary gains obtained due to the adoption of EE measures partially offset the cost increase due to the uptake of renewable energy and alternative fuels. However, if the emission intensity needs to be reduced below 1.84–1.94 tCO_2/tcs, there will be a steep increase in the cost of production due to the high cost of CO_2 abatement associated with CCS, green hydrogen, and CCU.

In an alternative scenario (shown in green on the graph), if the cost of abatement for CCS reduces to USD 50/tCO_2, then CCS will be preferred over technologies such as slag heat recovery and top-pressure recovery turbines. In such a scenario, the near-zero steel would have only a 20 per cent premium. Therefore, the government must focus on creating a CCS ecosystem in the country to achieve its long-term decarbonisation targets.

Figure ES3 A 25% reduction in emissions is possible without any price increase for BF-BOF



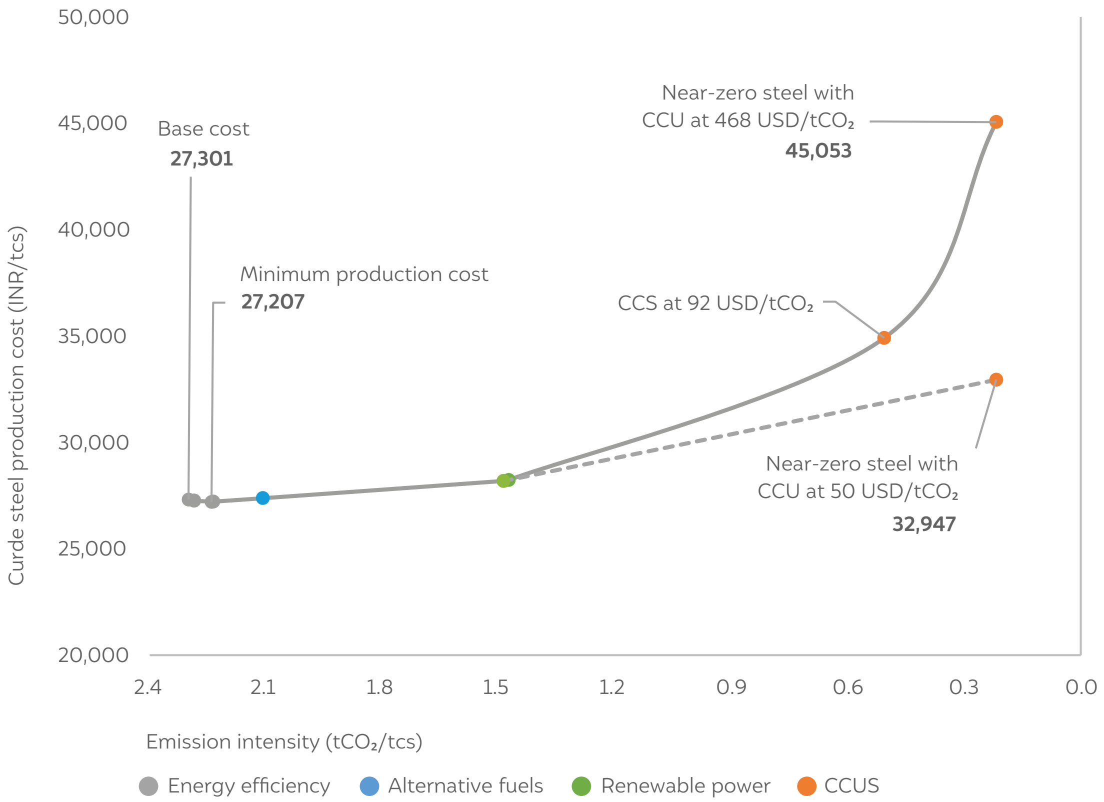
Source: Authors' analysis

Figure ES4 shows the change in the cost of producing crude steel vis-à-vis emission intensity for the coal DRI-IF route. Similar to the BF-BOF pathway, there is initially no significant decrease in the cost of steel as the emission intensity decreases, as very few energy efficiency technologies are available for the process. Beyond EE, the cost of steel increases steeply with a decrease in emission intensity due to the higher mitigation costs associated with renewable energy, CCS, and CCU. In the base case, achieving near-zero emissions is 65 per cent more expensive compared to a scenario where steel has an emission intensity of 2.3 tCO_2/tcs. If the CCS cost reduces to USD 50/tCO_2, and right-of-way is not an issue, then the cost increases by only 21 per cent, compared to the base case.

The emission intensity of coal DRI-EAF steel can be reduced by 6 per cent while achieving a 3 per cent reduction in production cost through the deployment of energy efficiency technologies in BFs (this route has a 62 per cent share of hot metal in the EAF) and EAF units. Although the steel cost starts increasing quickly beyond this, a 30 per cent reduction in emission intensity can be achieved without any net change in the cost. In the base case, near-zero steel will cost 64 per cent more. However, with the deployment of CCS at USD 50/tCO_2, the increase will only be 21 per cent.

The cost of producing gas DRI-EAF steel is reduced by 1.6 per cent after the adoption of all EE measures. A 17 per cent reduction in emission intensity can be achieved without any cost increase, mainly due to the use of RE. In the base case, the near-zero emissions steel is expected to cost 41 per cent more than conventional steel. However, if CCS can be deployed at USD 50/tCO_2 across all steel plants, then the cost of steel will increase by only 15 per cent over the current production costs.

Figure ES4 **An 8 per cent reduction in emissions is possible without any price increase for coal DRI-IF**



Source: Authors' analysis

B. Key recommendations

We recommend the following measures to achieve net-zero in the steel industry:

- The recently announced Indian Carbon Market (ICM) should set targets on energy intensity such that the adoption of all EE measures is incentivised. Nearly all energy efficiency technologies (except slag waste heat recovery) discussed in this study have a high technological readiness level (TRL) of TRL 11.
- Renewable power should be incentivised, as it will play a pivotal role in decarbonisation. The central government should provide long-term waivers on interstate open access charges for the steel industry. State governments should support the steel industry by waiving or reducing open access charges for renewable power at the state transmission unit level.
- Shaft furnaces are a means to decarbonise BF-BOF steelmaking. For capacity addition in BFs, gas DRI production with coke oven gas should be prioritised, thereby reducing the demand for natural gas. This approach aids in reducing coal-based production while promoting the growth of gas-based processes, which are beneficial for transitioning towards the utilisation of green hydrogen.
- The government of India should develop a policy for CCS that will eventually lead to the development of an effective CCS ecosystem in India. Since hydrogen will play a key role in its implementation, the next phase of the National Green Hydrogen Mission should focus on this agenda.
- The steel industry needs access to large volumes of low-cost finance in order to decarbonise. While big steel players can raise money from the market based on their strong balance sheets, small-scale industries will need new financial solutions to decarbonise.
- Research and development efforts must be bolstered by creating an inclusive, overarching ecosystem for the entire industry instead of individual companies conducting internal research. This is especially critical for fuel switching – specifically for rotary kilns – and CCUS.

For India to achieve its net-zero carbon emissions goal by 2070, actions taken by the steel industry will have an important role to play. While a substantial amount of new capacity will be deployed in the coming decade, the fact remains that the existing capacity is sizeable and relatively young. Therefore, several decarbonisation measures need to be taken by the industry collectively, not only to achieve our climate ambitions, but also to ensure the sustainable growth and development of Indian industry.

Steel plants in India rely mostly on coal-based production pathways.

Image: iStock

1. Introduction

The Indian steel industry produced 125.3 million tonnes of crude steel (Mtcs) in 2022, making it the second largest in the world (Worldsteel 2023). The industry comprises nearly 2 per cent of the gross domestic product (GDP) of the country (PIB 2018). Approximately 12 per cent of the steel produced is exported (Worldsteel 2023), netting a gross export revenue of nearly USD 13 billion in 2021–22 (Press Trust of India 2022). The per-capita steel consumption in India is only 74.7 kg, compared to the world average of 229 kg (PIB 2021a), suggesting an immense scope for growth. In light of this, the *National Steel Policy 2017* aims to increase India's per-capita steel consumption to 158 kg by 2030. It targets a steel production capacity of 300 million tonnes per annum (Mtpa), compared to the current 154 Mtpa (Ministry of Steel 2017).

The growth of the Indian steel sector must be balanced with the country's climate commitments

However, the growth of the Indian steel sector must be balanced with the country's climate commitments. The sector contributes 12 per cent to the total national and 31 per cent to the total industrial CO_2 emissions (GHG Platform India, n.d.). At the 26th Conference of Parties (COP26), India pledged to achieve net-zero CO_2 emissions by 2070 (PIB 2021b). Recently, India updated its nationally determined contributions and is targeting a 45 per cent reduction in the emission intensity of its GDP by 2030 vis-à-vis the 2005 levels (PIB 2022a).

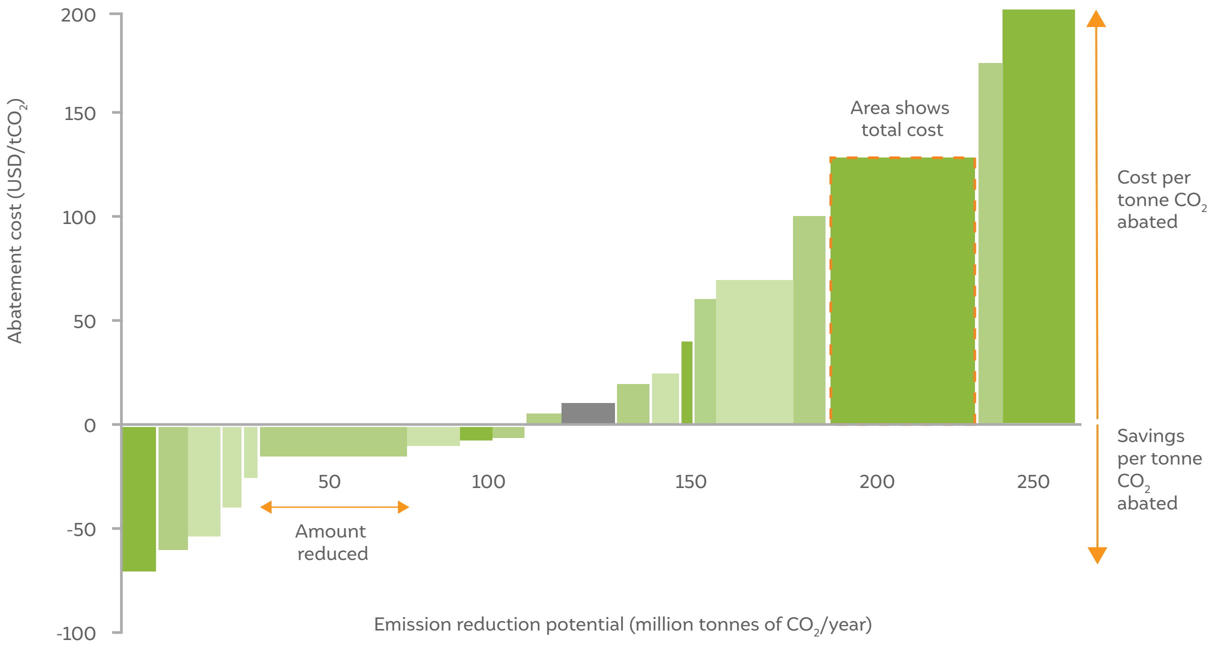
The steel sector offers significant opportunities for India to achieve its climate targets, given its large share in total emissions. However, the sector faces significant challenges in the coming decades due to its heavy reliance on solid fossil fuels and a lack of targeted initiatives for decarbonisation. The global average emission intensity of crude steel was 1.9 tCO_2/tcs in 2021 (Worldsteel 2022). Comparatively, the Indian average was estimated to be around 2.6 tCO_2/tcs in 2020 (PIB 2022b). India's steel sector has a higher emission intensity due to multiple reasons. In developed economies, the share of steel scrap in total steel production is relatively higher; the power grid is less carbon-intensive; sufficient high-grade iron ores are available, and lower-carbon fuels – such as natural gas – are available at affordable prices. Conversely, India has lower scrap availability, relatively lower grades of iron ores – only 18 per cent of Indian ores have a Fe content of greater than 65 per cent (Indian Bureau of Mines 2023) – more carbon-intensive electricity, and much more expensive natural gas.

A consequence of the lack of affordable natural gas and high-grade raw materials is that the Indian steel industry prefers coal-based blast furnaces and rotary kilns for primary ironmaking due to competitive production costs. Of the 154 Mtpa of steelmaking capacity (as of 2021–22), only 11 Mtpa uses gas-based technology that can be relatively easily decarbonised by switching to green hydrogen and renewable power (JPC 2022a). There are several decarbonisation options for coal-based steelmaking capacities, some mature and others in the early stages of commercialisation. Our study elucidates the different options available for the existing steelmaking capacity to achieve net-zero emissions and provides a consolidated view of reduction potentials and associated costs using marginal abatement cost (MAC) curves.

Marginal abatement cost curves provide the building blocks for achieving net-zero emissions

MAC curves show the incremental costs an entity will incur when implementing various technologies as well as pathways to reduce emissions from the baseline value. MAC curves plot the annualised CO_2 mitigation cost (USD/tCO_2) of a given mitigation technology (Y-axis) against the total mitigation potential (tCO_2) of that technology (X-axis). The annualised mitigation costs range from negative to positive. A negative cost indicates a net economic gain from deploying that technology, whereas a positive cost indicates that the entity will incur net additional expenses to mitigate its emissions. The sum of all values on the Y-axis indicates the total annualised cost per unit of emissions if all measures are implemented simultaneously to achieve net-zero emissions. The sum of all the X-axis values indicates the total CO_2 emissions from the industry. The area under each block provides the total cost – capital expenditures (CAPEX) and operational expenditure (OPEX) – to implement the mitigation option. MAC curves help industries identify and prioritise decarbonisation technologies, fuels, and pathways for achieving net-zero emissions. They also help the government develop policies for carbon pricing based on emission reduction targets.

Figure 1 **A typical MAC curve comparing various carbon abatement measures**



Source: Authors' illustration

In the subsequent sections of the report, we will discuss the major steelmaking routes followed by the Indian steel industry, establish baseline emissions, detail the potential impacts of various emission mitigation technologies and provide policy recommendations to allow concrete action for the step-wise decarbonisation of the existing capacity.

2. Steel production routes in India

Image: iStock

Primary steel production involves two major steps: conversion of iron ore to iron, followed by conversion of iron to steel. Although steel can be produced from steel scrap, two major routes are used globally for primary steel production, that is, the production of steel from iron ore. These are the blast furnace–basic oxygen furnace (BF-BOF) and the direct reduced iron–electric arc furnace/induction furnace (DRI-EAF/IF) routes. Larger plants typically use the BF-BOF and DRI-EAF pathways, whereas smaller plants use the coal-based DRI-IF pathway. Steel can also be produced through the blast furnace–electric arc furnace (BF-EAF) process as an alternative to the conventional BF-BOF route. In addition, the pig iron produced in the BF can also be utilised in the DRI-EAF or IF route (as a percentage of the total metallic charge that includes DRI and scrap in various proportions).

In India, iron is mainly produced by the following routes:

- **Blast furnace (BF) route:** Accounts for 66.4 per cent of the ironmaking capacity in India (JPC 2022a). It is used mainly in large integrated steel plants. In this process, the ore is reduced by carbon to remove oxygen, producing liquid hot metal as well as impurities in the form of slag. The BF route is entirely coal-based. It processes high-grade coking coal in a coke oven to produce the coke required by the furnace. Almost all BFs today substitute a small amount of coke with pulverised coal to decrease production costs, as pulverised coal injection (PCI) coal is cheaper than coking coal.
- **Direct reduction of iron (DRI) route:** In this route, the iron ore is exposed to a reducing atmosphere of carbon monoxide at high temperatures, resulting in oxygen being removed from the ore in the form of CO_2. Since the production of iron from its ore occurs without melting, it is called direct-reduced iron or sponge iron. The DRI route is employed by around 280 plants. Most of these are smaller units, with approximately 100 plants having a capacity between 100 and 200 tonnes per day (tpd). There are also approximately 20 large DRI plants with a capacity greater than 1,000 tpd. The DRI route accounts for 33.6 per cent of ironmaking capacity, approximately 79 per cent of which utilises coal while the remainder uses gas (JPC 2022a). Two gas-based plants use a blend of natural gas and coke oven gas. One gas-based plant uses coal gasification technology. For our analysis, we assume that the fuel used in all cases is natural gas, as the type of fuel and blend percentages were difficult to ascertain. Another gas-based plant uses plant off-gas as a reductant; we considered this plant a part of the BF capacity.

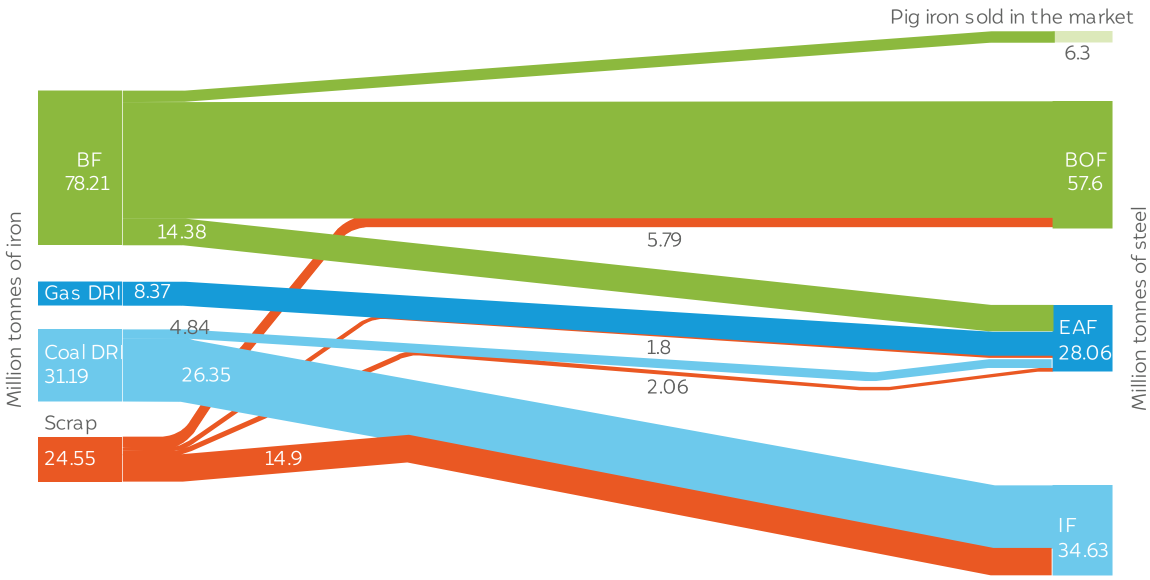
In India, there are three major pathways for producing steel from iron:

- **Basic oxygen furnace (BOF) route:** The BOF route primarily uses hot metal and scrap to produce steel. In this process, the hot metal from the blast furnace is charged into the basic oxygen furnace along with some additives. Highly pure oxygen gas is injected into this furnace from the bottom, which further oxidises the remaining carbon and other elements – such as silicon, manganese, phosphorus, and sulphur – to produce liquid steel with the desired carbon content. The liquid steel is typically cast into semi-finished steel products such as slabs, blooms, and billets via the continuous casting route or teemed into large ingots. In India, approximately 48 per cent of steelmaking capacity uses the BOF route (JPC 2022a).
- **Electric arc (EAF)/induction furnace (IF) route:** Electric furnaces are of two types: electric arc furnaces (EAF) and electric induction furnaces (EIF). These furnaces produce the heat required to melt, primarily, sponge iron and/or scrap steel, and any required additives, to produce crude steel. Some EAFs in India take a mix of hot metal, sponge iron, and scrap, as the charge, depending on the availability of scrap, the required composition of steel, and a few other process parameters. Typically, EAFs are employed by larger plants, while smaller plants and independent scrap steel processors use IFs. While IFs are available in smaller sizes and are more economical to install, there is little control over the resultant steel quality, as IFs cannot refine steel. Therefore, IF steel is typically of lower quality compared to EAF steel. EAFs and IFs account for 23 and 29 per cent of steelmaking capacity in India, respectively.

Various combinations of the above ironmaking and steelmaking routes exist for steel production in India. Figure 2 shows a Sankey diagram that links the flow of iron to the different steelmaking routes. The data for the Sankey diagram has been derived from the plant-wise capacities and segment-wise production numbers reported by the Joint Plant

Committee (JPC) of the Ministry of Steel (JPC 2022a; JPC 2022b). The values on the left indicate the amount of iron produced across various processes, while the numbers on the right show the total steel production across different pathways. Although the largest amount of iron is produced via the BF route, a significant portion – 14.4 million tonnes (Mt) – is used for producing steel via EAF. About 6.3 Mt is directly sold in the market as pig iron, and the rest – 57.6 Mt – is used for producing steel in BOF.

Figure 2 The BF-BOF route is the most extensively used path for steelmaking in India



Source: JPC (2022a); JPC (2022b); authors' analysis

Note: The conversion factors used are as follows: 1 tonne of crude steel (tcs) = 1.1 tonne of hot metal (tHM); 1 tcs = 1.25 tonne coal DRI; 1 tcs = 1.1 tonne gas DRI; 1 tcs = 1.1 tonne scrap.

All DRI produced in gas-based shaft furnaces is processed in the EAF for producing steel. At the national level, EAFs also use a small share – about 4.8 Mt – of DRI from coal-based rotary kilns, primarily in large steel plants. Figure 2 shows only an approximate share of scrap-based steelmaking across various production routes because the quantities of scrap used in primary steelmaking versus secondary steelmaking are not clearly established in the published literature. Based on industry inputs, we assume that the charge mix in the basic oxygen furnaces consists of 91 per cent hot metal and 9 per cent scrap. We estimate the scrap share in EAF based on the amount of iron produced in co-located rotary kilns, shaft furnaces, and blast furnaces, per the total EAF steel output reported by JPC. We also assume that the remaining 14.9 Mt of scrap is used for producing steel in IFs. Our assessment indicates that the national average charge mix for the IFs is about 61 per cent DRI and 39 per cent scrap. IFs have a greater average scrap share, as they process cheaper, locally collected scrap. Nonetheless, such complexities make national-level estimations of emissions, energy use, raw material use, and fuel consumption highly complicated and data-intensive.

The emission intensity of steel in India depends significantly on the production process, type of fuel, source of power and the share of scrap.

Image: Sabarish Elango/CEEW.

3. Average emission intensity of Indian steel

Before calculating the potential for abatement of CO_2 emissions, we establish a base case emission for the steel industry for 2021–22. Since India does not have any nationalised sector- and process-specific emissions reporting – such as the United States Environmental Protection Agency's Greenhouse Gas Reporting Programme (US EPA n.d.) – we used publicly accessible data pertaining to the Indian steel industry from their sustainability reports and inputs from industry experts. We collected data at various levels of aggregation – plant, state, and country – and made some overarching assumptions where no local data was available. The data included the consumption, prices, and quality of raw materials and fuel. The production capacity and output of steel plants, location, any pre-existing mitigation measures, etc., were input into the model.

The study is based on data collected at plant, state, and country level

We made overarching assumptions regarding the emission factors for fuel combustion, captive power plant (CPP) efficiency, electricity consumption, production process parameters, etc. This data was directly obtained from the literature or sustainability reports of steel companies. Information on the plant-level capacities, process routes, production, and scrap shares was either taken or derived from JPC data (JPC 2022a; JPC 2022b).

Figure 3 depicts the energy and raw materials used as inputs for each steelmaking route. Here, we consider that, on average, BFs in India use 420 kg of coke and 130 kg of PCI per tHM output. The sintering process for iron ore consumes 1.63 GJ of thermal energy per tonne of sinter, while the coke-making process consumes 3.20 GJ of thermal energy per tonne of coke. We assumed the blast furnace charge consisted of 60 per cent lump ore and 40 per cent sinter. Based on feedback from industry representatives, we assumed that the charge mix of the BOF unit consisted of 91 per cent hot metal and 9 per cent scrap. The total power consumption was about 384 kWh/tcs (Jin et al. 2017). A detailed breakdown of power consumption is indicated in Figure 3(a). Based on industry inputs and the considered penetration levels of energy-efficient technologies, we assumed that waste heat recovery (WHR) contributes 25 per cent of the electricity required while the remaining is obtained from captive thermal power plants.

For the coal DRI-IF route, the entire thermal energy required for DRI production is obtained from coal. In this study, we consider that coal DRI plants use 1.57 tonnes of iron ore lumps or 1.38 tonnes of iron ore pellets per tonne of DRI produced (Nduagu et al. 2022). We also assumed a 100 per cent pellet use for DRI plants that have captive pellet-making units and a 100 per cent lump-ore consumption for those that do not, bringing the average ore consumption to 1.53 t/tDRI (77 per cent lumps and 23 per cent pellets). We assumed a typical coal consumption of 1.30 t/tDRI – 5 per cent lower if ore pellets are used – based on industry reports. Expert inputs suggest an equal share of imported and domestic coal, with the former coming mainly from South Africa, Indonesia, and Australia. We assumed that DRI plants with a capacity greater than 300 tpd have installed waste heat recovery boilers (WHRBs) to generate power from kiln off-gases. In line with industry inputs, we supposed a net power output of about 300 kWh/tDRI.

The inputs to the IF consist of 61 per cent of DRI and 39 per cent of steel scrap. The total average electricity consumption in this pathway is considerably higher than the BF-BOF route at 906 kWh/tcs, of which 806 kWh is consumed in the IF, 85 kWh in the DRI plant, and the remaining 16 kWh in the iron ore pellet plant. We assumed that DRI plants and integrated steel plants use captive power while standalone IF plants use grid power. On average, 56 per cent of the total electricity is sourced from the grid, 20 per cent through WHR, and the remaining 24 per cent through CPP. This is depicted in Figure 3(b).

The coal DRI-EAF route (Figure 3d) uses 1.27 t coal/tDRI the lower coal consumption is due to the larger share of ore pellet use. The mix of material input to the EAF is 62 per cent hot metal, 26 per cent DRI, and 13 per cent scrap, as there are some large integrated steel plants with co-located blast furnaces and DRI kilns. The overall electricity consumption in this route is much lower compared to the coal DRI-IF route at 418 kWh/tcs, of which 380 kWh is consumed by the EAF, 25.9 kWh for DRI production, and 11.6 kWh by the pellet plant. The lower electricity consumption in EAF units is due to the use of hot metal that significantly reduces the power required for melting the iron.

In the gas DRI-EAF route, shown in Figure 3(c), the reductant used is reformed natural gas. This process consumes 280 standard cubic metres (scm) of natural gas and 1.38 tonnes of iron ore pellets – 100 per cent share of pellets – per tonne of DRI. Based on the scrap balance over the entire steel sector, we estimate that the inputs to the EAFs in gas DRI plants consist of 29 per cent hot metal, 58 per cent DRI, and 13 per cent scrap. This route consumes 528 kWh/tcs of electricity, of which 392 kWh are consumed by the EAF, 76 kWh for DRI production, and 60 kWh by the pellet plant. Unlike other steelmaking routes, we assumed the electricity was entirely sourced from the CPP. The gas-based DRI plants directly introduce hot DRI in the EAF, thereby reducing the power consumption by 250 kWh/tcs compared to the coal DRI-IF process. In the latter, hot DRI charging is not possible as the DRI must undergo magnetic separation from the char and dust exiting the kiln together.

The mix of material input to the EAF is 62% hot metal, 26% DRI, and 13% scrap, as there are some large integrated steel plants with co-located blast furnaces and DRI kilns

Figure 3 Coal plays a significant role in the Indian steel industry

(b) Inputs for BF-BOF steelmaking

BF inputs

Iron ore
1.51 t/tHM
(60% lump, 40% sinter)
1.63 GJ/t sinter produced
56.01 kWh/t sinter produced

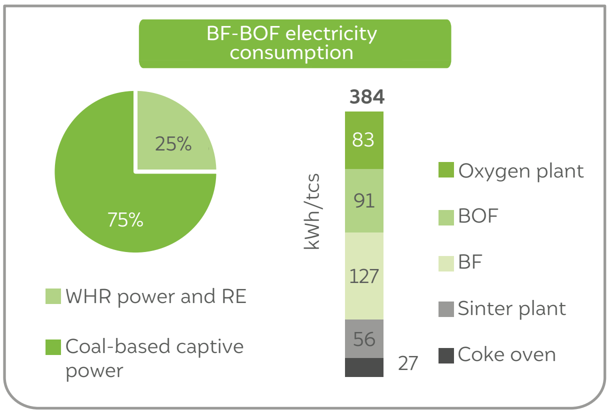
Coke
420 kg/tHM
3.20 GJ/t coke produced

Pulverised coal
130 kg/tHM

BOF inputs

Hot metal (from BF)
1.00 t/tcs
91% constituent of crude steel

Steel scrap
0.10 t/tcs
9% constituent of crude steel



(b) Inputs for coal DRI-IF steelmaking

Coal DRI inputs

Iron ore
1.53 t/tDRI
(77% lump, 23% pellet)
65 kWh/t pellet produced

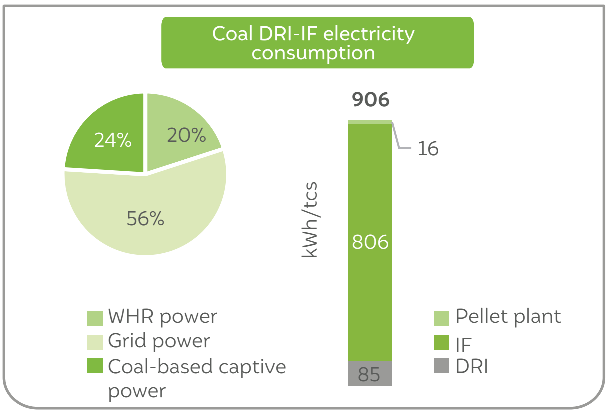
Feed end coal
770 kg/tDRI
(50% domestic, 50% imported)

Injection-end coal
515 kg/tDRI
(50% domestic, 50% imported)

IF inputs

DRI
0.76 t/tcs
61% constituent of crude steel

Steel scrap
0.43 t/tcs
39% constituent of crude steel



(c) Inputs for gas DRI-EAF steelmaking

Gas DRI inputs

Iron ore
1.38 t/tDRI
(100% pellet)
65 kWh/t pellet produced

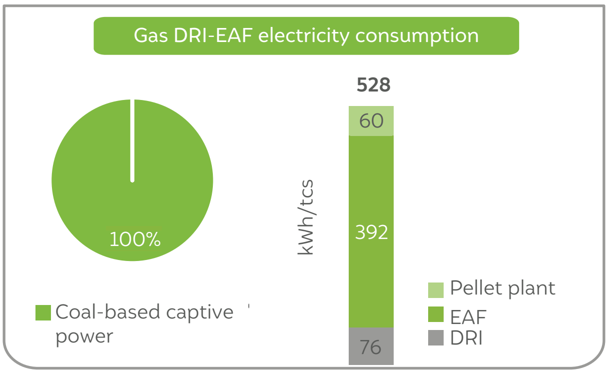
Natural gas
280 scm/tDRI
(100% imported)

EAF inputs

DRI
0.64 t/tcs
58% constituent of crude steel

Hot metal (from BF)
0.32 t/tcs
29% constituent of crude steel

Steel scrap
0.14 t/tcs
13% constituent of crude steel



(d) Inputs for coal DRI-EAF steelmaking

Coal DRI inputs

Iron ore
1.48 t/tDRI
(53% lump, 47% pellet)
65 kWh/t sinter produced

Feed-end coal
760 kg/tDRI
(50% domestic, 50% imported)

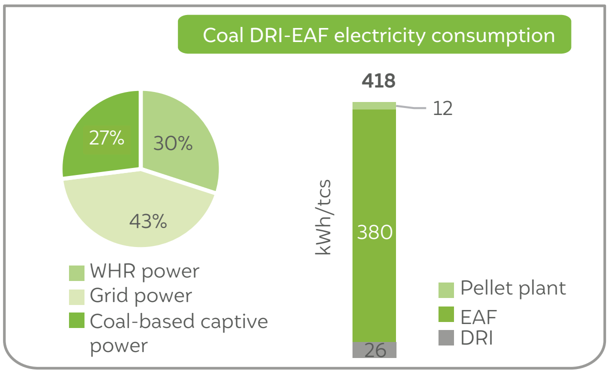
Injection-end coal
510 kg/tDRI
(50% domestic, 50% imported)

EAF inputs

DRI
0.33 t/tcs
26% constituent of crude steel

Hot metal (from BF)
0.69 t/tcs
62% constituent of crude steel

Steel scrap
0.14 t/tcs
13% constituent of crude steel



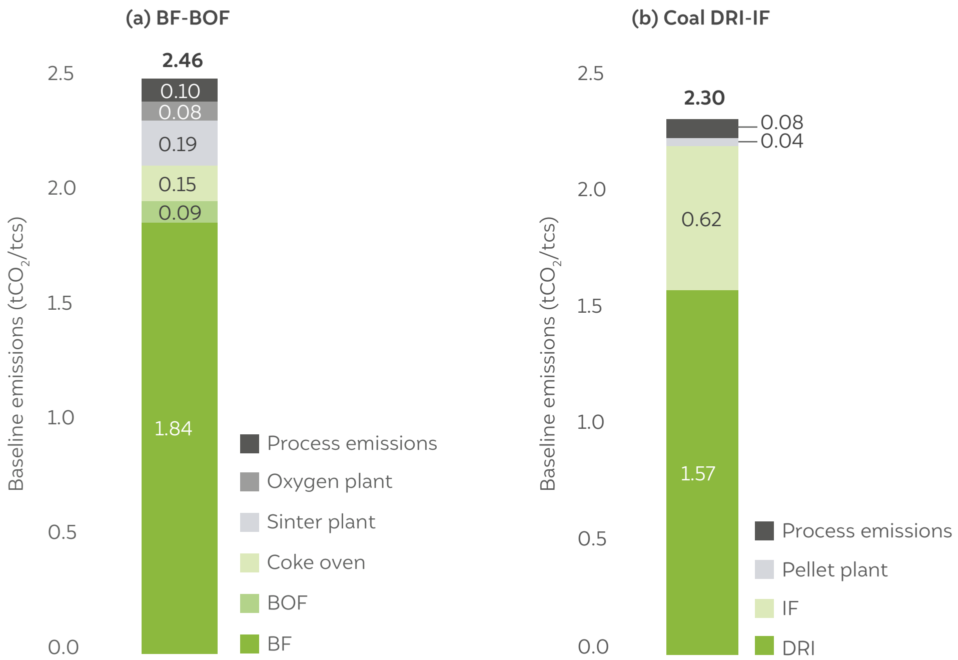
Source: Authors' analysis

Figure 4 shows the emission intensities across various steel production pathways. For a given plant, we calculated the emission intensities by considering the emissions from the iron produced in that plant and the embedded emissions of iron coming from other plants to meet the requirement of steel production.

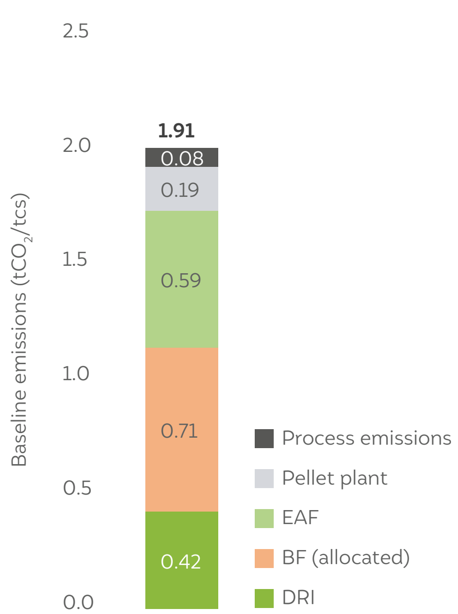
Our assessment indicates that the BF-BOF route has an average emission intensity of approximately 2.46 tCO_2/tcs, with most emissions arising from the BF. The coal DRI-IF route has an average emission intensity of about 2.30 tCO_2/tcs. However, this is the average for all steel produced through this route, including independent IF units that primarily recycle scrap. The DRI-IF process is the most energy- and emission-intensive; for integrated DRI-IF plants, the intensity can be as high as 3.02 tCO_2/tcs.

The coal DRI-EAF route reports a higher average emission intensity of 2.51 tCO_2/tcs because it includes the emissions from the BF process that provides the hot metal. The gas-based DRI-EAF plants have the lowest emission intensity of primary steelmaking, at 1.91 tCO_2/tcs. This figure accounts for emissions from the 29 per cent share of hot metal in the EAF and, thus, is higher than the 1.40–1.60 tCO_2/tcs from purely gas-based DRI-EAF plants that do not use hot metal (Nduagu et al. 2022).

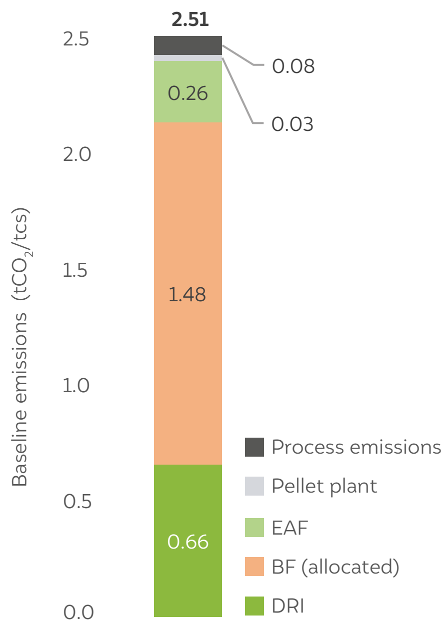
Figure 4 **The gas DRI-EAF route is the least emission-intensive**



(c) Gas DRI-EAF



(d) Coal DRI-EAF



Source: Authors' analysis

Note: The emission intensity includes a scrap share of 9 per cent for BF-BOF, 39 per cent for coal DRI-IF, and 13 per cent for coal DRI-EAF and gas DRI-EAF.

From our assessment, we estimated the total emissions from the Indian steel industry to be 297 million tonnes of CO_2 ($MtCO_2$) in 2021–22. Table 1 provides the break-up of emissions by production pathway. The coal BF-BOF route produced the most emissions, as it has the largest share of steelmaking. The coal DRI-IF route has a lower emission intensity due to the high scrap share considered in our assessment; it has the second-highest total emissions due to the large quantity of steel thus produced. In comparison, the coal DRI-EAF and gas DRI-EAF routes have lower total emissions due to a relatively small share in overall production. Our assessment indicates that the overall average emission intensity of steel in India is around 2.36 tCO_2/tcs.

Table 1 Base case emissions from the Indian steel industry totalled 297 $MtCO_2$ in 2021–22

Pathway	Production in 2021–22 (Mtcs)	Production share (%)	Total emissions ($MtCO_2$)	Emission intensity (tCO_2/tcs)	Hot metal share (%)	DRI share (%)	Scrap share (%)
BF-BOF	57.6	48	185.82	2.46	91	0	9
Coal DRI-IF	34.6	29	79.71	2.30	0	61	39
Coal DRI-EAF	15.0	12	15.46	2.51	61	26	13
Gas DRI-EAF	13.1	11	15.72	1.91	29	58	13
Total	**120.3**	**100**	**296.72**	**2.36**			

Source: JPC (2022a); JPC (2022b); authors' analysis

*Includes emissions from pig iron sold directly.

Note 1: Figures may not tally due to rounding.

Note 2: The emission intensity of a given route was calculated by considering both the iron produced by plants employing that route as well as the allocated emissions of iron from other plants.

Note 3: The emission intensity of coal DRI-IF is lower than BF-BOF and coal DRI-EAF because we have considered integrated plants, which consume only about 15 per cent scrap, and standalone IF plants, which can consume as much as 80 per cent scrap, under the same overall route. With 15 per cent scrap, the emission intensity of integrated DRI-IF plants can be higher than 3 tCO_2/tcs.

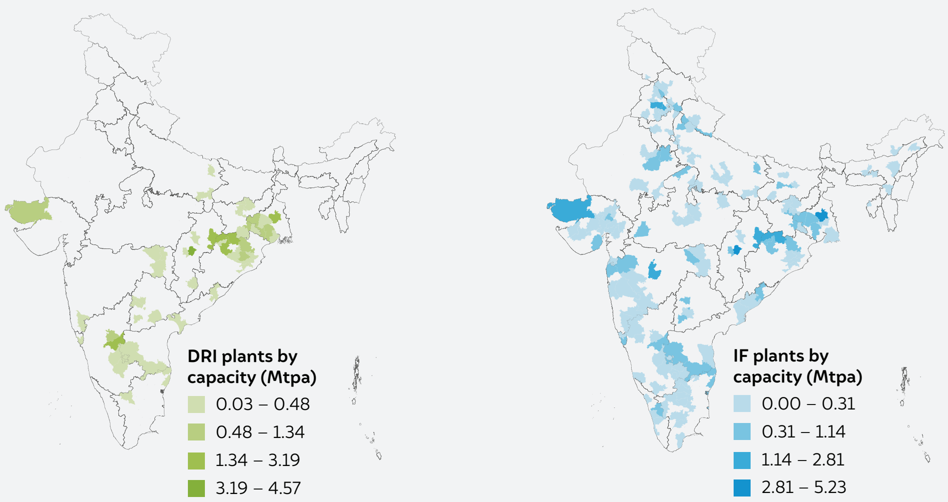
Box 1 Effect of scrap share on the emission intensity of coal DRI-IF steel

Induction furnaces in India are either co-located with DRI plants or run as standalone operations. The standalone IF plants typically purchase DRI and scrap from the open market to produce steel. The DRI plants are mainly located in the southern and eastern parts of the country. In contrast, IF plants are spread across the country (see Figure 5(a)). According to industry representatives, the steel may have been produced with a higher share of DRI or scrap, depending on their location. Thus, standalone IF plants may either be primarily DRI-based or scrap-based. The IFs located in southern and eastern India, near DRI plants, use 10–15 per cent scrap, and the remaining share is DRI. However, the IFs in areas that do not have DRI plants could be using up to 80–90 per cent scrap, whereas the DRI share is only 10–20 per cent. Our assessment indicates that 44 per cent of IF capacity is in districts that do not produce any DRI. It is expected that these IFs primarily use scrap for producing steel. Consequently, the average scrap use in IFs is 39 per cent.

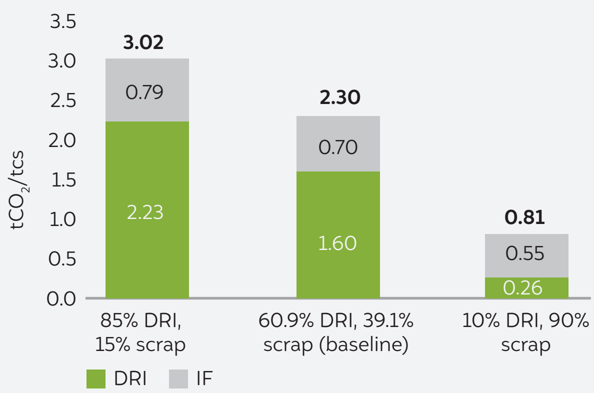
The emission from the steel produced is directly linked to the share of scrap in it, as shown in Figure 5(b). Since scrap recycling minimises the emissions from ironmaking, the resultant emission intensity of steel can vary significantly based on the scrap share. The DRI-based IF units consume about 85 per cent DRI and 15 per cent scrap. However, scrap-based IF units are currently consuming more than 90 per cent scrap. Nonetheless, due to a lack of clear information, we did not classify them as such; instead, we supposed all IF plants to follow the coal-based DRI-IF route. Therefore, the overall scrap share for this route at the country level is high (39 per cent).

Figure 5 The share of scrap significantly affects the emission intensity of steel

a. DRI and IF plants in the country



b. Scrap-based steelmaking is the least emission-intensive pathway



Source: Authors' analysis

4. Methodology

Image: iStock

The various technology options we considered for the MAC curves can be broadly divided into four categories:

- **Energy efficiency:** involves reducing the energy consumption per unit output in existing equipment or generating thermal or electrical energy through WHR.
- **Renewable power:** uses renewable energy (RE) sources to meet the electrical power requirement while offsetting the captive and grid power consumption in steel plants.
- **Fuel switching:** involves switching from incumbent fuels – such as coal and natural gas – to those with lower carbon intensities such as biomass and green hydrogen.
- **Carbon management:** involves managing remaining emissions by carbon capture, utilisation, and storage (CCUS) and carbon offsets through afforestation.

Figure 6 shows the various emission abatement options under these four categories. We referred to reports published by the US Environment Protection Agency and ASEAN for the data used for the EE category (JISF n.d.; US EPA 2012). Multiple industry representatives opined that the efficiency gains mentioned in these publications have not yet been achieved in Indian steel plants. Following the industry inputs, we assumed that energy-efficient technologies have an 85 per cent real-world efficacy against the claims made by the original equipment manufacturers (OEMs). In our assessment, we studied 14 energy efficiency technologies for BF-BOF, 5 for coal DRI, 10 for EAF, and 1 for IF.

For renewable power, we assumed that the power required post-adoption of all EE measures is sourced completely from renewable power plants. We calculated the tariffs of such a system based on a reference tariff for a grid-scale, wind-solar-battery hybrid power plant (ReNew 2021) and the open-access charges levied by different state distribution companies for wheeling power (CEEW Centre for Energy Finance 2023). We also considered the potential replacement of incumbent fuels with cleaner alternatives.

Any remaining emissions after EE measures, renewable power, and fuel switching were addressed under the emission management category, which examines the role of CCUS. Based on Mukherjee and Chatterjee (2022), Srinivasan et al. (2021), and IEA (2022), we calculated the mitigation costs of two forms of carbon management: carbon capture and storage and carbon capture and utilisation. Since existing capture technologies have a limited capture efficiency of about 85 per cent (IEA 2022), we treated the remaining emissions as residuals that must be abated through offset mechanisms such as afforestation.

Figure 6 **Carbon abatement options for steelmaking**

(a) Oxygen steelmaking

14 Energy efficiency technologies	• Sinter cooler heat recovery • Increasing sintering burner efficiency • Coal moisture control (CMC) • Coke dry quenching (CDQ) • Increasing PCI rate • Coke oven gas (COG) use in DRI production	• Top-pressure recovery turbine (TRT) • Hot stove: Sensible heat recovery • BOF gas: Sensible heat recovery • Preventive maintenance • Energy monitoring system • Variable speed drives • Cogeneration • Slag heat recovery
1 Renewable power	• Coal-based CPP to RE	
3 Alternative fuels	• Biomass injection in BF • Natural gas injection in BF • Green H_2 injection in BF	
3 Carbon management technologies	• CCS • CCU • Carbon offsets (afforestation)	

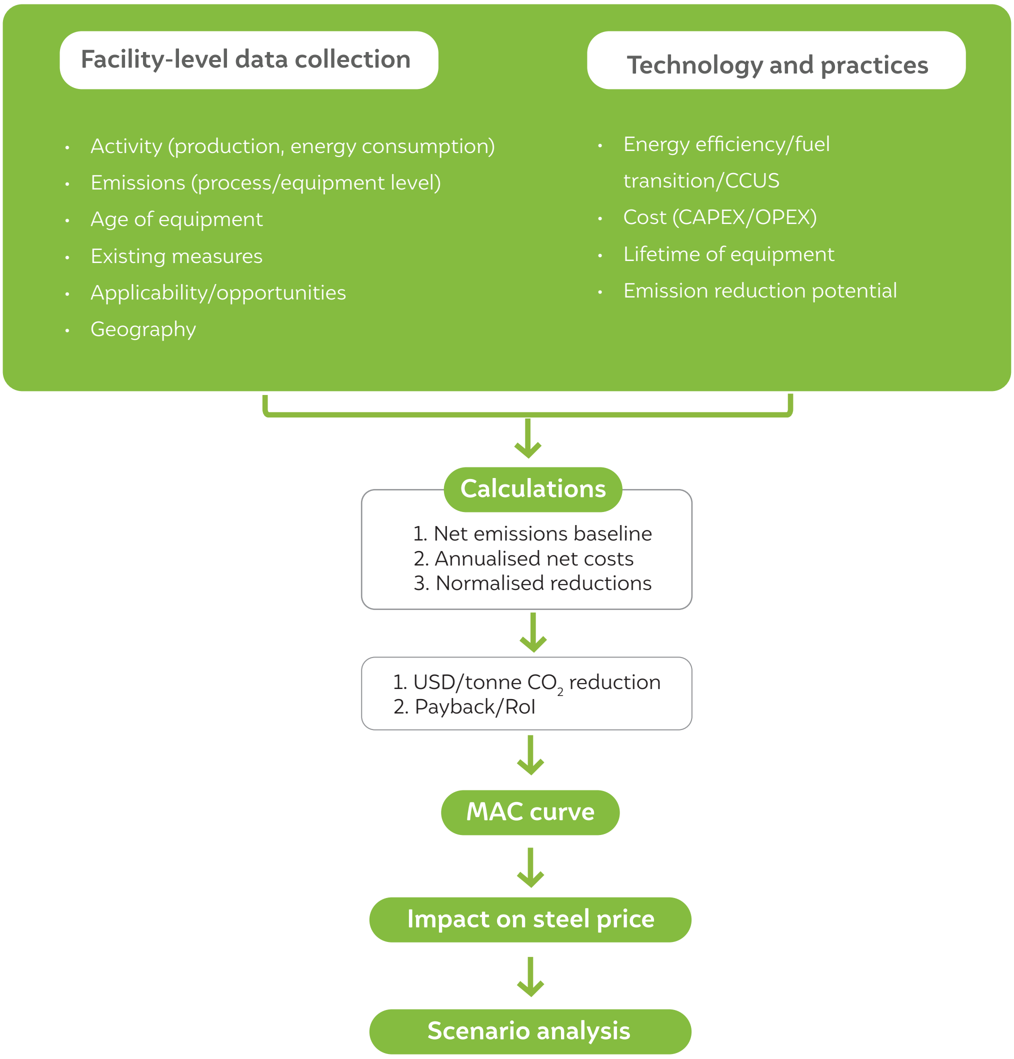
(b) Electric steelmaking

15 Energy efficiency technologies	• Efficient blowers for kilns • VVFDs for shell air fans • Mullite-based kiln lining • Kiln flue gas WHR power • DRI char WHR power • EAF gas WHR power • EAF charge preheating • Bottom stirring/stirring gas injection in EAF • Eccentric tapping of EAF • Oxyfuel burner/lancing in EAF • Optimised slag foaming in EAF • Optimised EAF power control • Higher-power EAF transformer • Scrap pretreatment system for EAF/IF • Efficient dedusting system for EAF
1 Renewable power	• Coal-based CPP/grid to RE
2 Alternative fuels/raw materials	• Higher-quality imported coal use in DRI kilns • Green H_2 injection in DRI shaft furnaces
3 Carbon management technologies	• CCS • CCU • Carbon offsets (afforestation)

Source: Authors' compilation based on JISF (n.d.) and US EPA (2012).

The evaluation of the abatement cost for each of the mitigation options involves three steps. First, facility-level data is collected. Second, the collected data is used to estimate the average MAC. Finally, the MACs of the mitigation technology are plotted against the emission-reduced if the technologies were adopted and, subsequently, scenario analysis is conducted. This process is schematically represented in Figure 7. To evaluate the MAC, we considered a discounted payback for the required CAPEX over the lifetime of the equipment. Based on industry feedback, we assumed the annual OPEX for the equipment to be a percentage of the CAPEX, or a function of the net fuel, or electricity consumed to operate the equipment.

Figure 7 Schematic representation of our methodology



Source: Authors' compilation

The technology options, their MACs, and their abatement potentials are discussed in the respective subsections in this chapter. We have grouped the steel production routes into two categories for clarity: BF-BOF and DRI-EAF/IF. The latter includes coal and natural gas-based processes. It should be noted that while some amount of pig iron from BFs is consumed in the DRI-EAF/IF route, we have included reductions for the BF portion in the BF-BOF MAC curves and the DRI portion in the DRI-EAF/IF curves. Therefore, emission intensity from the MAC curves will not match the intensities provided in Table 1, as some of the iron flows across different pathways.

4.1 Energy efficiency

Energy efficiency – a low-hanging fruit in the current emissions scenario – allows the reduction of emission intensity of a product without any major changes to the process or its inputs. Figure 8 shows the average reduction in specific energy consumption across various production pathways for India based on information from The Japan Iron and Steel

Federation (n.d.) and the US EPA (2012). The penetration levels of these energy-efficient technologies are based on the information available in the literature (IEA 2020; JISF n.d.) and anecdotal inputs provided by the industry.

Figure 8(a) represents the reduction in electrical energy requirement achieved by deploying energy-efficient measures for the BF-BOF pathway. A significant amount of power can be generated by adopting technologies such as coke dry quenching (CDQ) (51.7 kWh/tcs), top-pressure recovery turbine (TRT) (37.8 kWh/tcs), slag heat recovery (13 kWh/tcs), and cogeneration (13 kWh/tcs). The power generation estimates are based on a WHR system efficiency of 26.5 per cent, for a heat rate of 3,200 kcal/kWh.

Slag heat recovery has not yet been adopted in the Indian steel industry. Therefore, this estimation is based on data obtained from literature and industry stakeholders. The total power generation potential of cogeneration from off-gases is 97.0 kWh/tcs (Morrow III et al. 2014). However, industry data suggests that these off-gases are used for multiple other applications in steel plants. For instance, we estimated that about 46 per cent of coke oven gases are directed towards other applications – such as sintering and reheating furnaces (hot stoves) – to meet the thermal energy demand. Therefore, we assumed that only 75.5 kWh/tcs could be obtained from the cogeneration system. In the current analysis, we propose using coke oven gas (COG) for DRI production and as a BF fuel to reduce coal consumption instead of power generation. After excluding the COG usage, the power generation potential reduces to 13 kWh/tcs. The power consumption in the BF-BOF process can be reduced further by 19.6 kWh/tcs by adopting various energy-efficient measures such as variable speed drives, energy monitoring systems, and preventive maintenance. In total, we estimate that 135 kWh/tcs could be generated through various EE options.

Energy efficiency measures reduce the emission intensity of steel without substantial process changes

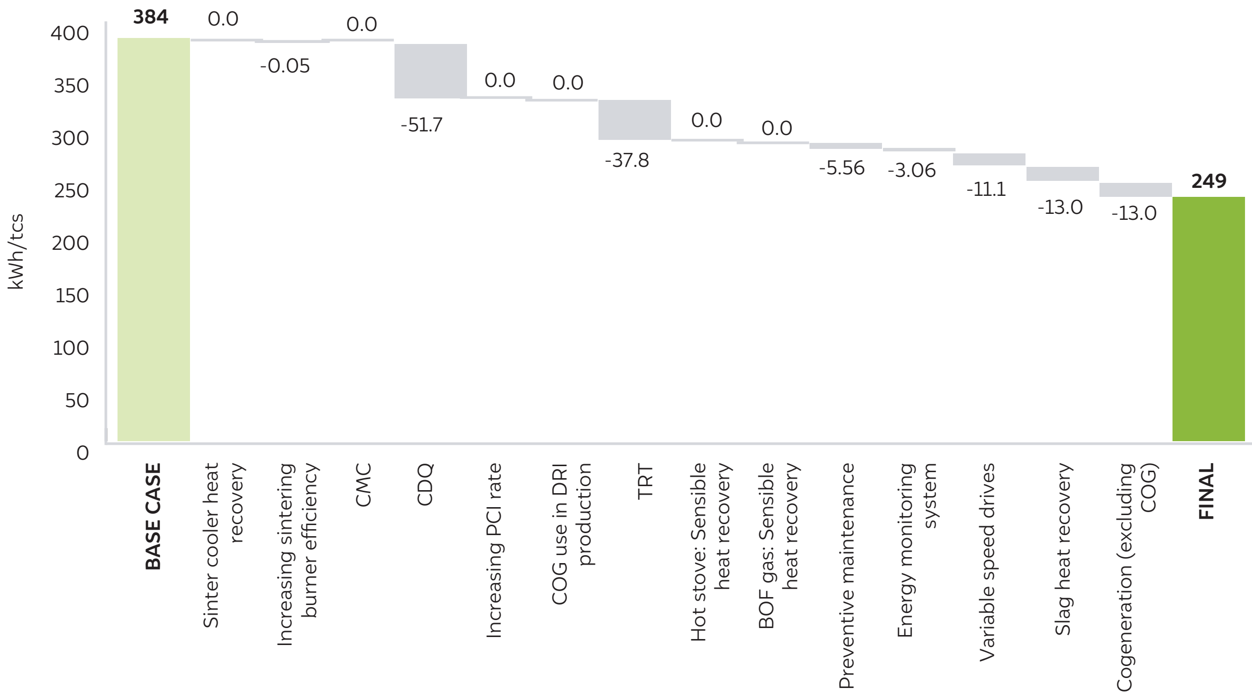
Figures 8(b) and (c) show the electricity reduction potential for the coal DRI-IF and coal DRI-EAF routes, respectively. For the coal DRI-IF route, the reduction in electricity consumption is not significant—a reduction from 906 kWh/tcs to 830 kWh/tcs is realistically possible. This reduction can mainly be attributed to measures such as WHR from rotary kiln off-gases and the usage of variable voltage and frequency drives (VVFD) in shell fans and scrap preheating.

In contrast to the coal DRI-IF process, a significant reduction in power consumption can be achieved in the coal DRI-EAF route. Figure 8(c) shows that the power consumption can be reduced from 418 kWh/tcs to 279 kWh/tcs for an EAF unit utilising 62 per cent hot metal. It should be noted that the power consumed for hot metal production is not a factor in this analysis. Measures such as EAF charge preheating (37.7 kWh/tcs), EAF WHR power generation (using an organic Rankine cycle) (20.2 kWh/tcs), EAF oxyfuel burner (12.5 kWh/tcs), etc., contribute significantly to the total reduction in power consumption.

Through EE, the gas DRI-EAF process can achieve a reduction of 35.2 kWh/tcs, while the coal DRI-EAF process can reduce up to 130.5 kWh/tcs. This difference can be explained by the fact that there are no specific energy efficiency measures for the gas DRI process. In contrast, the coal DRI process can benefit from technologies such as char waste heat recovery. In Figures 8(c) and (d), the differences in savings potential between coal DRI-EAF and gas DRI-EAF for the same technologies occur because of differences in the charge mix and existing penetration levels of the technologies. Specifically, for EAF charge preheating, there are greater savings in coal DRI-EAF plants, as both DRI and scrap are assumed to go through the preheating stage. In gas DRI-EAF, the DRI is already hot; only the scrap is preheated.

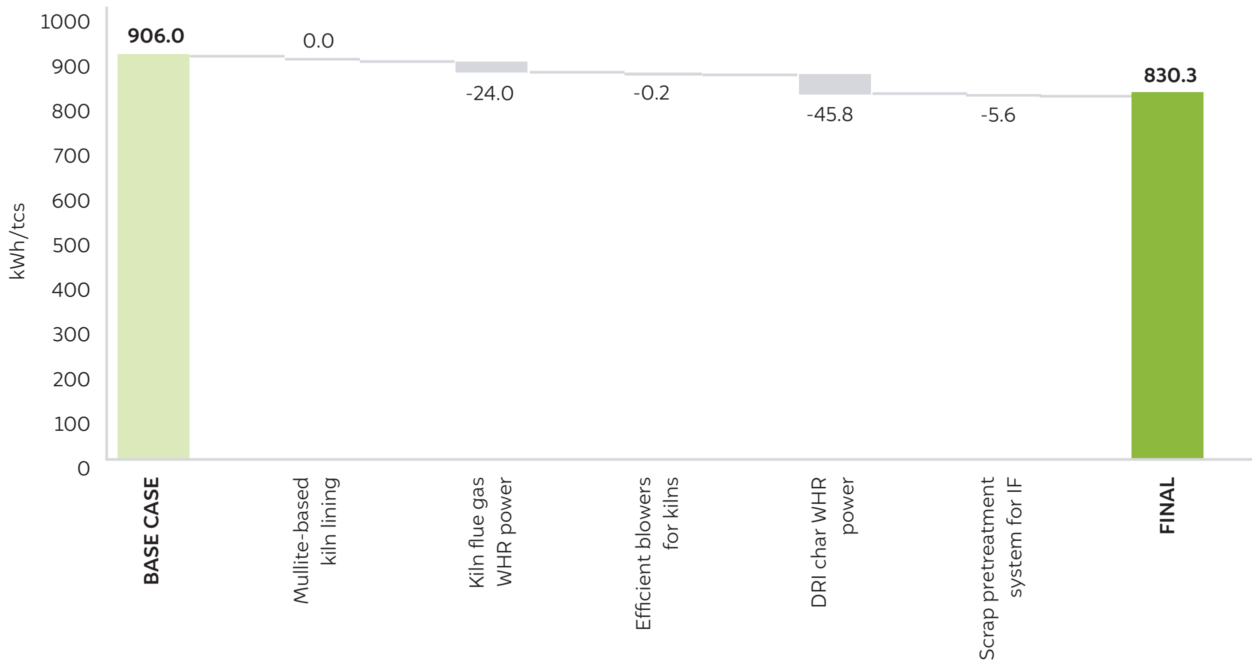
Figure 8 The energy efficiency of Indian steel plants has considerable room for improvement

(a) Electricity reduction potential in BF-BOF



Charge mix:
Hot metal: 91%, DRI: 0%, Scrap: 9%

(b) Electricity reduction potential for coal DRI-IF

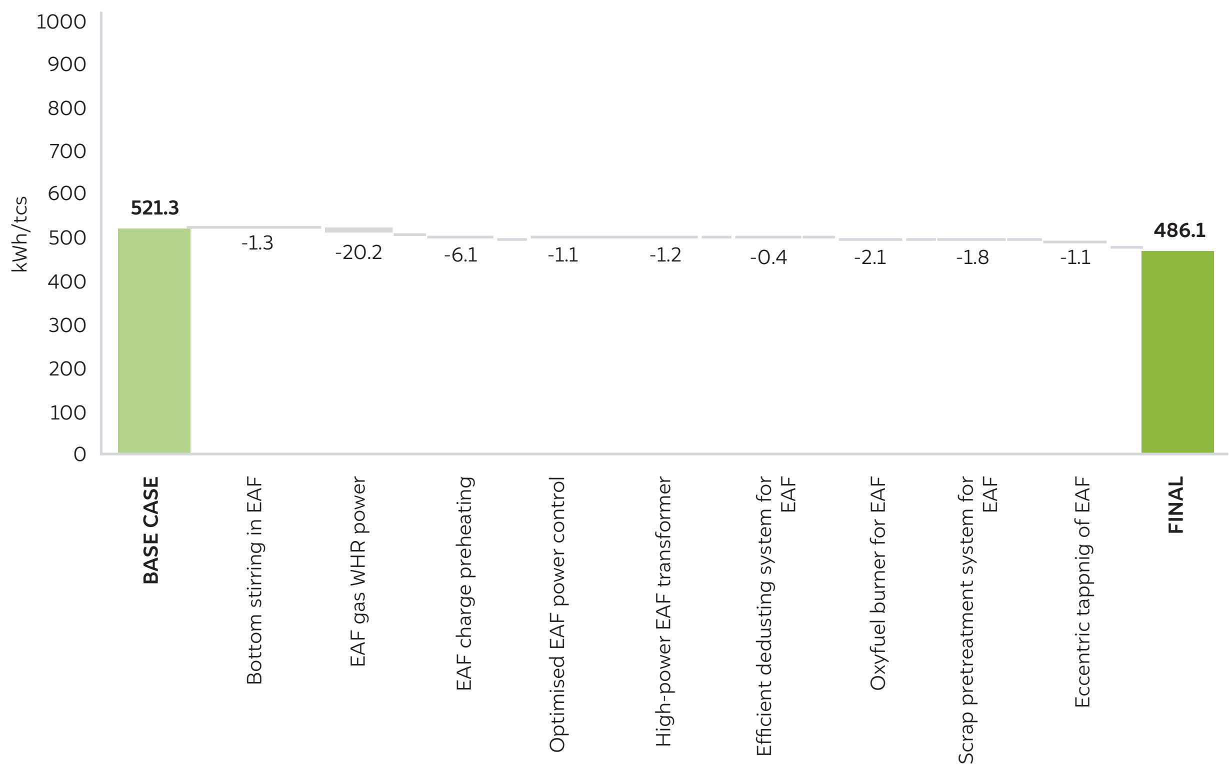


Charge mix:
Hot metal: 0%, DRI: 61%, Scrap: 39%

(c) Electricity reduction potential for coal DRI-EAF

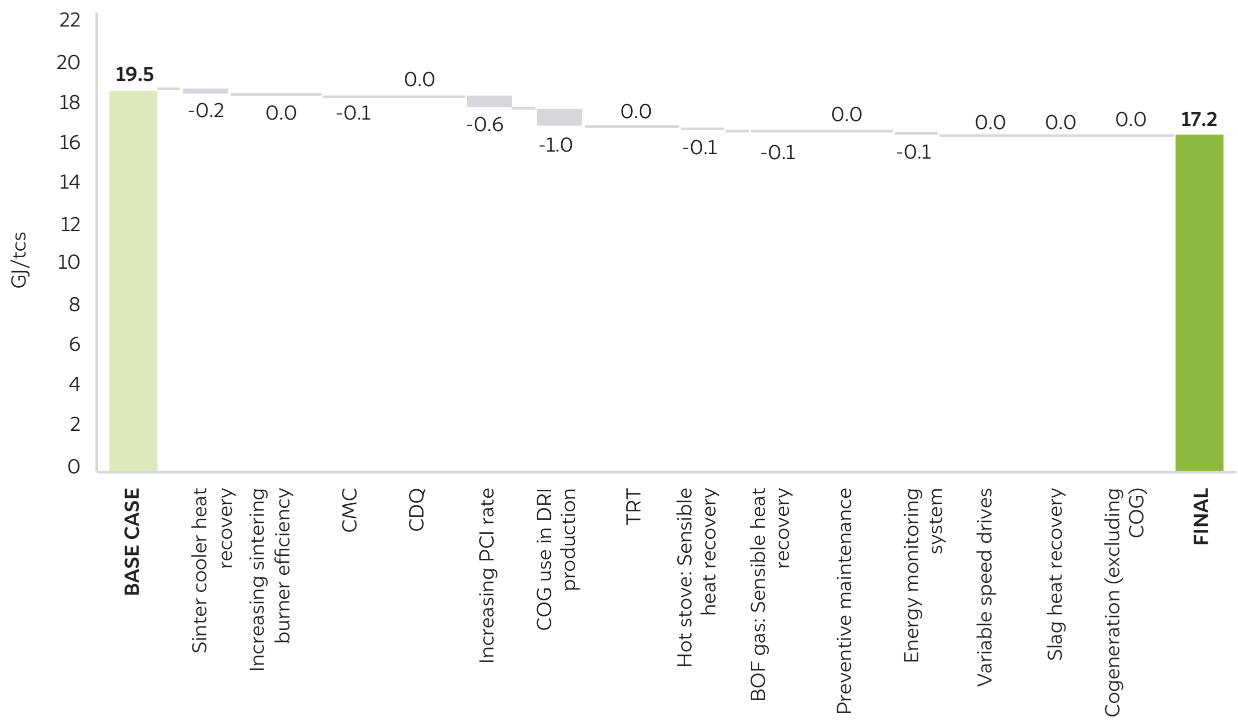
Electricity consumption for hot metal production not accounted for.
Charge mix:
Hot metal: 61%; DRI: 26%; Scrap: 13%

(d) Electricity reduction potential for gas DRI-EAF



Electricity consumption for hot metal production not accounted for.
Charge mix:
Hot metal: 29%; DRI: 58%; Scrap: 13%

(e) Thermal energy reduction potential for BF-BOF*



Charge mix:
Hot metal: 91%, DRI: 0%, Scrap: 9%

Source: Authors' analysis based on JISF (n.d.) and US EPA (2012)

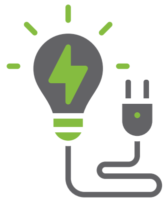
*Note: Thermal energy reduction potential for other routes are minimal as the mitigation measures mainly focus on electrical efficiency

Figure 8(d) represents the reduction in electricity consumption due to EE measures for the gas DRI-EAF route. Our analysis shows that power consumption can be reduced from a peak of 521 kWh/tcs to 486 kWh/tcs. The reduction in this pathway is limited, as the gas DRI process is already quite efficient. However, measures such as EAF WHR (20.2 kWh/tcs) and charge preheating (6.1 kWh/tcs) contribute significantly to the reduction. Similar to the coal DRI-EAF route, these estimations are limited to the use of EE in the EAF unit and exclude any power consumed during the production of hot metal.

Figure 8(e) represents the reduction in thermal energy consumption due to the deployment of EE measures in the BF-BOF route. It shows that the thermal energy consumption can be reduced from 19.5 GJ/tcs to 17.2 GJ/tcs – a 11.8 per cent decrease. Measures such as the recovery of BOF gas and sensible heat, preventive maintenance, and sinter cooler heat recovery are the major contributors to this reduction. Measures such as CDQ, TRT, and slag heat recovery do not play any role in reducing thermal energy consumption, as they primarily generate electricity (Figure 8(a)). We have not shown similar figures for the other routes, as the reductions are predominantly through electrical efficiency measures and not thermal efficiency ones.

4.2 Renewable power

Steel production requires a significant amount of electricity. As shown in Figure 8a, the BF-BOF process consumes about 249 kWh/tcs after all EE measures are in place. The DRI-EAF and DRI-IF processes consume about 279 kWh/tcs and 830 kWh/tcs, respectively, due to the higher electricity requirement in the EAF/IF versus the BOF process. A significant share of this electricity requirement is met by the CPP within the premises of the integrated steel plant, typically using a coal-based thermal power plant. The remainder is sourced from the grid or WHR units. This power requirement can be met using RE as well.

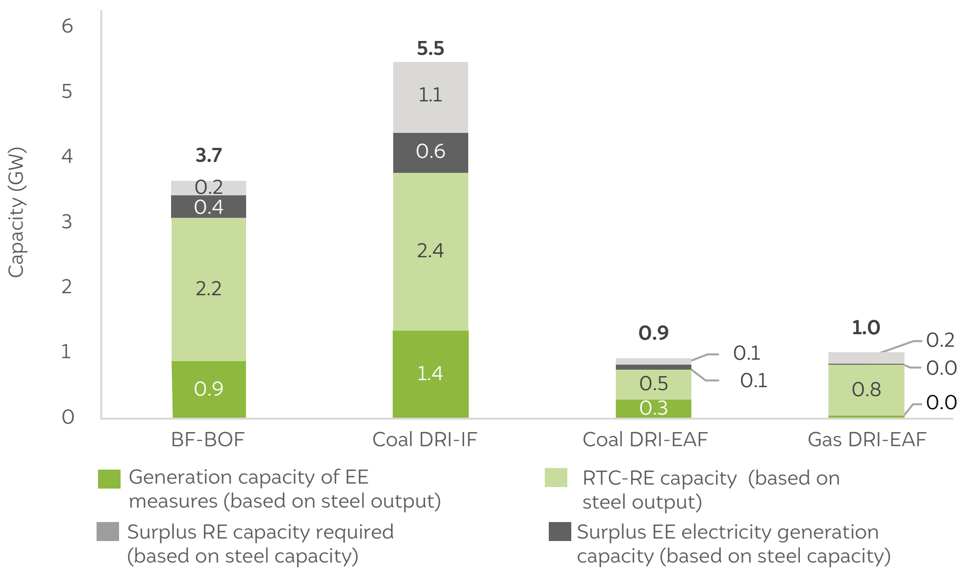


The Indian steel industry needs 5.9 GW of RTC RE to meet the power requirement for crude steel production

Figure 9 shows the round-the-clock (RTC) power requirement across the various production pathways. Our research indicates that considering the actual production volumes, the steel industry needs about 8.3 GW of RTC power to meet its power requirement for crude steel production, in the absence of energy-efficient measures. If finished steel production is also considered, then the total power requirement increases to 9.7 GW. These requirements are based on the actual steel production. If the requirement is calculated based on the production capacity of steel, the total RTC power requirement will be 13.2 GW.

The share of the required RE capacity across the different steelmaking routes is represented as the green region in Figure 9. The RTC power requirement across various production routes is presented in the figure as well. Within each route, the power generation is indicated across three categories. First, as evident from Figure 8, some energy efficiency technologies produce power (indicated in grey) and, consequently, reduce the overall RE requirement, especially in the BF-BOF route. Similarly, WHR in the coal DRI process will significantly reduce the overall RE requirement. Secondly, RTC RE is needed to bridge the gap between the total electricity needed and the electricity generated by EE technologies. Our research indicates that even after accounting for the power generated through energy efficiency measures, the steel industry will need an extra 5.9 GW of RTC RE for crude steel production across all pathways. If the power requirement is calculated according to the production capacity, then the total RTC RE requirement will be 7.5 GW.

Figure 9 RE power will play a significant role in the decarbonisation of the steel industry



Source: Authors' analysis

Note: Portions in green indicate the power capacity corresponding to the actual steel production in 2021–22, whereas portions in grey indicate the capacity corresponding to the total steel capacity in India.

Steel plants may not have sufficient land resources to install renewable power plants to meet their power demand. Therefore, these plants will depend on open access mechanisms to meet their power demand and, consequently, reduce their emissions footprint. However, transmitting GW-scale, RTC, clean electricity from an RE power plant to a steel plant requires using state-owned grid infrastructure, which will entail significant wheeling costs.

The high cost of open access mechanisms may affect the uptake of RE in the steel industry

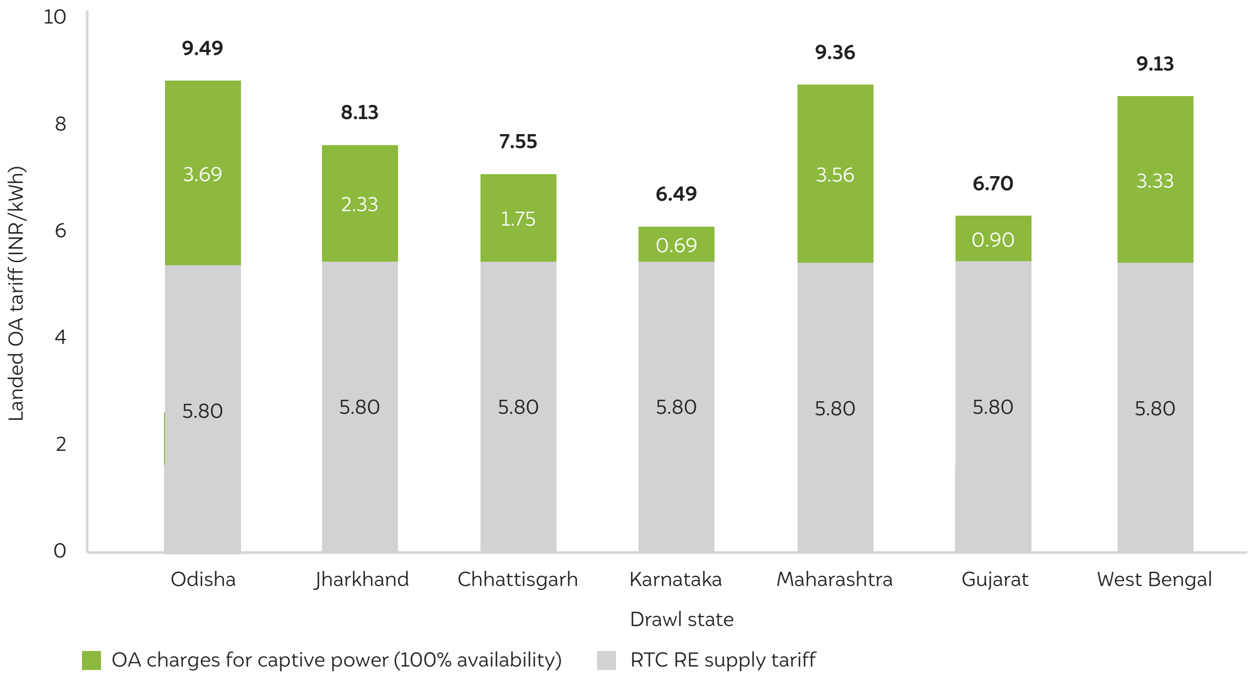
In the base case, we assumed that CPP generate electricity at INR 3.72/kWh (Ramakrishnan 2018) and considered the electricity tariffs of the respective states (PFC 2022). In addition, RTC RE will essentially offset the captive (coal-based) and grid electricity consumption. We calculated the cost of generating RTC RE and the solar, wind, and battery capacities required to meet the power demand based on a recent tender for grid-scale, wind-solar-battery hybrid power plants (ReNew 2021). These power plants can supply 400 MW of RTC RE using the combined output of a 400 MW solar power plant, a 900 MW wind power plant, and 100 GWh of battery storage. Per the prices and terms of this tender, we assumed that RTC RE power is available at INR 3.60/kWh at the generation point, with an 80 per cent availability on an annual basis. We assumed that the remaining power (20 per cent) is obtained from additional grid-scale battery storage systems costing INR 11/kWh (PIB 2023). This will result in an average tariff of INR 5.8/kWh at the generation point. We obtained the landed costs of RTC RE across various states – including banking charges – from the open access tariff calculator developed by the CEEW Centre for Energy Finance (2023).

Figure 10 shows the delivered cost of power across various states in India that have significant steel production capacities. We assumed that solar power is available within the state boundaries except for Jharkhand, Chhattisgarh, and West Bengal, which would import the power from Rajasthan. Similarly, states such as Odisha, Jharkhand, Chhattisgarh, and West Bengal do not have access to wind power within their state boundaries. Therefore, we assumed that these states would import wind power from Tamil Nadu through the interstate wheeling mechanism. Further, we considered that steel plants located in Karnataka, Maharashtra, and Gujarat can also access wind power within the state boundaries through an intrastate wheeling mechanism.

While there are significant differences in open access charges across states, our assessment shows that the weighted average delivered cost of RTC RE through the open access mechanism is INR 8.3/kWh, which is significantly higher than the cost of generating power through a coal-based CPP. As seen in Figure 10, there is a significant increase in price due to high RE open access charges. The higher cost of open access RE is expected to impact the cost of producing steel, depending on the extent of renewable power required for steel production. In our analysis, we took into account the open access charges for the major steel-producing states, as given in Figure 10. For the other states, we used the average cost.

At INR 8.3/kWh, the average abatement cost of RE is USD 60/tCO_2. However, if RTC RE were available at INR 3.6/kWh with a 100 per cent availability factor, the delivered price of RE would reduce to INR 5.8/kWh, resulting in a lower abatement cost of USD 25/tCO_2.

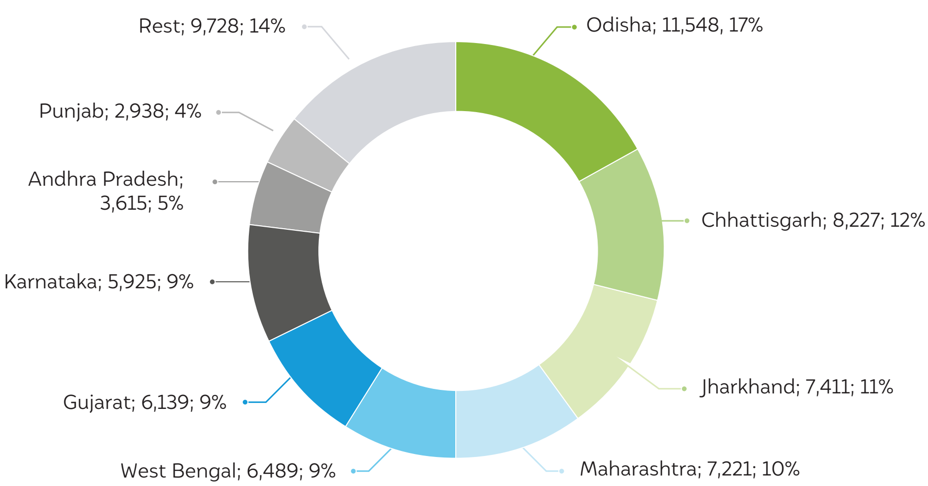
Figure 10 Significant variation in the landed cost of open access tariff is observed across states in India



Source: Authors' analysis based on CEEW Centre for Energy Finance (2023)

Figure 11(a) shows the state-wise distribution of power required for crude steel production. Odisha tops the list at 11,548 GWh – contributing 17 per cent to the total demand – as the state has among the largest steel capacities in India. Odisha is followed by other states having sizeable capacities, such as Chhattisgarh (8,227 GWh, 12 per cent), Jharkhand (7,411 GWh, 11 per cent), and Gujarat (6,139 GWh, 9 per cent). The remaining states cumulatively contribute 14 per cent to the total demand.

Figure 11 Around 70,000 GWh of electricity is required annually for crude steel production (state, production (MTPA), share (%))



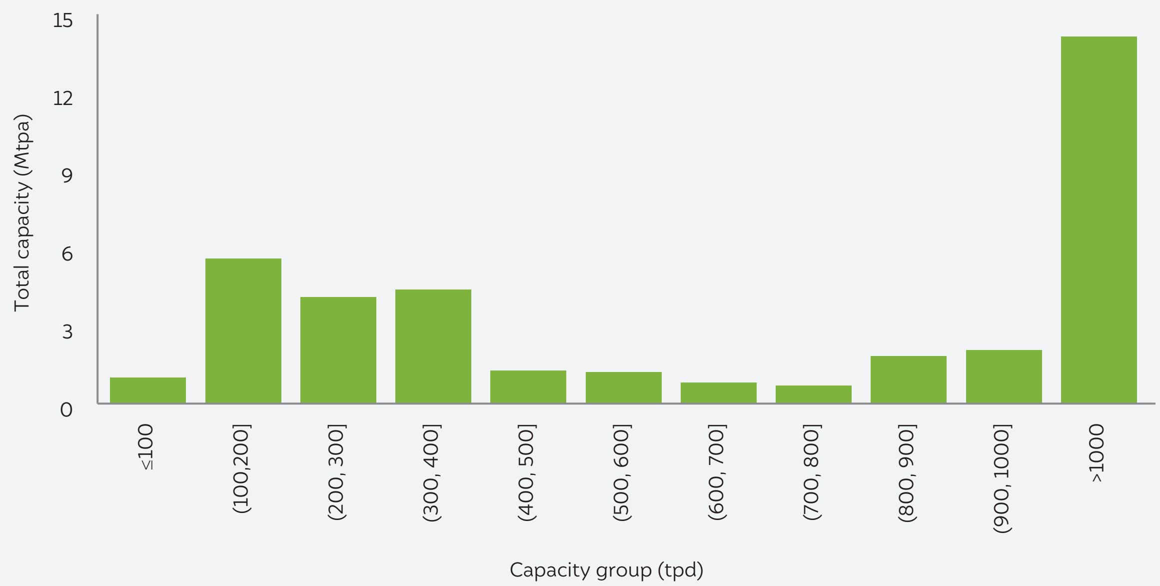
Source: Authors' analysis

Box 2 Unlocking the waste heat recovery potential in the DRI sector

Waste heat recovery from the rotary kiln flue gases has significant power generation potential, which can be used to meet the RTC power demand in the steel sector. Industry experts suggest that plants with a capacity larger than 300 tpd have already installed WHR systems for meeting the energy intensity targets set by the Bureau of Energy Efficiency (BEE) under the Perform, Achieve and Trade (PAT) scheme. However, smaller plants may not have installed WHR systems, as most of them were excluded from the coverage of the scheme.

Figure 12 shows the total steel production capacity distributed across various ranges of DRI plant capacities. The total DRI capacity having a kiln size lower than 300 tpd is 10.7 Mt. Typically, a 100 tpd kiln can support 1.5–1.9 MW of WHR system and generate 300 kWh of electricity per tonne of DRI (net). The total capacity of WHR across rotary kilns will thus be approximately 463 MW. This power can be used to meet the auxiliary load in the steel industry by wheeling through the open access mechanism.

Figure 12 **10.7 Mtpa of coal DRI capacity comprises plants smaller than 300 tpd**



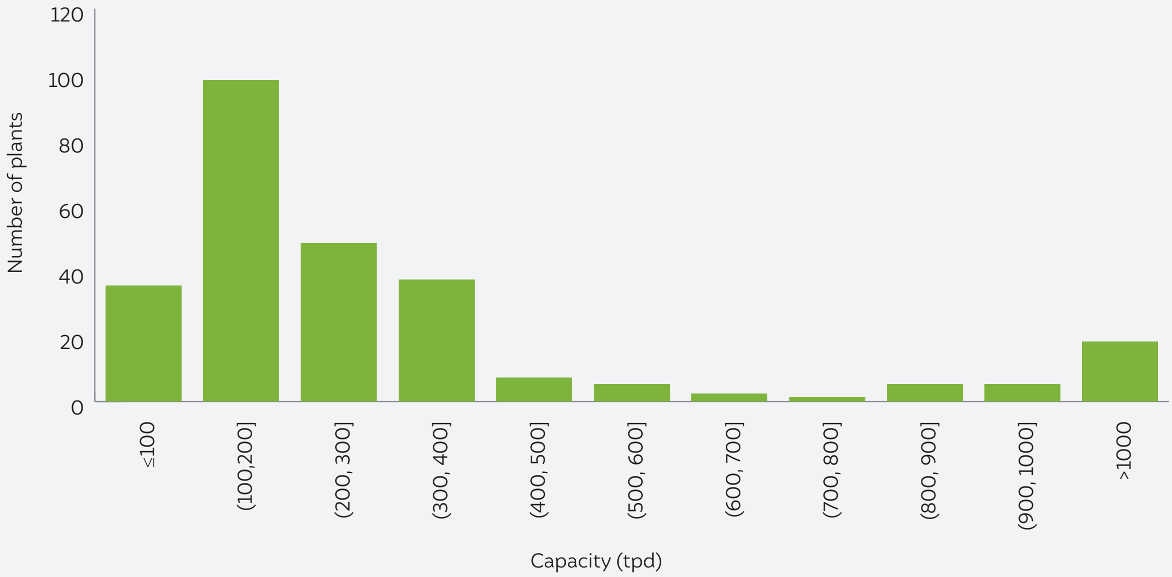
Source: JPC (2022a)

However, there are multiple challenges in unlocking the WHR potential in the DRI sector. Firstly, as shown in Figure 13, India has 159 kilns with a capacity lower than 300 tpd, having an average WHRB turbine size of only 3 MW. The average capacity of rotary kilns for sizes smaller than 300 tpd is 171 tpd. Assuming an average capital investment of INR 9 crore/MW (GGGI and CSTEP 2018), an average 3 MW capacity of WHRB needs an investment of about INR 27 crore.

Therefore, in the absence of any enforcement measures, such as the PAT scheme or carbon pricing, these plants prefer to invest in new rotary kilns for capacity expansion rather than setting up WHR units. These units can be mandated to install the WHR system if they are brought under the ambit of the PAT scheme. If not, the energy service companies (ESCOs) model can be considered for the small rotary kiln units, wherein the capital investment is borne by an ESCO, which shares a portion of the profit with the rotary kiln owner and earns a return on its investment by selling the power to a distribution company (discom) or on the power exchange.

Box 2 **Unlocking the waste heat recovery potential in the DRI sector**

Figure 13 **187 coal DRI plants have a capacity lower than 300 tpd**



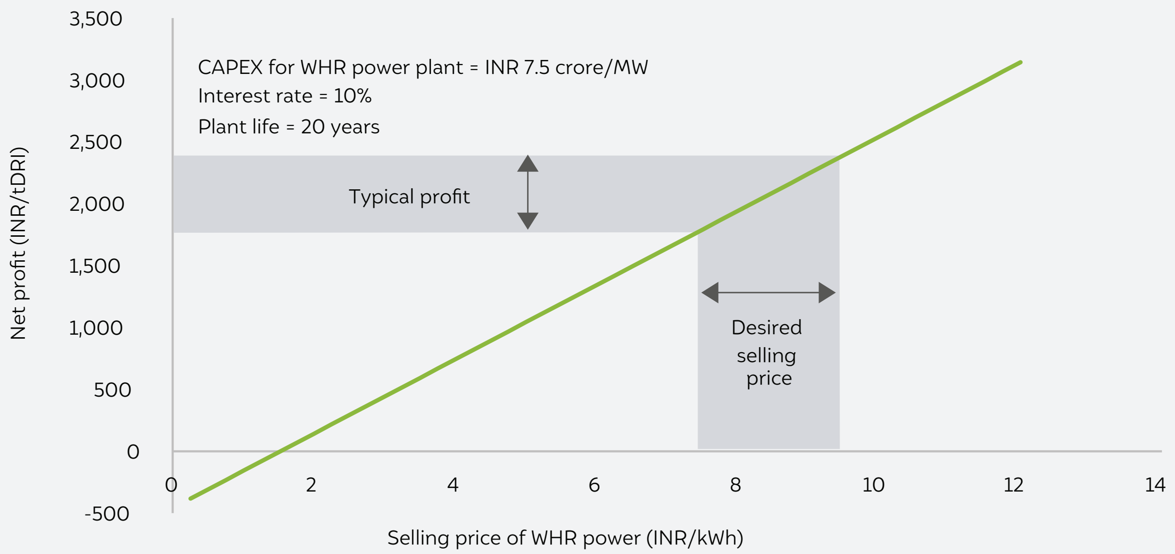
Source: Authors' analysis

Currently, approximately 32 per cent of total rotary kiln production capacity does not have co-located IFs. For kilns smaller than 300 tpd, 75 per cent of the capacity is comprised of standalone units. These kilns cannot consume the surplus power generated from the WHR system. Moreover, installing WHR systems will only make commercial sense if they can sell power to discoms. While a few states, such as Karnataka, are willing to pay INR 3.69/kWh (with annual escalation) for WHR power from the sponge iron industry (KERC 2017), other states pay much lower rates. The CAPEX component in the tariff for the WHR system alone is about INR 1.4–1.6/kWh. Therefore, states must derive a mechanism to offtake the WHR power at a mutually agreeable price.

Figure 14 shows the potential revenue generation per tonne of DRI after accounting for interest payments on loans obtained as CAPEX for installing waste heat recovery units. Revenue generation varies linearly with the selling price of the generated power to the discoms. We considered a CAPEX of INR 7.5 crore/MW, with an interest rate of 10 per cent spread over 20 years. Figure 14 shows that coal DRI plants need discoms to offtake power at INR 6–8/kWh to break even with a profit of INR 1,500–2,000/tDRI to prioritise setting up WHRBs instead of new kilns.

Box 2 **Unlocking the waste heat recovery potential in the DRI sector**

Figure 14 **Potential revenue generation using waste heat recovery in DRI units**



Source: Authors' analysis

The integrated steel plants can benefit by incentivising the installation of WHR in rotary kilns. As seen in Figure 9, the integrated steel plants need 3.06–3.64 GW of RTC RE power to meet their energy demand. The rotary kiln industry can potentially provide approximately 0.5 GW of RTC power – 13–15 per cent of the total power required – to integrated steel plants (ISPs). The WHR power does not carry any emissions burden, might be cheaper than RTC RE (which necessitates energy storage), and can be used by steel plants as their base load. Therefore, state governments should incentivise the wheeling of WHR power within their state boundaries, which will also allow them to create revenue opportunities. It is also important that ISPs located near rotary kilns be allowed right-of-way for setting up their power evacuation system, thereby increasing the viability of such projects.

Source: Authors' analysis

4.3 Alternative fuels

Alternative fuels have a critical role to play in the decarbonisation of most industrial sectors. However, out of the current technology mix, only gas-based shaft furnaces can entirely switch to green hydrogen. There is limited potential to uptake alternative fuels such as natural gas, biomass, or green hydrogen in blast furnaces. Further, there is a lack of research on the potential injection of alternative fuels in rotary kilns. The only fuel switch option in rotary kilns is to replace high-ash domestic coal with higher-quality, imported coal.

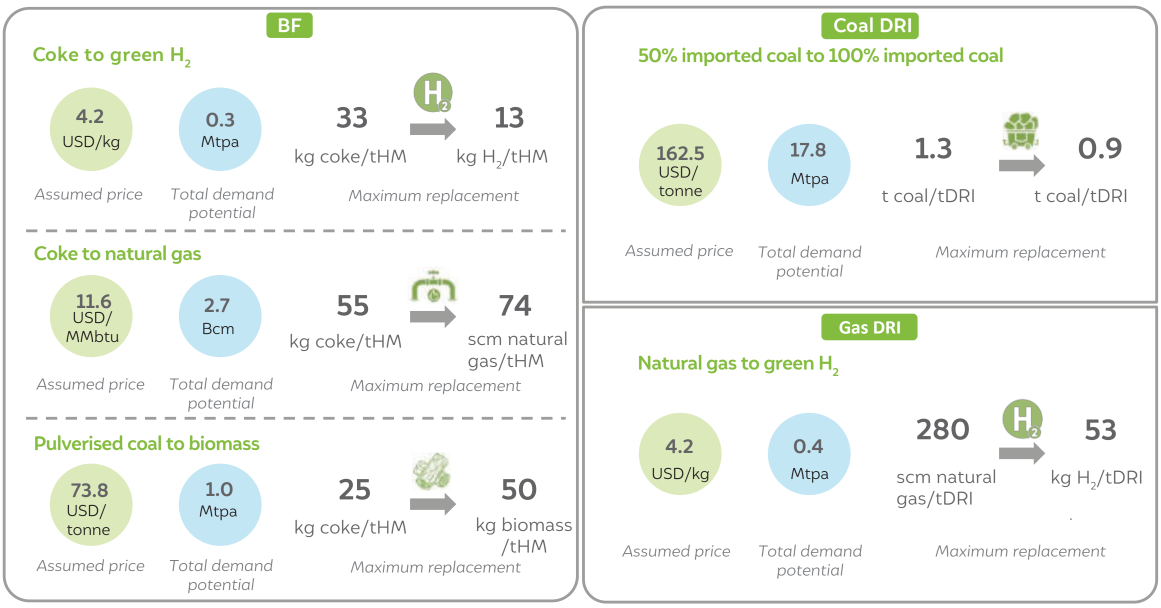
There is also a lack of research globally on the co-injection of alternative fuels simultaneously in blast furnaces. Therefore, we assumed that there was no co-injection of these fuels in the blast furnace currently. Our research indicates that 80 per cent of the blast furnaces in India have access to natural gas pipelines. Of this, we assumed that 50 per cent of blast furnaces could partially use natural gas to offset their coke consumption. Similarly, to show the effect of all types of fuel switching on the MAC curve, we assumed that 25 per cent of the blast furnace capacity opts for the injection of biomass pellets while the remaining 25 per cent uses green hydrogen. This has been shown schematically in Figure 15.

Green hydrogen can replace coke or PCI in the blast furnace as a reducing agent. Studies indicate that an injection of 28 kg/tHM of green hydrogen into blast furnaces can reduce PCI consumption by 120 kg/tHM (Yilmaz, Wendelstorf, and Turek 2017). One study indicates that 13 kg H_2/tHM could replace 33 kg/tHM of coke (Sato, Takahashi, Nouchi, and Ariyama 2015). In our analysis, we have assumed the latter. We have also assumed that green hydrogen is available at USD 4.20/kg based on the premise that it will be needed at a fixed hourly rate for all 8,760 hours in a year (Biswas, Yadav, and Baskar 2020).

Similarly, the literature suggests that natural gas can also be used as a reducing agent. Based on blast furnace models, we estimated that 74 Nm³ (or 50 kg) of natural gas can replace 55 kg of coke (Sato, Takahashi, Nouchi, and Ariyama 2015) at USD 8/GJ. It should be noted that the injection of natural gas and hydrogen will change the calorific value of the top gas and, therefore, could alter the way the top gas is used. As a result, our analysis considers that this change will subsequently cause reductions in thermal coal consumption for power generation (Pistorius, Gibson, and Jampani 2017). Considering that biomass has a carbon content upwards of 50 per cent, it could replace coke in the blast furnace as a reducing agent (Wang et al. 2015). The cost of biomass pellets was obtained from previous CEEW research (Selvaraj and Prakash 2021). Based on the literature, we assumed that 50 kg of biomass pellets could replace about 25 kg of PCI (Wang et al. 2015).

A few industries in India and abroad have attempted injecting gaseous fuels – such as natural gas and syngas – in rotary kilns without much success. While biomass or charcoal injection in rotary kilns is a theoretical possibility, there has been no demonstration of the same as yet. Therefore, switching from high-ash domestic coal to higher-quality, imported coal is the only decarbonisation lever considered with regard to fuel switching in rotary kilns. In the base case, we supposed that with a 50:50 blend of domestic and imported coal, the coal consumption in rotary kilns would be about 1.3 t/tDRI. From industry data, we found that kilns operating with just imported coal consume about 0.85–0.90 t/tDRI. This may reduce carbon emissions, but only slightly and at a price premium.

Figure 15 Coal consumption can be reduced significantly through the use of alternative fuels

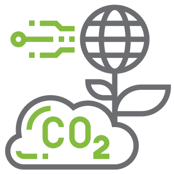


Source: Authors' analysis

Green hydrogen can replace natural gas in shaft furnaces. However, transitioning to green hydrogen will need additional electricity for heating hydrogen and iron ores as well as meeting the energy requirement for driving the endothermic reduction reaction of the iron ore. We assumed that this electricity is obtained from renewable energy sources. Further, industry experts and OEMs indicated that the existing shaft furnaces could shift to 30 per cent or more green hydrogen blended with natural gas without any significant modifications. However, there are discrepancies regarding the investment required for modifying shaft furnaces. Due to a lack of clear inputs, we presumed an approximate investment of 20 per cent of the plant CAPEX for this modification.

4.4 Carbon management

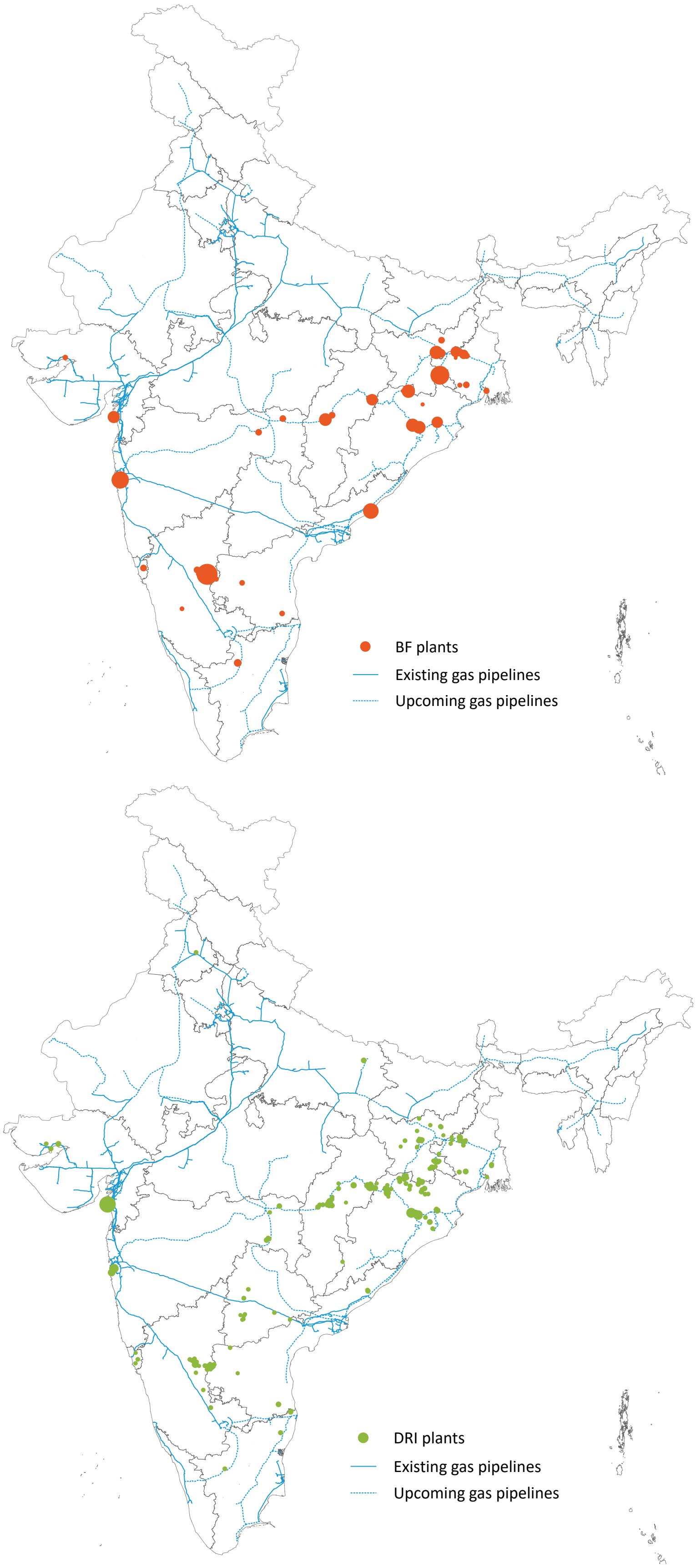
Decarbonisation through energy-efficiency, renewable-power, and fuel-switching measures alone cannot lead to net-zero emissions. A large share of emissions will be unabated even after the application of these mitigation options. The remaining emissions can only be mitigated through post-process capture. In this report, we examine two emission management techniques – carbon capture and sequestration (CCS) and carbon capture and utilisation (CCU). While CCS involves permanent geological storage of captured CO_2 (Bakshi, Mallya, and Yadav 2023), CCU involves the production of usable products – such as fuels and chemicals – from the captured CO_2. However, CCU products will need significant quantities of green hydrogen to blend with carbon to produce hydrocarbons.



A large share of emissions will need to be abated using post-process carbon capture technologies

We assumed that the steel plants in proximity to natural gas pipelines would choose CCS, as CO_2 pipelines can be built alongside existing gas pipelines to avoid right-of-way issues. The location of the pipelines in India and their distance from steel plants has been presented in Figure 16. Our analysis shows that 80 per cent of BF-BOF plants, all gas DRI-EAF plants, and 77 per cent of coal DRI-EAF and coal DRI-IF plants (by 2021–22 production) were found to be within a 25 km–radius of the nearest natural gas pipeline and, therefore, will not face significant right-of-way issues related to laying of CO_2 pipelines. Thus, on approximation, we assumed that 80 per cent of all plants choose CCS and the remaining 20 per cent choose CCU. Nonetheless, the CCUS pathway has a peak capture efficiency of only 85 to 90 per cent. The remaining CO_2 can be mitigated using offset mechanisms such as afforestation, which is highly dependent on the cost of land. Hence, we have not estimated the costs for such options.

Figure 16 Most steel plants in India can mitigate the right-of-way–related challenges to laying CO_2 pipelines



Source: Authors' analysis based on JPC (2022a) and GenesisRay Energy (2022)

The cost of CO_2 mitigation and its impact on the steel cost varies across the production processes.

Image: iStock

5. MAC curves and insights

Based on the data and assumptions taken for each mitigation measure under the four pillars, we calculated the emission reduction potential of each measure for the four steelmaking routes. Using the cost data obtained from the literature, we then calculated the MAC for each measure. The following sections elucidate the emission intensity reductions possible using the considered measures and show the MAC curves for each steelmaking route.

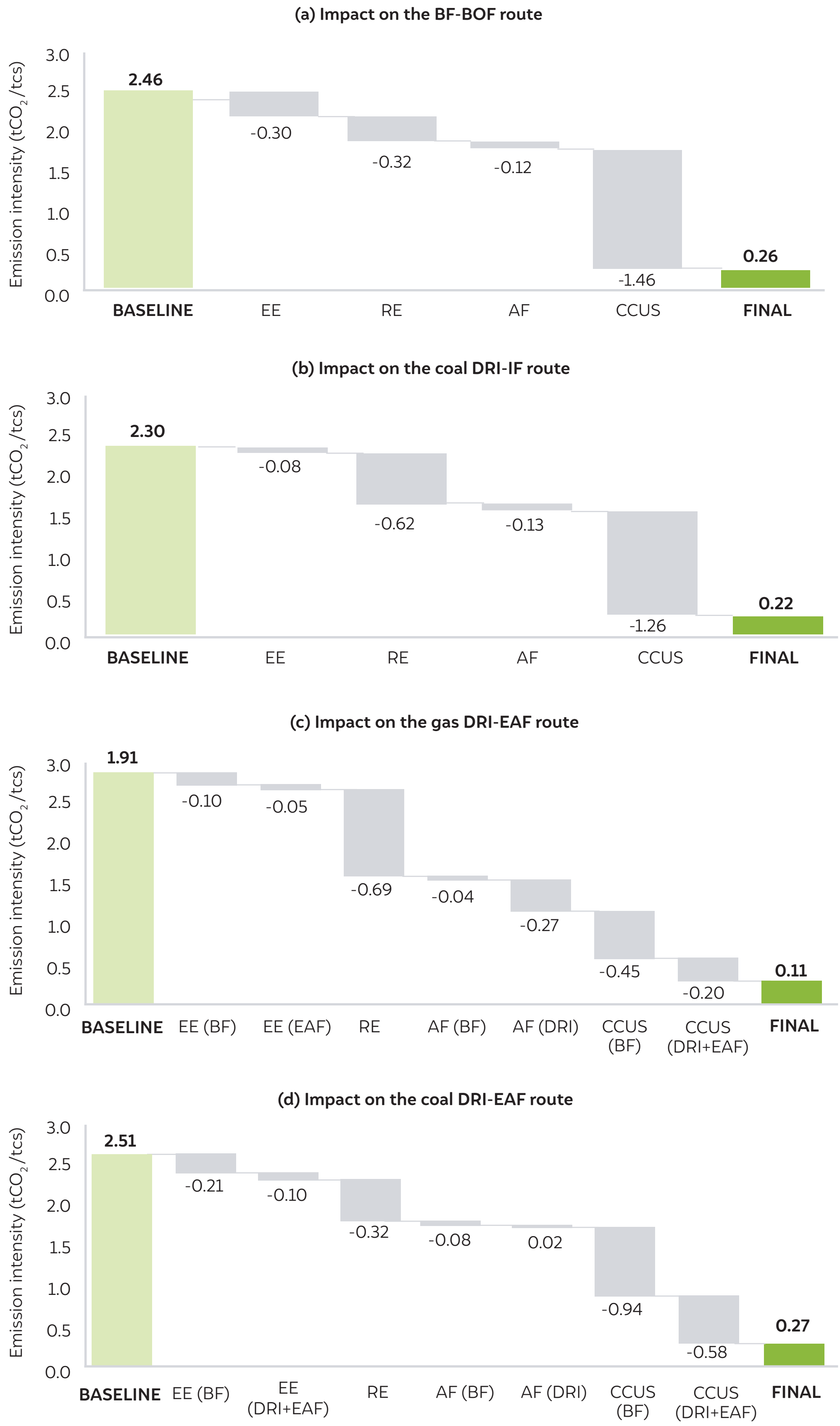
5.1 The net-zero trajectory for the steel industry

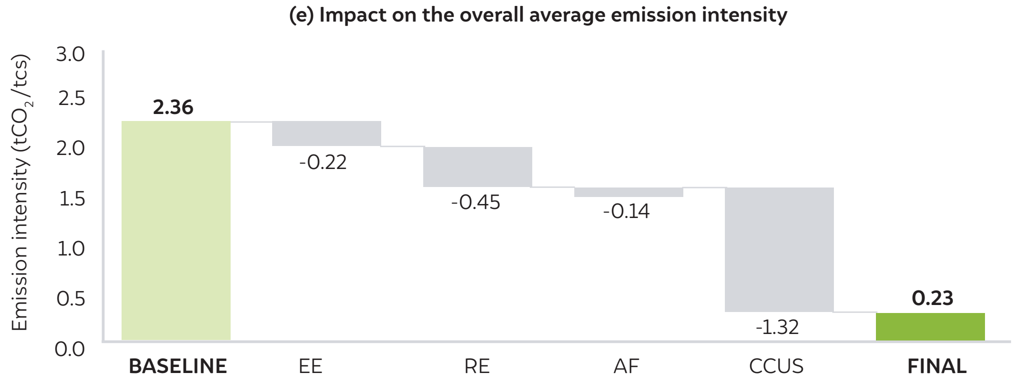
Figure 17 illustrates the net-zero trajectories for emission reduction in the steel industry across various production pathways. Our study shows that the current weighted average emission intensity of blast furnaces is approximately 2.46 tCO_2/tcs. We expect that with a 100 per cent penetration of all energy efficiency technologies, the emission intensity can be reduced by approximately 12 per cent to 2.16 tCO_2/tcs. It should be noted that this emission-intensity reduction does not consider any space constraint for the deployment of technologies in existing steel plants, which can be a significant bottleneck on the ground. However, these reductions do consider gains from yet-to-be-deployed technologies, such as waste heat recovery from steel slag.

12% reduction in emission intensity can be achieved in BF-BOF route by implementing all EE technologies

As shown in Figure 9, the BF-BOF pathway will need about 2.2 GW of RTC RE to offset coal-based captive power generation. Our research indicates that RE uptake can reduce the emission intensity of steel by 14 per cent to 1.84 tCO_2/tcs. Therefore, energy efficiency and renewable energy alone can reduce the emission intensity in the BF-BOF pathway by about 26 per cent. Beyond these measures, the use of alternative fuels can reduce the emission intensity further by around 5 per cent. However, our assessment indicates that about a 59 per cent reduction in emission intensity can be achieved through the CCUS pathway alone. The remaining emissions can be reduced by carbon offset through afforestation or other measures.

Figure 17 The impact of a decarbonisation measure depends on the steel production process





Source: Authors' analysis

The coal DRI-IF route has very little scope for emission reduction through energy efficiency. This is because kilns with a capacity higher than 300 tpd have already installed WHRBs. Only rotary kilns below 300 tpd can use WHRBs to reduce their emission intensity. Energy efficiency has a limited role to play in IFs due to the nature of the operation and the typically small capacities of IF units. The use of RE can potentially reduce the emission intensity of the coal DRI-IF route by 27 per cent. As is the case for the coal DRI-EAF and BF-BOF routes, fuel switching can only play a small role in reducing the emission intensity in the coal DRI-IF process. Further reduction is possible only through the CCUS pathway, which can reduce the emission intensity of the average coal DRI-IF process by 55 per cent independently.

The role of alternative fuels in mitigating emissions from the steel industry is limited

The coal DRI-EAF process employed by integrated steel plants uses a mix of DRI, hot metal, and scrap to produce steel. In the coal DRI-EAF route, energy efficiency can reduce the emission intensity by 13 per cent. This can be attributed primarily to a reduction in blast furnace emissions because of the use of EE measures in blast furnaces, followed by a marginal reduction in DRI and EAF emissions. Renewable energy–based electrification of EAF units will further reduce the emission intensity of steel production by 13 per cent. Fuel switching has a limited role to play in blast furnaces and rotary kilns and, consequently, reduces the emission intensity by merely 4 per cent. CCUS reduces the emission intensity by more than 61 per cent in the coal DRI-EAF route.

The gas DRI-EAF process uses a mix of hot metal, DRI, and scraps to produce steel. There is a significant role for EE measures to reduce emissions from hot metal production and, hence, through the gas DRI-EAF process. Broadly, energy efficiency can reduce the emission intensity of the gas DRI-EAF route by 8 per cent, followed by RE integration, which can reduce emissions by 36 per cent.

Implementing EE measures reduces electrical consumption in coal-based DRI-EAF from 418 kWh/tcs to 279 kWh/tcs and in gas-based DRI-EAF from 521 kWh/tcs to 486 kWh/tcs. Note that the coal DRI-EAF process consumes comparatively less electricity due to the addition of hot metal. With coal-based DRI and scrap alone, the power consumption can be as high as 800 kWh/tcs. In gas DRI-EAF, renewable power contributes more to emission reduction compared to coal DRI-EAF (see Figures 17 (c) and (d)). This is because of the assumption that the former has a higher emission intensity of power, as it relies completely on coal-based CPP, whereas the latter uses a significant amount of WHR power. Further, the share of DRI in the charge mix is much lower in the coal DRI-EAF process versus the gas DRI-EAF process on average (see Table 1). Therefore, based on the analysis of crude steel production, RE measures have a lower contribution to emission reduction for coal DRI production than for gas DRI production.

Switching from gas to green hydrogen has the potential to fully decarbonise the gas DRI-EAF process. However, based on the current costs of green hydrogen, using natural gas in shaft furnaces that are integrated with CCS is cheaper than switching to green hydrogen. Regardless of whether green hydrogen is used in the process, CCS is still required for the gas DRI-EAF process to capture the emissions from iron ore pelletisation and process emissions from the calcination of limestone used as a de-sulphurising agent. Nevertheless, shaft furnaces will quite likely be decarbonised primarily by green hydrogen when it becomes cheaper as a result of manufacturing at scale. The emissions burden from the hot metal used in the gas DRI-EAF route can only be reduced through CCUS – we estimate that 34 per cent of emission reduction can be achieved through this pathway.

Figure 17(e) indicates the weighted average emission intensity reduction pathway for the steel industry. EE can reduce the emission intensity of steel by 9 per cent, followed by RE measures, which can reduce the emission intensity by 19 per cent. As expected, alternative fuels have a limited role to play in decarbonising the current technology mix of the steel industry and can reduce the emission intensity by just 6 per cent. The CCUS pathway will have a critical role to play in the steel industry achieving net-zero emissions, as they will be responsible for reducing emissions by approximately 56 per cent. The remaining emissions will have to be reduced by carbon offset mechanisms such as afforestation or direct air capture integrated with CCUS.

5.2 MAC curves for the steel industry

Figures 18–21 depict the MAC curves for each steelmaking route. Figure 18 represents the MAC curve for the BF-BOF pathway. Regardless of where the hot metal from the BF is used for steelmaking, the total emission from the BF-BOF pathway is approximately 186 $MtCO_2$. The emission intensity of steel corresponding to major inflexion points has also been indicated at the bottom of the graph. The emission intensity of the BF-BOF pathway can be reduced from 2.46 tCO_2/tcs to 2.29 tCO_2/tcs with decarbonisation levers that have a negative cost of mitigation. This implies that steel plants can achieve an emission intensity of 2.29 tCO_2/tcs by reducing production costs. The bulk of the decarbonisation levers having a negative cost of mitigation are energy efficiency measures. Beyond this point, the steel production cost increases with a reduction in emission intensity.

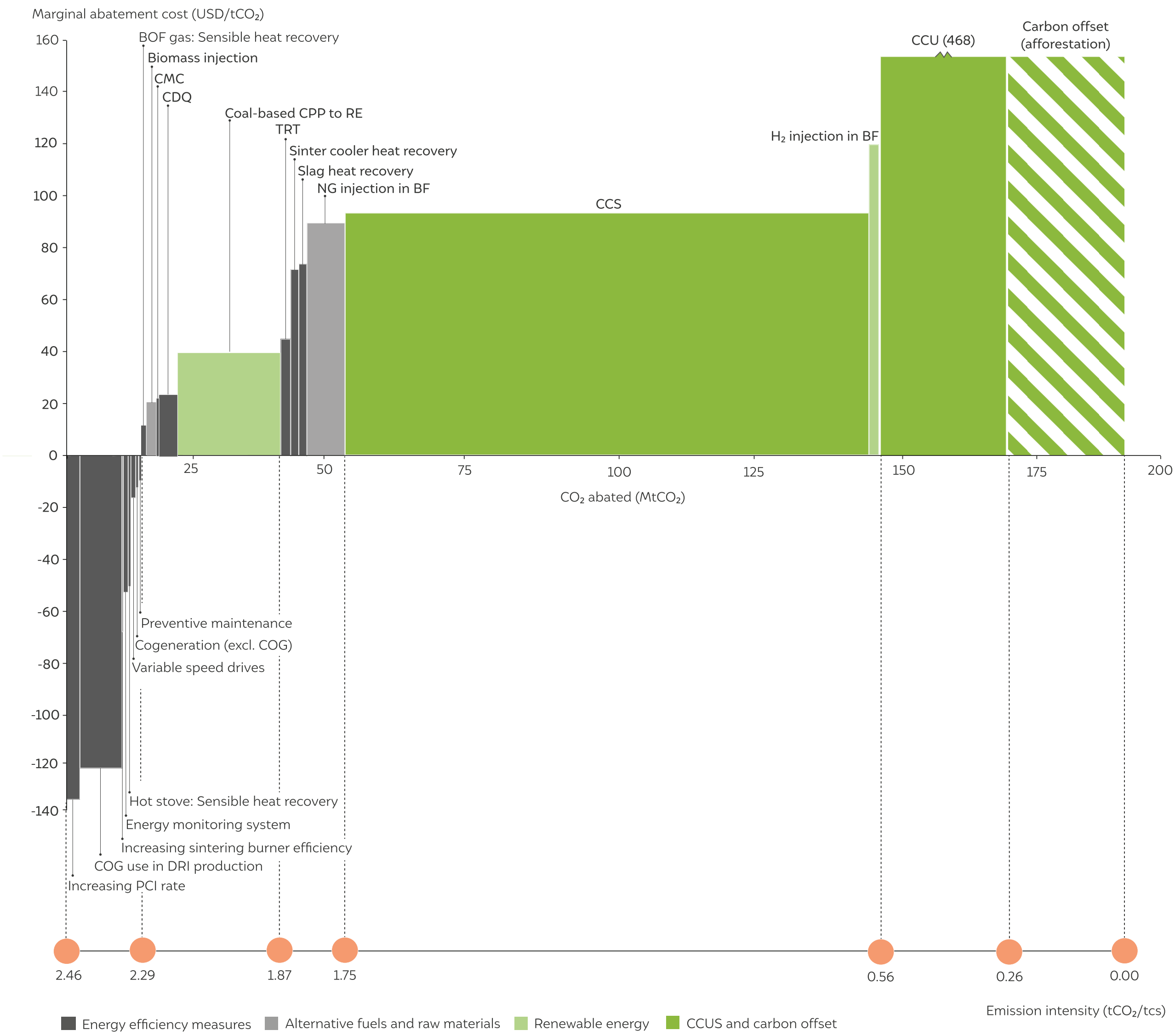
The emission intensity of BF-BOF steel can be reduced from 2.46 to 1.76 tCO_2/tcs without CCUS

At a carbon price of USD 92/tCO_2, the emission intensity of steel can be reduced to 1.76 tCO_2/tcs and abate 50 $MtCO_2$ in the process. Till this point, decarbonisation can be achieved by replacing captive power generation with renewable energy and using alternative fuels. Our analysis shows that a few energy efficiency technologies, such as TRT and CDQ, also have a positive cost of mitigation. Beyond 1.76 tCO_2/tcs, CCS is the only decarbonisation lever for integrated steel plants. We have indicated the use of green hydrogen as a decarbonisation option in the MAC curve. However, at the current costs, green hydrogen is not a decarbonisation solution, and industries would prefer CCS for decarbonisation. As discussed in Section 4.4, we considered an 80:20 split between CCS and CCU pathways based on the access to natural gas pipelines. While there are multiple pathways for producing fuels and chemicals through the CCU route, in this study, we considered the case of producing green methanol from the captured CO_2.

Methanol is a direct output of the petrochemical industry and has various commercial applications. It can be used as a fuel by blending in gasoline. Methanol is also a building block for sustainable aviation fuel and can also be used for producing green olefins. However, our analysis indicates that CCU has the highest cost of mitigation (USD 468/

tCO_2), primarily due to the high cost of green hydrogen today (assumed at USD 4.2/kg). As discussed earlier, the peak capture efficiency for CCUS is about 85 per cent. Consequently, net-zero steel can only be produced by using carbon offset pathways such as direct air capture or afforestation. However, given the uncertainty in the costs and sensitivity of afforestation to land prices, we have not considered the cost of mitigation through these pathways but have only indicated the amount of CO_2 that needs to be abated.

Figure 18 More than 70 per cent of BF-BOF emissions need carbon management to mitigate



Source: Authors' analysis

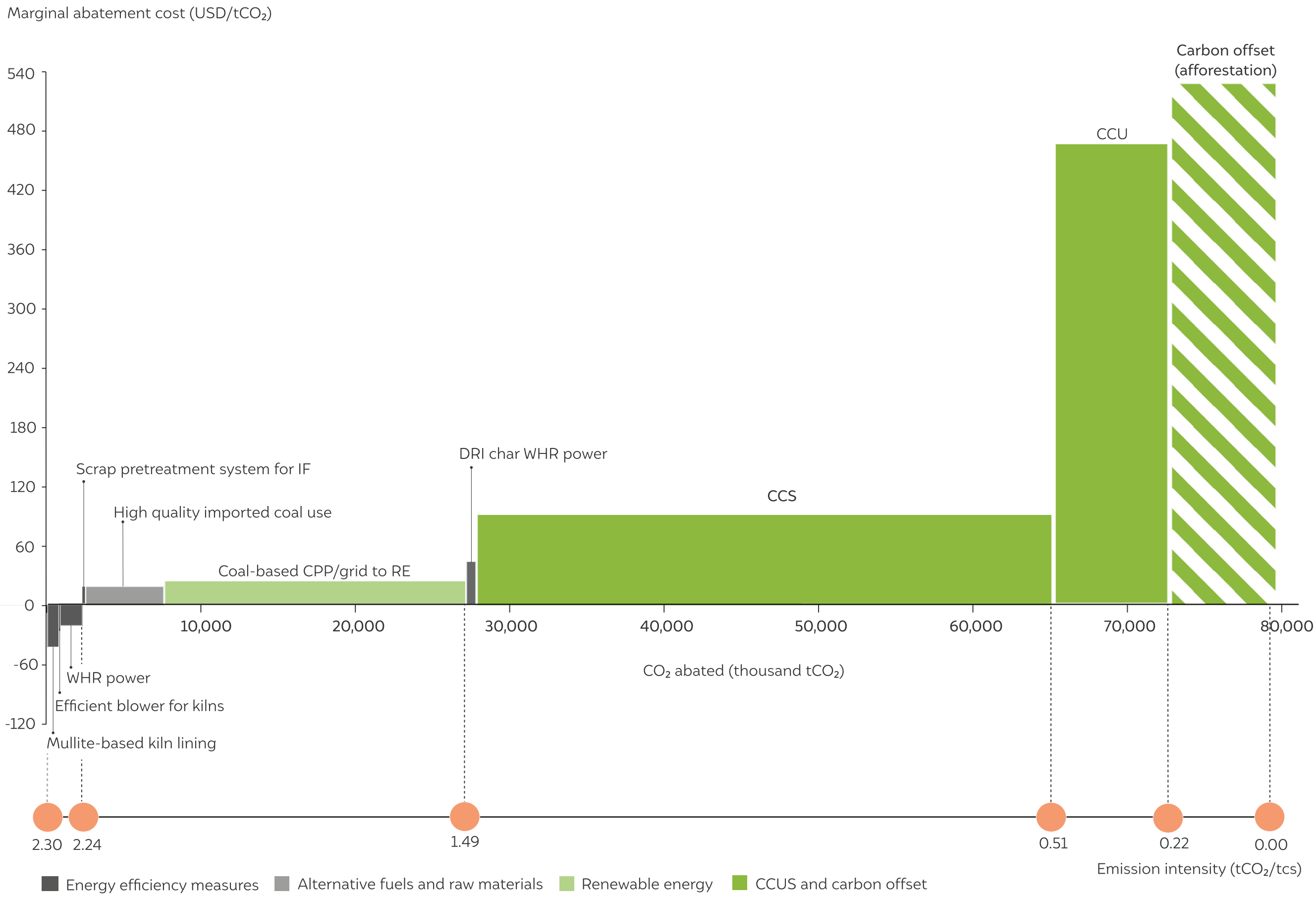
Note: The reductions for BF-EAF plants are included in the BF-BOF MAC curve. We assumed that these EAFs do not consume electricity because the hot metal provides the required heat.

The MAC curve for the coal DRI-IF route is shown in Figure 19. Although energy-efficient technologies, such as the use of VVFDs, mullite lining, and scrap pre-treatment, have a negative cost of mitigation, they are not expected to reduce the emissions from this pathway significantly. In our assessment, we considered a base case (50:50 ratio of imported and domestic coal) coal price of USD 107/tonne, while imported coal was set at USD 160/tonne, based on inputs provided by various plants. Given these prices, our assessment indicates that switching from domestic coal to imported coal can reduce emissions from this sector by

4.68 $MtCO_2$ and still have a negative cost of mitigation due to the significantly lower quantity of imported coal required per tonne of DRI output. When the price of imported coal reaches USD 176/tonne, the MAC becomes zero.

In addition to energy efficiency and switching to imported coal, the shift from grid electricity to open access–based RTC RE can reduce up to 21 $MtCO_2$ emissions. However, this reduction will come at a carbon price of USD 52/tCO_2. CCS will have a critical role to play in decarbonising the coal DRI route. Most coal DRI plants already have access to natural gas pipelines, implying that right-of-way for CO_2 pipelines, although challenging, will not impede the decarbonisation of this sector. However, a suitable CO_2 transportation and sequestration system still needs to be established in addition to the identification of geological reservoirs. This may take a minimum of two decades, even for the most promising reservoirs (Bakshi, Yadav, and Mallya 2023). Coal DRI plants that do not have access to gas pipelines can be decarbonised using the CCU pathway. For the CCU application, we assumed green methanol as the output. The remaining emissions can be reduced through carbon offset.

Figure 19 **The coal DRI-IF route has few EE options**

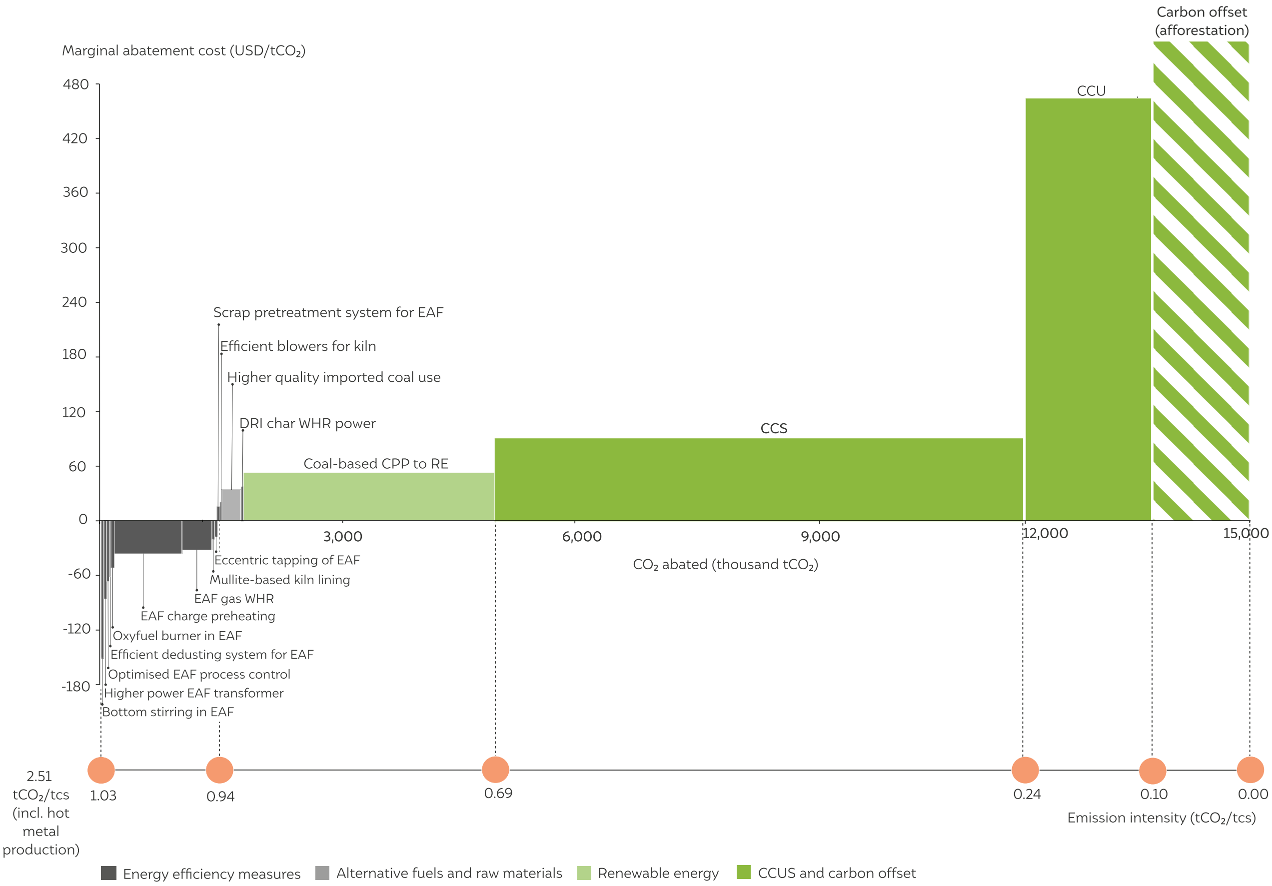


Source: Authors' analysis

The MAC curve for the coal DRI-EAF route (Figure 20) represents emissions only from the production of DRI and its conversion to steel. Note that the emissions attributed to the hot metal consumed in the coal DRI-EAF route have been represented in the BF-BOF process (Figure 18). There are multiple energy efficiency technologies in the coal DRI-EAF route that have a negative cost of mitigation. However, as seen in Figure 20, they have a limited role to play in mitigating emissions from the sector. The bulk of the emissions reduction in the coal

DRI-EAF pathway will happen through the use of renewable energy to offset captive power generation and the CCUS pathway. However, the mitigation cost for these technologies is above USD 60/tCO_2, which will have a significant impact on the cost of the steel produced through this pathway (see Figures 34–37).

Figure 20 The role of EE technologies in mitigating coal DRI-EAF emissions is small



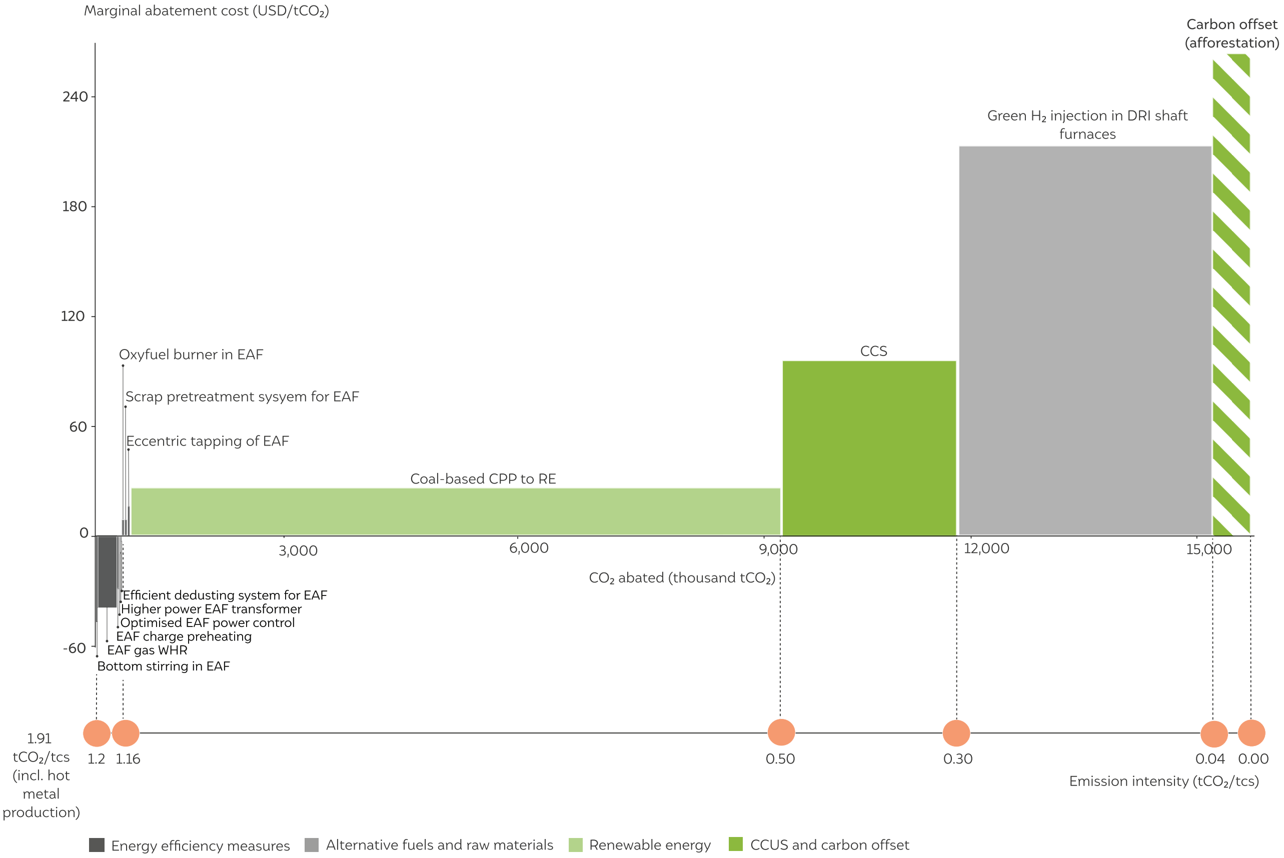
Source: Authors' analysis

Similar to the coal DRI-EAF route, the MAC curve for the gas DRI-EAF route represents emissions only from the production of DRI and its conversion to steel. It excludes blast furnace emissions that arise in the production of hot metal. As seen in Figure 21, energy efficiency has a limited role to play in reducing emissions from this route. However, the use of RE power in this pathway can mitigate 8.40 MtCO_2.

With regards to fuel switching, even though green hydrogen will be the eventual decarbonisation lever for shaft furnaces, at present, natural gas integrated with CCS is a cheaper and preferred option due to the higher cost of green hydrogen, as discussed in Section 5.1. Nonetheless, the cost of mitigation reduces to USD 42/tCO_2 if green hydrogen is available at USD 1.5/kg. If the cost of hydrogen comes down further to USD 1/kg, then the abatement cost becomes zero.

It should also be noted that we have included CCS in this study for mitigating emissions arising from iron ore pelletisation and direct process emissions due to the calcination of limestone, as such emissions can only be mitigated through the CCS pathway because it has a lower mitigation cost than CCU. Further, right-of-way for CO_2 pipelines will not be a challenge for this pathway as all gas-based DRI plants have access to natural gas pipelines.

Figure 21 RE provides a significant mitigation potential for gas DRI-EAF plants



Source: Authors' analysis

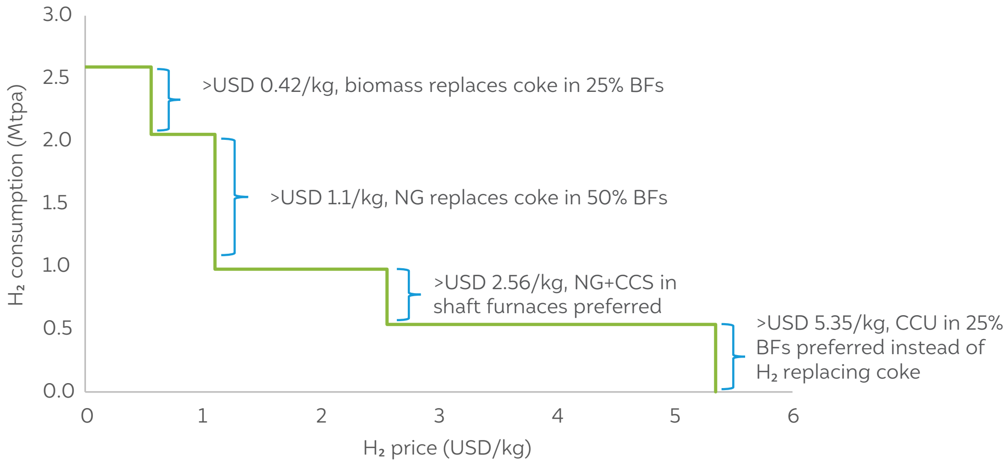
5.3 Role of alternative fuels for decarbonising the steel industry

Green hydrogen is one of the cleanest fuels for steel production. However, the cost and availability of green hydrogen remain a barrier to its rapid adoption. Therefore, although there is significant potential for using green hydrogen in steelmaking, the actual uptake will happen only if green hydrogen achieves cost parity with other decarbonisation options. Alternatively, the difference between the cost of green hydrogen and fossil fuels has to be bridged by some form of carbon price. India is in the process of introducing a national carbon market, with the steel industry being one of the major sectors within its ambit.

Figure 22 shows the amount of green hydrogen that can be used in the steel industry across various price levels. Based on the actual steel production in fiscal year 2021–22 across various routes, the steel industry can consume 2.59 Mtpa of green hydrogen using the BF-BOF and gas DRI-EAF routes if it is available at USD 0.56/kg or cheaper. Above this price, the use of biomass at USD 4.69/GJ in blast furnaces to replace coke becomes relatively cheaper, reducing the overall potential to 2.05 Mtpa. These estimates are based on our assumption that 25 per cent of blast furnaces use biomass (see base case Section 4.3). If the price of green hydrogen is higher than USD 1.10/kg, natural gas at the price of USD 13.78 per million British thermal units (MMBtu) will be preferred to replace coke in 50 per cent of blast furnaces (see Section 4.3), thereby reducing the potential to 0.98 Mtpa. For green hydrogen priced higher than USD 2.56/kg, it becomes more cost-effective for gas DRI shaft furnaces to continue using natural gas and deploy CCS for emissions mitigation.

Thus, the remaining potential for green hydrogen will be just 0.54 Mtpa in 25 per cent of blast furnaces (see Section 4.3) to replace the equivalent amount of coke. This potential is lost only at hydrogen prices higher than USD 5.35/kg, at which point these plants will need to undertake CCU at USD 468/tCO_2. We have assumed that these plants could not opt for CCS due to right-of-way issues for CO_2 pipelines.

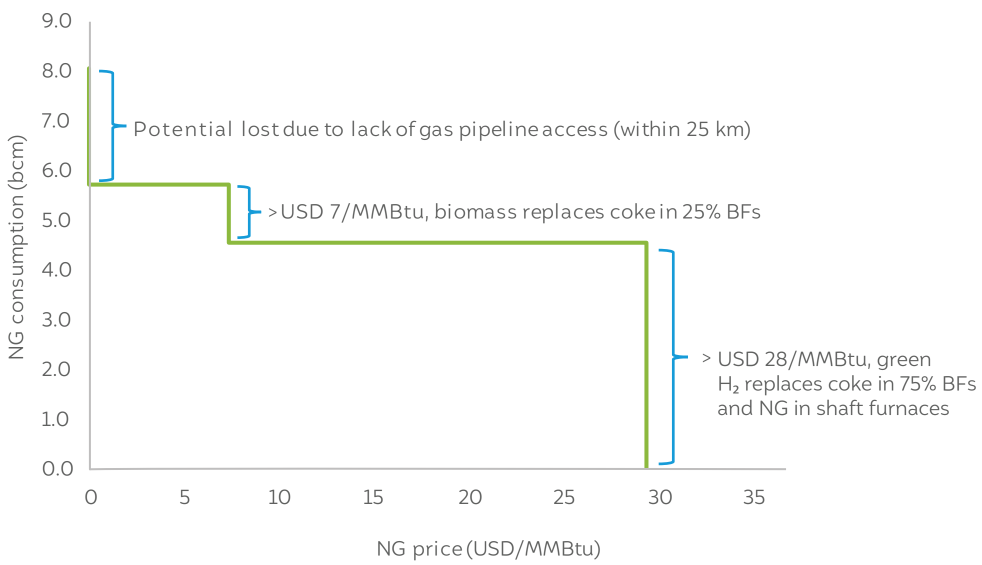
Figure 22 Viability of using green hydrogen in the Indian steel industry



Source: Authors' analysis

Figure 23 shows the viability of using natural gas in the steel industry. The steel industry can potentially use 8.07 billion cubic metres (Bcm)/year of natural gas in gas DRI-EAF and BF-BOF plants if access to gas pipelines is not a challenge. However, as implied in Section 4.4, 20 per cent of BF-BOF plants in India do not have access to gas pipelines. Consequently, the total potential for the usage of natural gas is reduced to about 5.72 Bcm. If the gas price is higher than USD 7.40/MMBtu, 25 per cent of blast furnaces will switch to biomass, which is at USD 4.69/GJ, to replace coke (see Section 4.3). Thus, the potential of gas consumption is reduced to 4.54 Bcm. Green hydrogen at USD 4.2/MMBtu becomes more favourable than natural gas only when the latter is costlier than USD 29.54/MMBtu.

Figure 23 Viability of using natural gas in the Indian steel industry

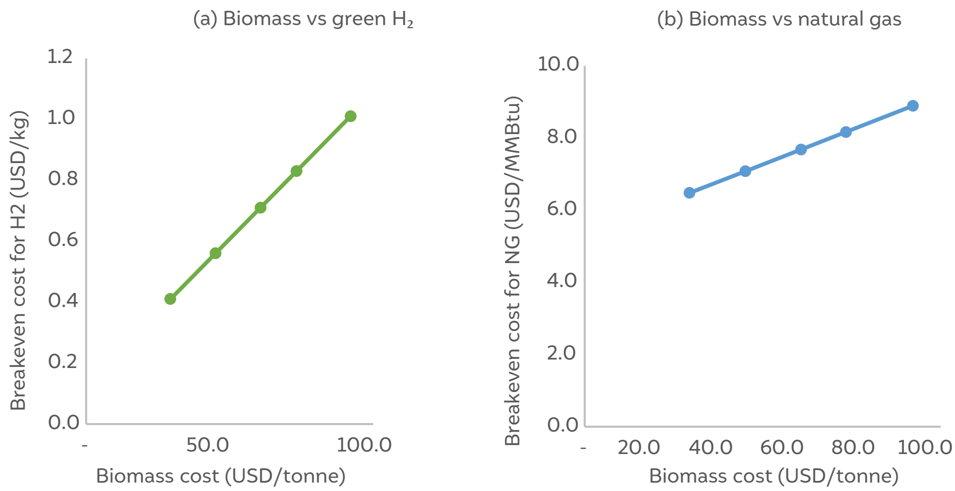


Source: Authors' analysis

Green hydrogen, natural gas, and biomass are competing alternative fuels for use in BFs. However, no literature or pilot study has studied the effects of co-injection of these fuels as yet. Figure 24 shows the cost competitiveness of these alternative fuels in BFs by plotting the breakeven cost of green hydrogen and natural gas as a function of the cost of biomass. The delivered cost of biomass pellets, which has been obtained from crop residue for a transport distance of 200 km, is USD 4.7/GJ. For this cost of biomass pellets, the delivered cost of green hydrogen should be as low as USD 0.83/kg. In contrast, the breakeven price of natural gas is much higher than the cost of biomass at any given point in the graph. For a biomass pellet cost of USD 4.7/GJ, the breakeven price of natural gas is USD 7.74/MMBtu.

Presuming that green hydrogen is unlikely to reach a cost of USD 0.83/kg in the near future and the challenges with achieving a delivered natural gas price of less than USD 10/MMBtu, it is likely that crop residue–based biomass will be the most widely used alternative fuel in the BFs if the challenges related to its price stability and supply chain are addressed. We expect that BFs in India can consume 1 Mtpa of biomass pellets based on the production from this route in fiscal year 2021–22.

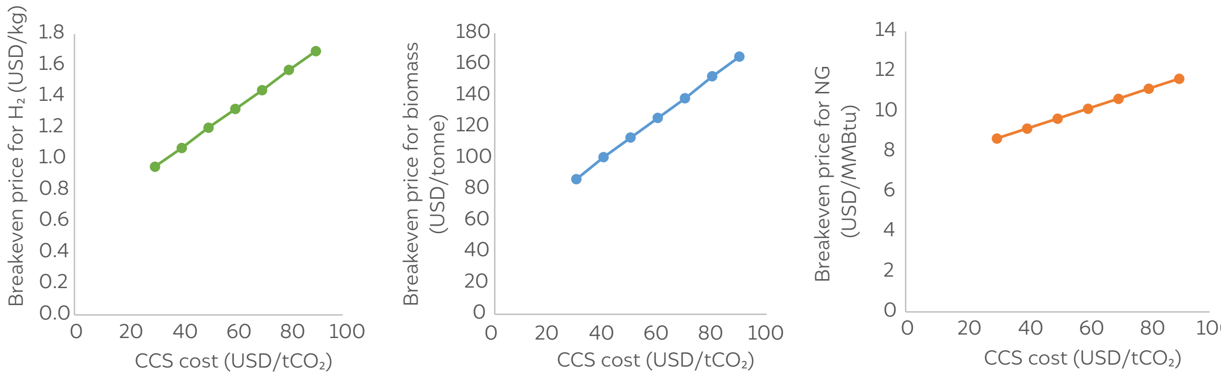
Figure 24 The cost of green hydrogen must come down steeply to be preferred over biomass



Source: Authors' analysis

Integrated steel plants will switch to alternative fuels only if their cost of mitigation is lower than that of using coal integrated with CCS. Figure 25 shows the breakeven prices of hydrogen, biomass, and natural gas as functions of the cost of using coal along with CCS. Breakeven prices of each of these alternative fuels increase linearly with the cost of coal and CCS. The coal consumption represented here is only for the BF-BOF route, after deploying energy-efficient measures that result in a net reduction in coal consumption. At the lower end of the price of coal with CCS, at USD 30/tCO_2, the breakeven price of biomass is the least at USD 5.5/GJ, followed by hydrogen, at approximately USD 0.95/kg, and natural gas, at USD 8.2/MMBtu. At the higher end of the price of coal with CCS, USD 90/tCO_2, the breakeven price of hydrogen is USD 1.7/kg and for natural gas, it is USD 11/MMBtu.

Figure 25 **The cost of CCS dictates the prospects of using alternative fuels in blast furnaces**



Source: Authors' analysis

Note: A coking coal price of INR 18,000/tonne and a pulverised coal price of INR 7,600/tonne have been assumed.

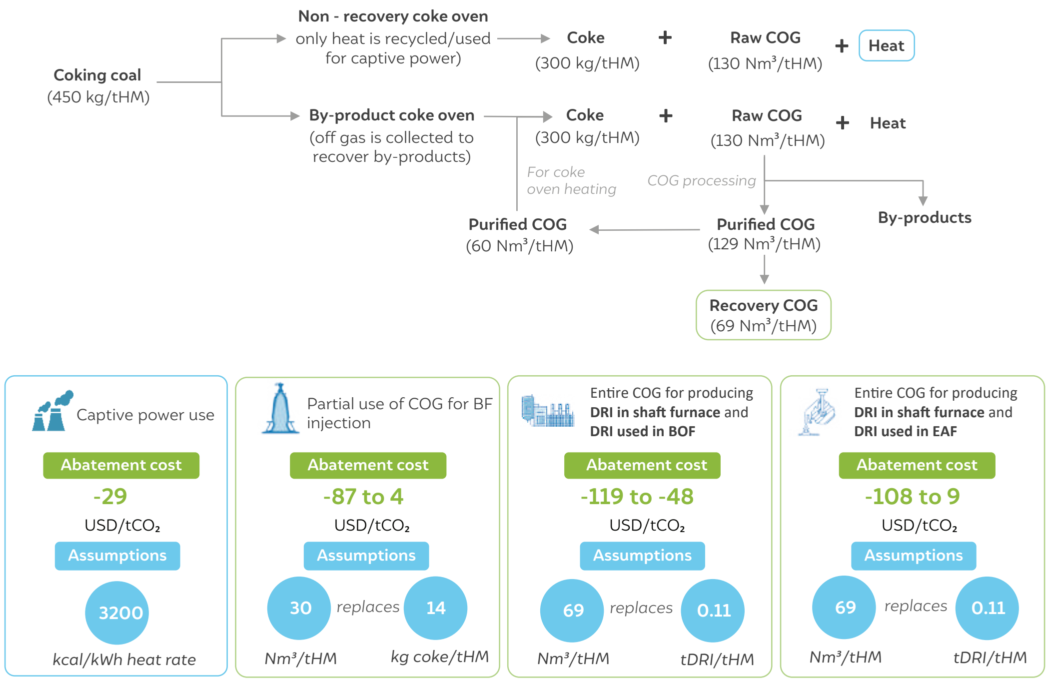
5.4 Best use of industrial off-gases in integrated steel plants

In the steel industry, COG is utilised as a source of gaseous fuel in reheating furnaces. Some amount of COG is also used for power generation. However, since the current assessment only considers processes till crude steel production, we assumed that after meeting the requirements of the coke oven, the entire volume of COG becomes available for the three options: DRI production, electricity generation and injection in BF. A detailed discussion on the competing uses of COG across these three applications is given below.

Integrated steel plants produce various off-gases such as COG, BF top gas, and BOF gas. As seen in Figure 26 these off-gases can be used in multiple ways. The COG retrieved from the coke oven can be used for captive power generation or injected into a BF for substituting PCI or as fuel for DRI production in a shaft furnace after volatile materials have been removed from the gas stream. The DRI produced in these shaft furnaces, along with scrap, can be used to produce steel in either EAF or BOF. It is important to identify and prioritise options to utilise these fuel sources since they maximise revenues by reducing the amount of coal consumed and, in turn, reduce emissions. This section discusses the various competing uses of off-gases and showcases a methodology for identifying the best options based on the cost of CO_2 mitigation.

Traditionally, a fraction of the COG produced in the coke oven – approximately 46 per cent – is consumed in the coke oven itself to provide energy for the coke-making process. In non-recovery type coke ovens, due to the presence of volatile matter in the mixture, the COG is only partially combusted in the coke oven, which leads to its inefficient use. Therefore, if recovery-type coke-making ovens are used, the COG can be captured and better utilised in various other avenues, as shown in Figure 26. It can be used for three applications: to offset thermal coal used in CPPs, partially replace the coke used in BFs, and as a reducing agent for producing DRI in shaft furnaces. This section presents a comparison of all three cases and identifies the best use of COG.

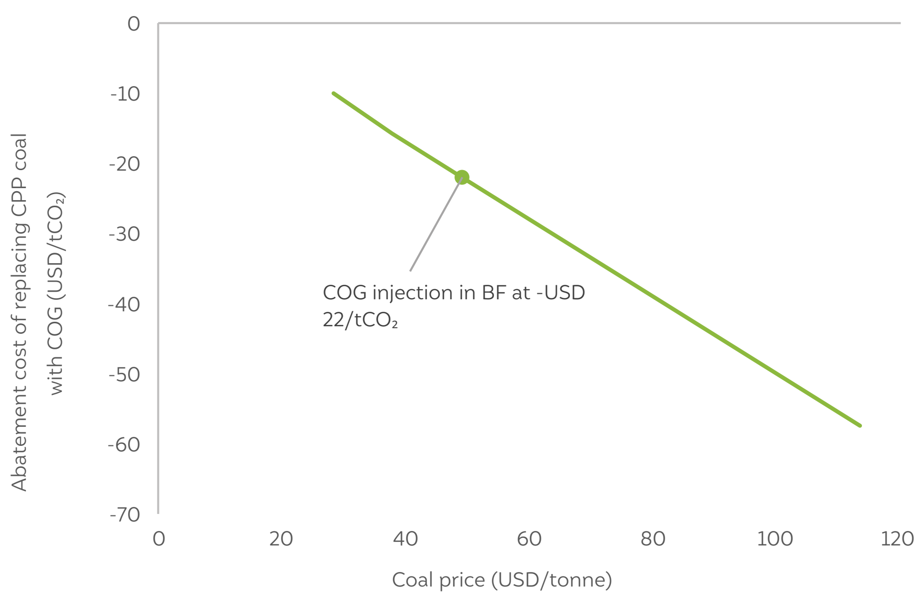
Figure 26 COG use as fuel for DRI-BOF has the lowest abatement cost



Source: Authors' analysis

If 100 per cent of the net COG production or 69 Nm³/tHM is used for captive power generation at a heat rate of 3,200 kcal/kWh, the abatement cost is estimated to be -USD 29/tCO_2. This results in mitigating 106 kg CO_2/tcs in emissions. Our analysis indicates that the cost of mitigation reduces to -USD 60/tCO_2 if coal prices are doubled (Figure 27).

Figure 27 Cost of abatement as a function of the CPP coal cost



Source: Authors' analysis

The redirection of COG into the BF makes this an EE measure. To maintain the prescribed thermochemical conditions in the BF, a maximum of 0.1 t COG/tHM, or about 213 Nm³/tHM, can be injected into it (IspatGuru 2014). The minimum amount of COG that can be injected into a BF is approximately 30 Nm³/tHM. There are very few demonstrations of COG injection in BFs. Therefore, in this study, we considered the injection of the bare minimum quantity of COG, which replaces 14 kg coke/tHM. By considering the minimum possible injection of COG, we also minimise any risks associated with the co-injection of alternative fuels. This application of COG has an abatement cost of -USD 87/tCO_2 to USD 4/tCO_2, at an injection rate of 30 Nm³/tcs or 43 per cent of total COG use. The low end of the abatement cost has been estimated in a scenario where coal-based thermal power plants offset the reduction in COG power generation. For the median scenario, RE power has been used to offset COG power production. For the high-end scenario, grid power replaces COG power generation. This has been summarised in Table 2.

COG can also be used as a DRI fuel if the presence of unsaturated hydrocarbons, tars, methane, and other sulphur compounds is eliminated in the gas stream through pre-processing mechanisms (Midrex Technologies, n.d.). If the entire COG produced per tHM is used as a DRI fuel, and the DRI is subsequently used for steelmaking in a BOF, all the scenarios assessed have a negative MAC in the range of -USD 119/tCO_2 to -USD 48/tCO_2, as shown in Table 2. This suggests that the abatement cost is the lowest in a scenario where coal-based TPP is used to offset COG power generation. For the median scenario, grid power has been used. For the high-end scenario, RE power has been used.

Table 2 **Using COG for producing DRI in a shaft furnace has one of the lowest abatement costs**

Sr. No.	Process	Amount of COG Nm³/tcs (% of net production)	CO_2 mitigated (kg CO_2/tcs)	Cost of abatement (USD/tCO_2)
1	**Captive power use**			
	Use of COG to offset captive power demand	69 (100)	106	-29
2	**Partial use of COG for BF injection**			
a)	Use of coal-based TPP to meet captive power demand	30 (43)	19	-87
b)	Use of grid power to meet captive power demand		36	4.43
c)	Use of RE to meet captive power demand		61	2.57
3	**Using entire COG for producing DRI in shaft furnace; DRI used in BOF**			
a)	Use of coal-based TPP to meet captive power demand	69 (100)	89	-199
b)	Use of grid power to meet captive power demand		166	-58
c)	Use of RE to meet captive power demand		202	-48

Sr. No.	Process	Amount of COG Nm^3/tcs (% of net production)	CO_2 mitigated (kg CO_2/tcs)	Cost of abatement (USD/tCO_2)
4	**Using entire COG for producing DRI in shaft furnace; DRI used in EAF**			
a)	Use of coal-based TPP to meet captive power demand	69 (100)	49	-108
b)	Use of grid power to meet captive power demand		121	9
c)	Use of RE to meet captive power demand		232	5

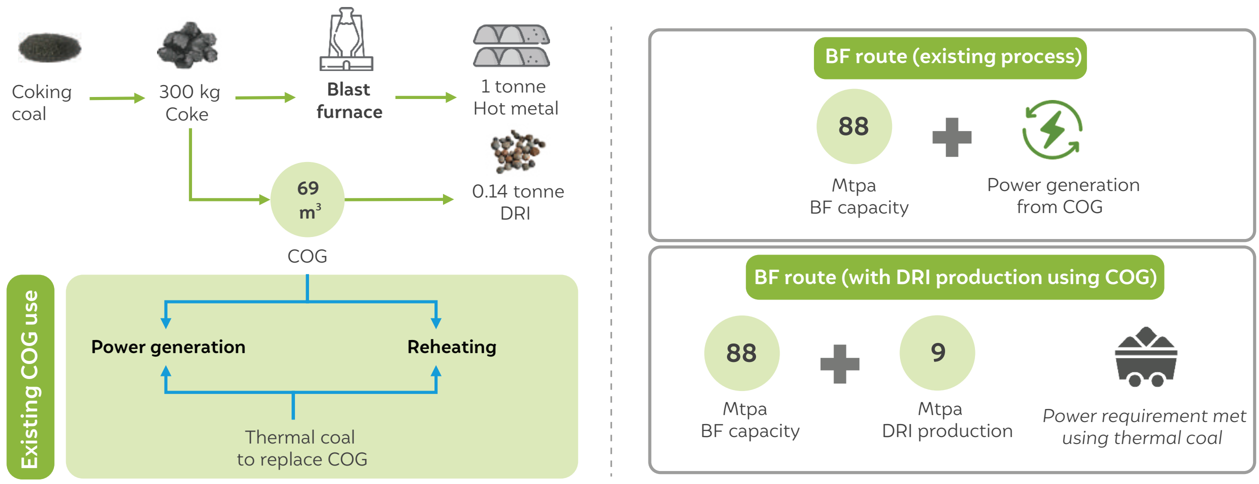
Source: Authors' analysis

As shown in Figure 28, traditionally, the COG produced in BF plants is used solely for power generation. Alternatively, if the DRI produced in the shaft furnace is used for steelmaking in an EAF, the range of abatement costs in different scenarios is estimated to be slightly higher due to the additional CAPEX of the EAF unit as well as the corresponding power requirement. For the scenarios described in this section, the abatement costs vary from -USD 108/tCO_2 to USD 9/tCO_2. While the cost of mitigation for using the COG for DRI production in a shaft furnace and, subsequently, using it in an EAF is approximately -USD 108/tCO_2, it abates merely 49 kg CO_2/tcs in emissions. Nevertheless, our assessment indicates that the best use of COG is to produce DRI.

India can potentially install 9 Mtpa of shaft furnaces for DRI production using COG. However, there are challenges to this. Of the existing 88 Mtpa of BF capacity, the plant capacities vary from 0.01 Mtpa to 12 Mtpa. The median hot metal production capacity in India is 0.54 Mtpa. In an alternative scenario, where COG is used as DRI fuel, an additional 0.001 Mtpa DRI can be produced in the smallest plant, 0.054 Mtpa in the median plant, and 1.27 Mtpa in the largest plant. The commercial-scale DRI plants have a capacity of at least 0.5 Mtpa to 0.8 Mtpa. This demonstrates that while India is a prospective market for shaft furnaces, OEMs must develop modular shaft furnaces, which use COG as a fuel, for successful adoption.

The use of COG for DRI production will also need policy support. The government should ensure reliable access to open access–based RE to encourage ISPs to move away from captive TPP and free up COG volumes for usage in shaft furnaces.

Figure 28 **9 Mtpa of additional DRI can be produced from India's existing BF capacity of 88 Mtpa**

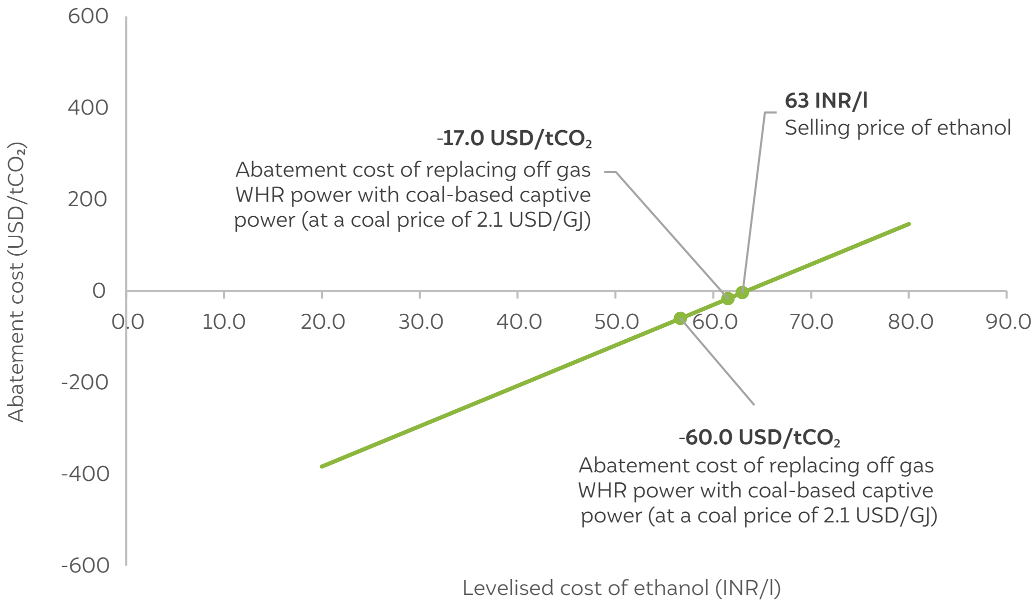


Source: Authors' analysis

Similar to COG, the BF top gas also has competing uses. It can be recycled into the BF by way of top gas recycling. It can be used for captive power generation and, because it is rich in carbon monoxide, it can be used for producing bioethanol as well. Today, almost the entire volume of top gas produced in steel plants is used either to meet process heat demand or for captive power generation. However, top gas–recycling has challenges. For instance, since nitrogen and carbon monoxide have similar molecular weights, it is difficult to separate in the process stream; and this leads to nitrogen accumulation in the BF. Due to such reasons, we did not consider it as an option for decarbonisation.

The only other option available for using BF top gas is producing bioethanol through gas fermentation or any other technology. Figure 29 shows the abatement cost of ethanol production using CO-rich BF top gas as a function of the levelised cost of ethanol production. The cost of CO_2 abatement has been obtained by assuming that producing one tonne of ethanol would abate 1.91 tonnes of CO_2 and that the selling price of bioethanol should be INR 63.45/litre to make it a competitive alternative (Press Trust of India 2021). The capital cost component of gas fermentation technology is about INR 15–25/litre (ABC Techno Labs India n.d.). Therefore, we do not show the cost of CO_2 mitigation for a bioethanol cost lower than INR 20/litre. If the levelised cost of ethanol is in the price range of roughly INR 20–63/litre, using top gas to produce bioethanol is preferred over using it for process heat demand or captive power generation. The abatement cost of replacing coal in CPP is approximately -USD 17/CO_2 at a thermal coal cost of USD 2.1/GJ. If the cost of thermal coal increases to USD 6/GJ, then the abatement cost further reduces to -USD 60/tCO_2. The exact breakeven price depends on the cost of thermal coal. If thermal coal is expensive, then the breakeven cost of bioethanol is lower and vice versa.

Figure 29 Utilising top gas for captive power plants has a lower cost of abatement than producing bioethanol



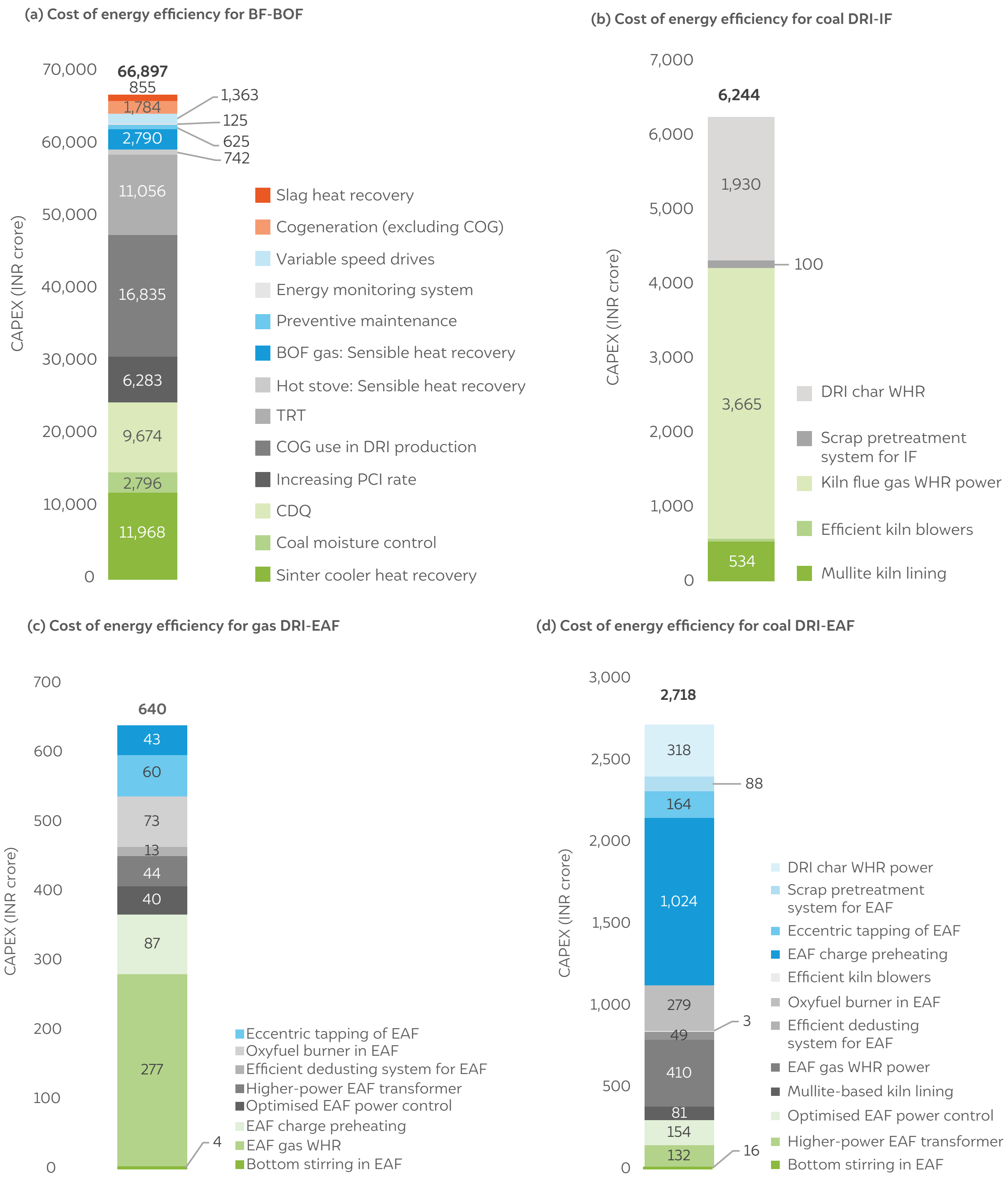
Source: Authors' analysis

5.5 Investment sizing the net-zero transition in the steel industry

Figures 30 (a)–(d) show the capital expenditure for deploying EE measures across the different steelmaking routes. For simplicity of presentation, we accounted for the CAPEX for the hot metal used as part of the input charge mix only in the BF route and not in other pathways that also use it. Since the BF-BOF process is the most mature and most common steelmaking route, globally, there have been significant advancements in the availability of energy-efficiency technologies. As seen in Figure 30(a), the cost of adopting all the EE measures for BF-BOF would add up to over USD 9 billion (INR 67 thousand crore). The major portion of this cost can be attributed to technologies such as BOF gas sensible recovery, cogeneration, and slag heat recovery. The technology for heat recovery from steel slag has not been installed in India yet, although steel plants abroad are utilising the heat from slag for other purposes, such as preheating blast air (Fleischanderl, Neuhold, and Fenzl 2018).

For coal DRI-IF, significant CAPEX investment is needed for WHR from kiln off-gas and char. Figure 30(b) shows the capital expenditure for deploying energy efficiency measures for the coal DRI-IF process. The cumulative CAPEX amounts to USD 833 million (INR 6,224 crore), a significant portion of which is for waste heat recovery from flue gases and char for power generation. Compared to BF-BOF, the share of CAPEX for WHR from kiln flue gases and char in coal DRI-IF is significantly higher due to a lack of other energy efficiency measures for the process. This is primarily because the rotary kiln process used for coal DRI production is used in India predominantly to utilise the lower grades of coal available domestically. As such, there is little scope for significant improvements in energy efficiency for this technology.

Figure 30 **Deploying all possible energy efficiency measures will cost more than INR 75,000 crore**



Source: Authors' analysis based on JISF (n.d.) and US EPA (2012)

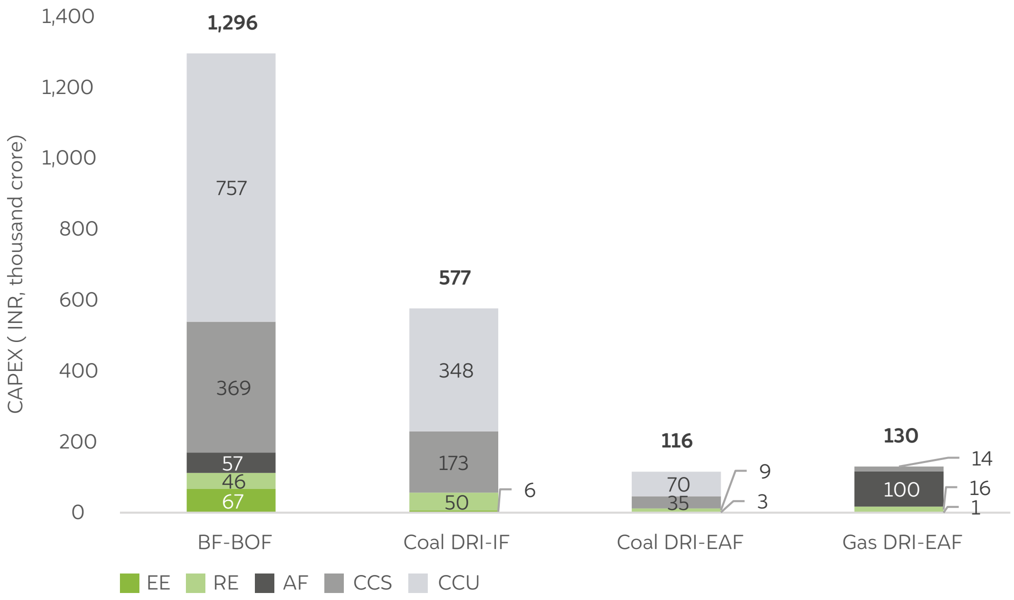
The gas DRI-EAF pathway would require the least CAPEX to transition to net-zero steelmaking at USD 85 million (INR 640 crore) as shown in Figure 30(c). This is because there is little capacity for gas DRI-EAF in the country. It should be noted that in this analysis, we have only considered EE measures for the EAF steel production process and not for the DRI production in the shaft furnace, as no major efficiency measures can be retrofitted in that process.

Figure 30(d) represents the CAPEX requirement for different EE measures for the coal DRI-EAF process. The total CAPEX requirement here is approximately USD 362 million (INR 2,718 crore), of which a third is due to EAF charge preheating. This is followed by WHR power generation from DRI kiln char and EAF off-gases.

Figure 31 summarises the CAPEX requirement for each steelmaking pathway across all decarbonisation measures, including energy efficiency, RE power use, alternative fuels, and carbon management measures. Across all pathways, except gas DRI-EAF, the CAPEX for CCS and CCU make up a significant share of the total. In the case of CCU, a large share of the CAPEX is required for setting up CO_2 capture plants, a methanol conversion facility, and a hydrogen production unit that provides a steady stream of hydrogen required for methanol production. Similarly, the CAPEX for CCS includes the significant cost of a CO_2 capture plant alongside the cost of building dedicated pipelines that transport CO_2 from generation points (steel plants in this case) to storage locations, and the cost of sequestering the transported CO_2 in geological formations.

The CAPEX represented here for alternative fuels denotes the cost of electrolysers and the RE plants of the required capacity. Other decarbonisation measures, such as RE and EE, purely represent the CAPEX of the infrastructure required to implement them. The CAPEX for achieving net-zero production in the BF-BOF process is the highest at USD 173 billion (INR 12.96 lakh crore), followed by the coal DRI-IF process, which requires a total CAPEX of USD 77 billion (INR 5.77 lakh crore) to achieve net-zero emissions. The coal DRI-EAF process requires significantly lower CAPEX to decarbonise at USD 15.4 billion (INR 1.16 lakh crore), while the gas DRI-EAF process, which has the lowest production capacity amongst all steelmaking routes, requires USD 17.3 billion (INR 1.30 lakh crore) of CAPEX to achieve net-zero emissions. The stark difference between the CAPEX requirement for BF-BOF and the rest is that the former is the dominant steelmaking process in India today. Nevertheless, achieving near-zero in the steel sector will need an investment of USD 283 billion (INR 21.2 lakh crore). However, if the cost of green hydrogen decreases to USD 1/kg, then the total CAPEX requirement for achieving near-zero emissions will decrease to USD 182 billion (INR 13.6 lakh crore) due to a significant decrease in the cost of CCU. If the industry chooses to decarbonise by using only CCS, then the investment requirement is USD 197 billion (INR 14.8 lakh crore).

Figure 31 **Achieving net-zero emissions in the steel sector will need an investment of INR 2,119 thousand crore**



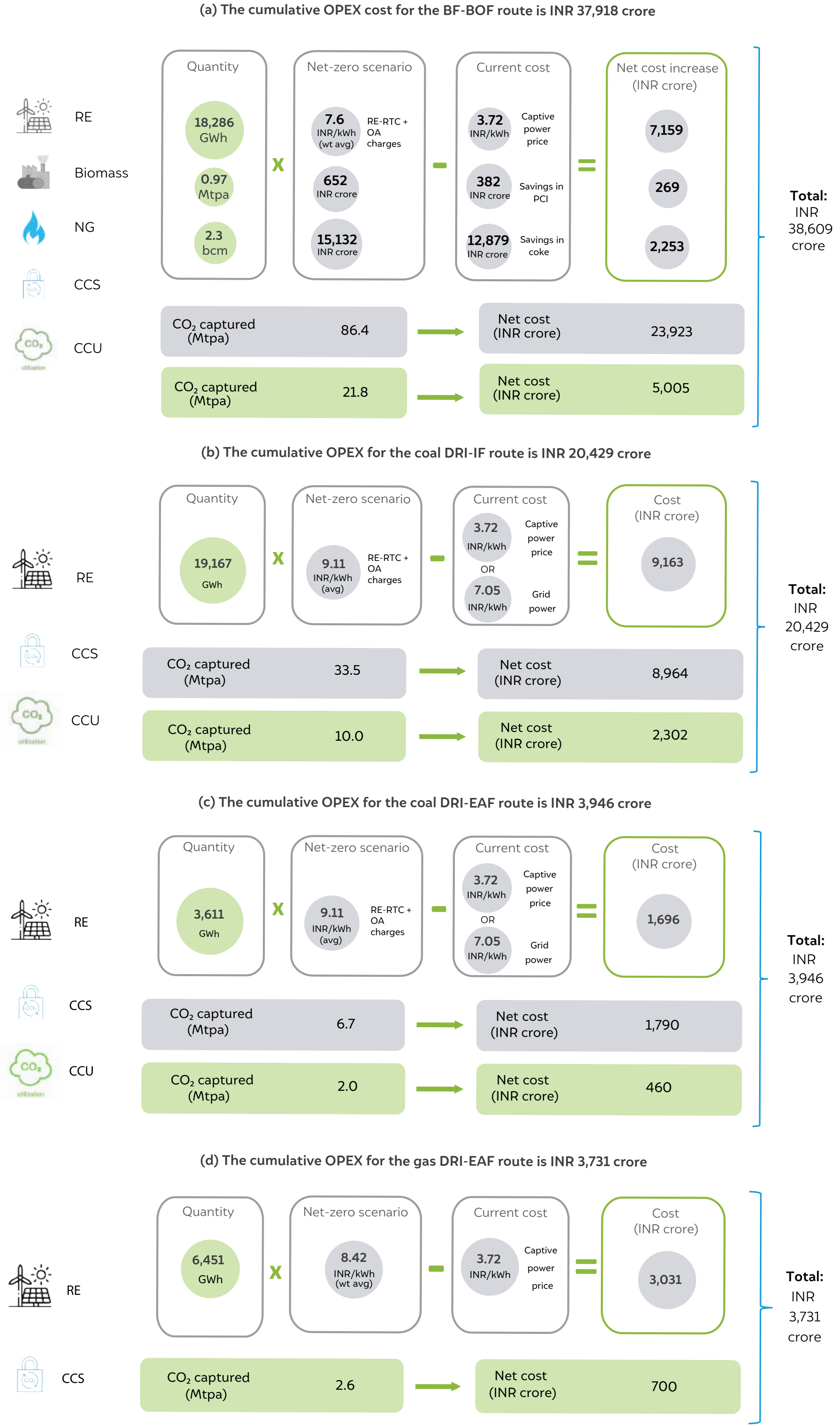
Source: Authors' analysis based on JISF (n.d.) and US EPA (2012)

Figures 32 (a)–(d) illustrate the quantity and the corresponding changes in the yearly operational costs for steelmaking across different pathways in a net-zero scenario. The adoption of carbon mitigation measures in the BF-BOF process results in the largest net increase in OPEX by USD 5.1 billion (INR 38,609 crore). For the coal DRI-IF process, the net increase is USD 2.7 billion (INR 20,429 crore). The coal DRI-EAF process requires an additional USD 526 million (INR 3,946 crore). The gas DRI process requires an additional USD 497 million (INR 3,731 crore) in a net-zero scenario.

In the case of BF-BOF and gas DRI-EAF, the increase in OPEX due to the use of RE power represents purely the open access charges that have to be borne by the manufacturer. However, in the case of coal DRI-IF/EAF steelmaking, a large share of smaller units procure power from the grid while the larger units use captive power. Therefore, the increase in OPEX due to the open access charges levied on RE power depends on their earlier usage, that is, captive or grid power.

The use of alternative fuels in place of conventional fossil fuels also adds to the increase in OPEX. Further, the deployment of CCS and CCU includes the cost of transporting CO_2 through pipelines as well as other auxiliary operating costs associated with power consumption (Mukherjee and Chatterjee 2022; Srinivasan et al. 2021). It should be noted that replacing natural gas with hydrogen injections in the BF for the BF-BOF process and in the shaft furnace for the gas DRI-EAF process also incurs OPEX. However, the CAPEX contributes more significantly to the cost of hydrogen. Per our CAPEX estimation, the net cost increase to replace conventional fossil fuels would be minimal. Therefore, they have not been represented in Figure 32.

Figure 32 The OPEX cost to decarbonise the BF-BOF process is the highest



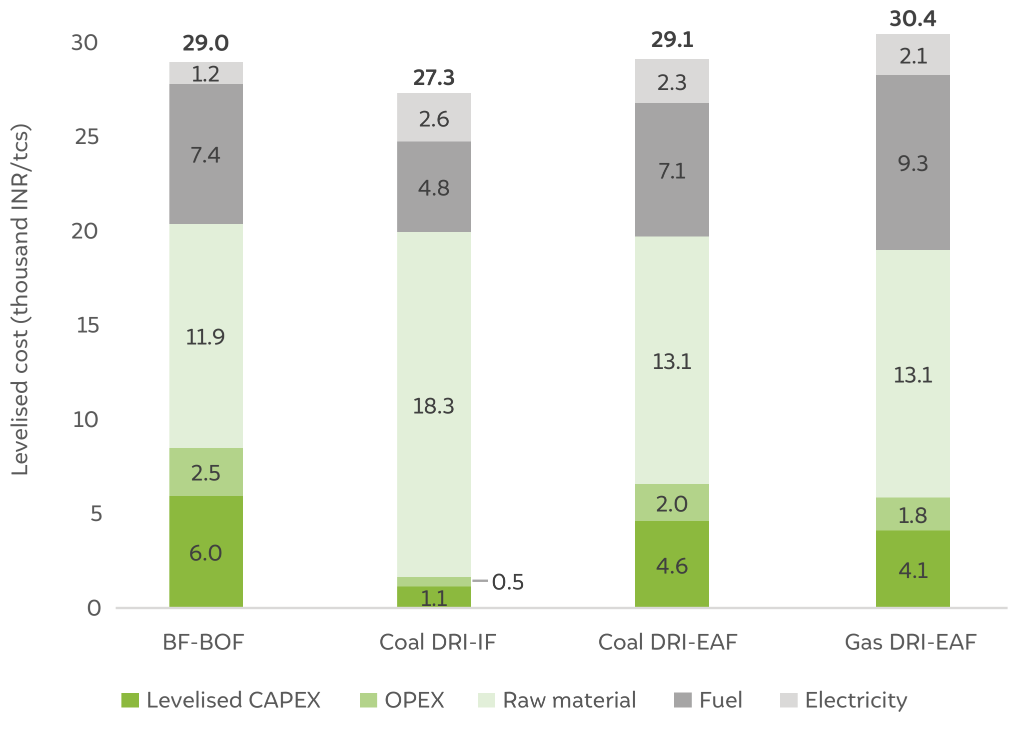
Source: Authors' analysis based on JISF (n.d.) and US EPA (2012)

5.6 Effect of decarbonisation on the cost of producing steel

The adoption of carbon mitigation technologies and pathways will affect the cost of producing steel due to the requirement of additional CAPEX and OPEX. The increase in cost would depend on the cost of CO_2 mitigation across different production pathways and their associated emission intensities. To estimate the change in production cost with respect to the emission intensity, we first established the base case by calculating the levelised cost of steel (LCOS) for each of the steelmaking pathways by considering the annualised CAPEX, OPEX, raw material, fuel, and electricity costs for each production pathway. This has been represented in Figure 33. The raw materials and fuel costs contribute significantly to the overall levelised cost. It should be noted that we have assumed annualised CAPEX over 20 years for a new plant. In reality, DRI plants, especially, may recover their CAPEX in less than 10 years.

The price of coal DRI-IF is relatively lower due to its lower CAPEX compared to other options. However, the cost of raw materials used in this process is higher due to the high share of scrap (39 per cent). The cost of coal DRI-EAF is comparable to BF-BOF, given that the EAF charge consists of 62 per cent of hot metal, 26 per cent of DRI, and 12 per cent of scrap. Gas DRI-EAF has the highest cost primarily because of the high price of natural gas compared to coal. The gas DRI shaft furnace is also more CAPEX-intensive than equivalently sized coal DRI plants.

Figure 33 The levelised cost of steel produced through the gas DRI-EAF route is the highest

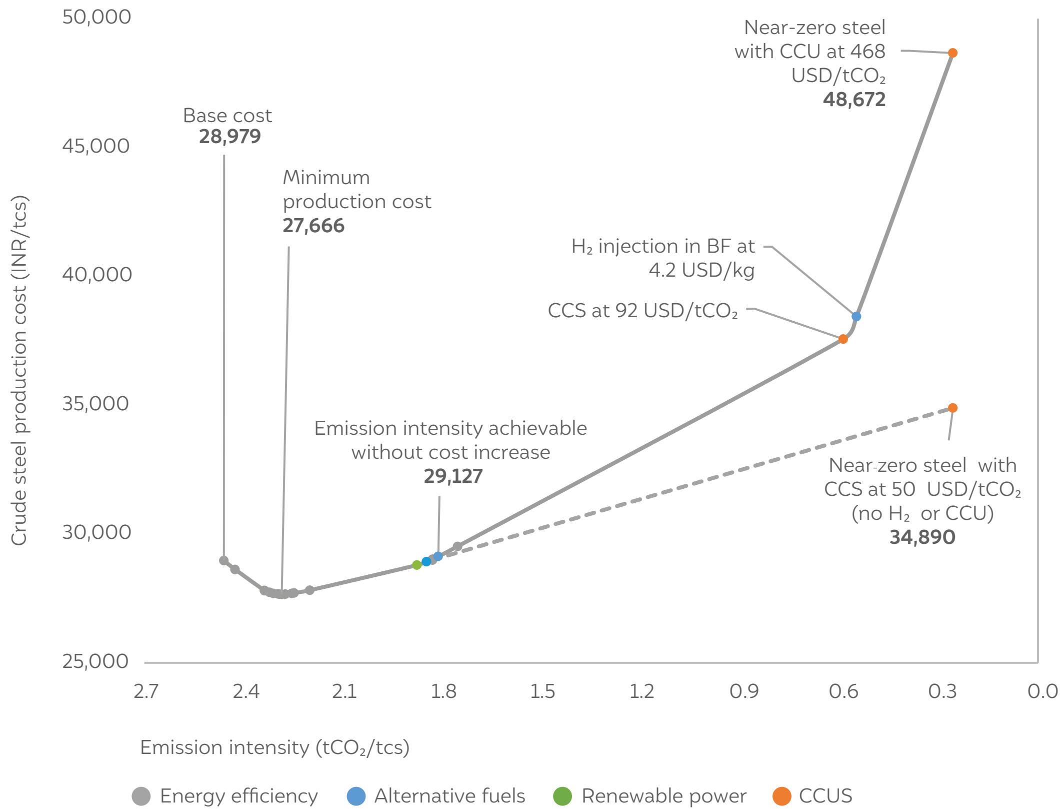


Source: Authors' analysis

Figures 34–37 illustrate the change in the price of steel with varying emission intensity across different production pathways. For the BF-BOF process, Figure 34 shows that the cost of steel reduces by 5 per cent while achieving a 7 per cent reduction in emission intensity, primarily due to the deployment of EE measures. At the lowest production cost, the emission intensity of steel is 2.29 tCO_2/tcs. If it is reduced beyond this, then the cost of producing steel will increase. However, our analysis shows that the BF-BOF process can achieve an emission intensity of 1.84 tCO_2/tcs without any increase in production costs. If COG is not used for producing DRI but is used in reheating furnaces and captive power plants, then the production cost breaks even at 1.94 tonnes CO2/tcs.

The gains obtained by adopting EE measures partially offset the increase in cost due to the uptake of renewable energy and alternative fuels. However, if the emission intensity needs to be reduced below 1.84 tCO_2/tcs, then there is a steep increase in the cost of steel due to the high cost of CO_2 abatement associated with CCS, green hydrogen, and CCU. In an alternative scenario (shown in green on the graph in Figure 27 (a)), if the cost of abatement for CCS reduces to USD 50/tCO_2 and steel plants do not have challenges related to the right-of-way for laying CO_2 pipelines, then CCS will be preferred over technologies such as slag heat recovery and TRT. In such a scenario, the near-zero steel would have only a 20 per cent premium. It is, therefore, imperative that the government focus on creating a CCS ecosystem in the country to achieve long-term decarbonisation targets.

Figure 34 On average, a 25% reduction in emissions is possible without any price increase for steel produced by the BF-BOF route

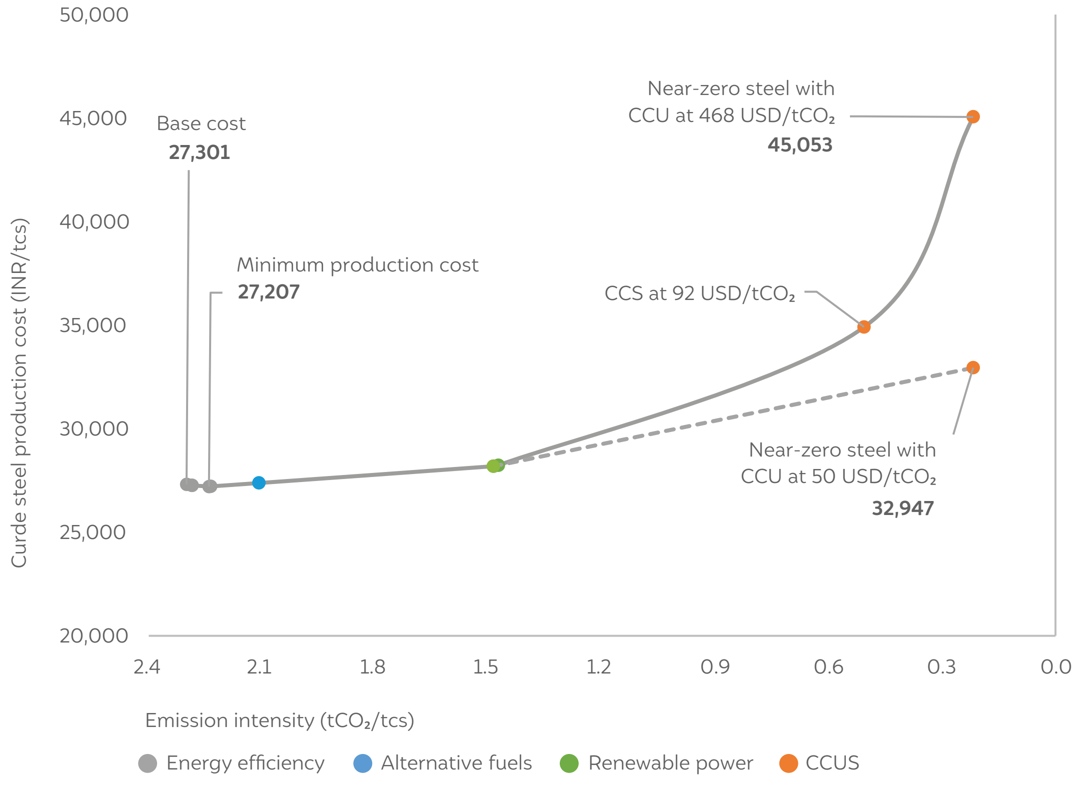


Source: Authors' analysis

Figure 35 shows the change in the cost of producing crude steel with emission intensity for the coal DRI-IF route. Compared with the BF-BOF pathway, initially, there is no significant decrease in the cost of steel with emission intensity, as there are very few energy-efficient technologies for the process. Further, the cost of steel increases steeply with a decrease in emission intensity, primarily due to the higher mitigation costs associated with renewable energy, CCS, and CCU. In the base case, the near-zero emissions steel is 65 per cent more expensive compared to a scenario where steel has an emission intensity of 2.3 tCO_2/tcs. If the

CCS cost is reduced to USD 50/tCO_2, and right-of-way is not an issue, then the cost of steel increases by only 21 per cent, compared with the base case.

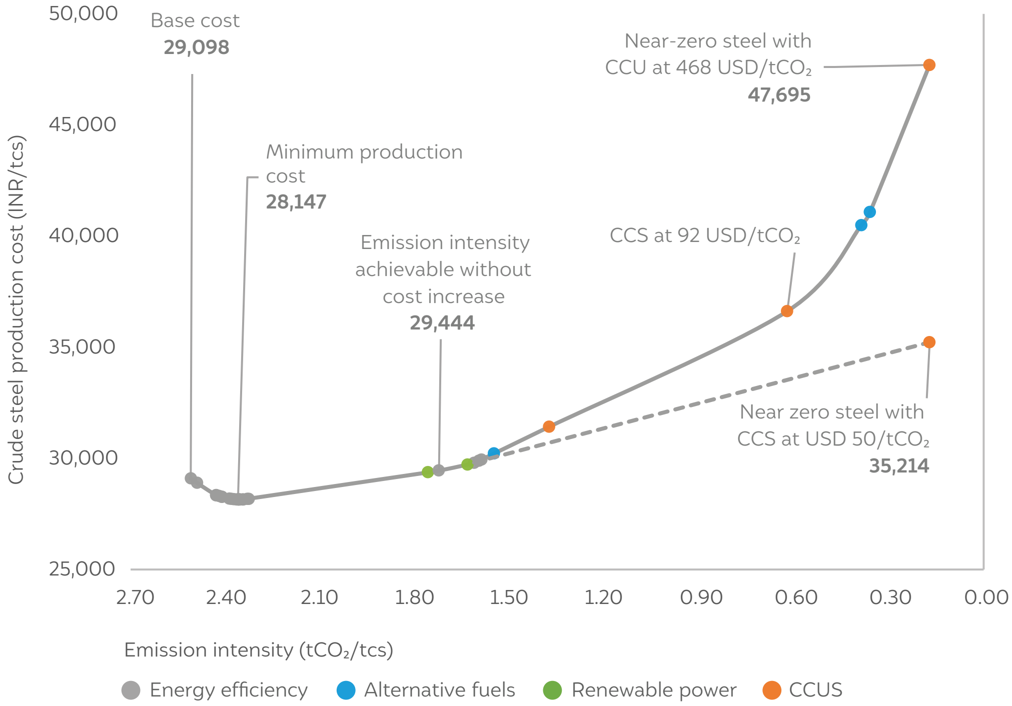
Figure 35 On average, an 8% reduction in emissions is possible without any price increase for steel produced using the coal DRI-IF route



Source: Authors' analysis

The coal DRI-EAF process uses 62 per cent hot metal, 12 per cent scrap, and only 26 per cent DRI. Therefore, the curve for change in production cost with emission intensity is similar to the BF-BOF pathway. Figure 36 shows that the emission intensity of steel can be reduced by 6 per cent while achieving a 3 per cent reduction in production cost, primarily due to the deployment of energy efficiency technologies in BFs and EAF units. Beyond this point, although there is a steep increase in the cost of producing steel, our results show that a 30 per cent reduction in emission intensity can be achieved without any change in production costs. In the base case, we expect that the near-zero steel will be 65 per cent more expensive than the steel produced today. However, with the deployment of CCS at USD 50/tCO_2, the cost of steel is expected to increase by only 20 per cent.

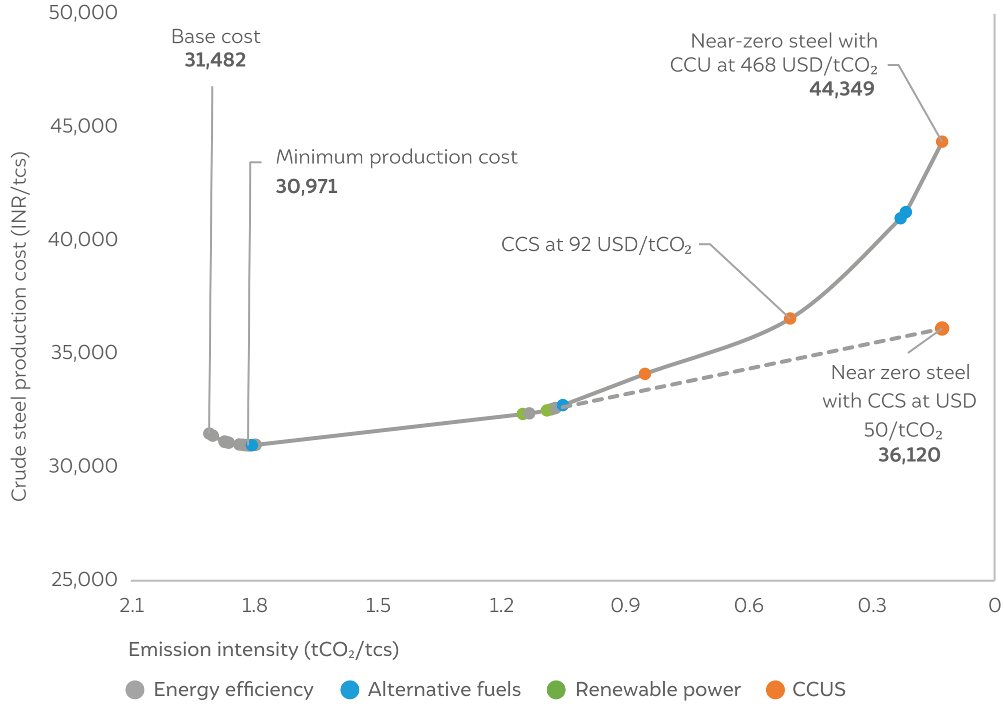
Figure 36 **On average, a 30% reduction in emission is possible without any price increase for steel produced by the coal DRI-EAF route**



Source: Authors' analysis

The gas DRI-EAF route uses 29 per cent hot metal, 12 per cent scrap, and 58 per cent DRI. Our analysis indicates that the cost of producing steel is reduced by 1.2 per cent due to the adoption of all EE measures, especially for EAF units. Further, as shown in Figure 37, a 17 per cent reduction in emission intensity can be achieved without any increase in the cost of production. In the base case, the near-zero emissions steel is expected to cost 41 per cent more than conventional steel. However, if CCS can be deployed at USD 50/tCO_2 across all steel plants, then the cost of steel increases by only 14 per cent over current production costs.

Figure 37 On average, a 20% reduction in emissions is possible without any price increase for steel produced using the gas DRI-EAF route



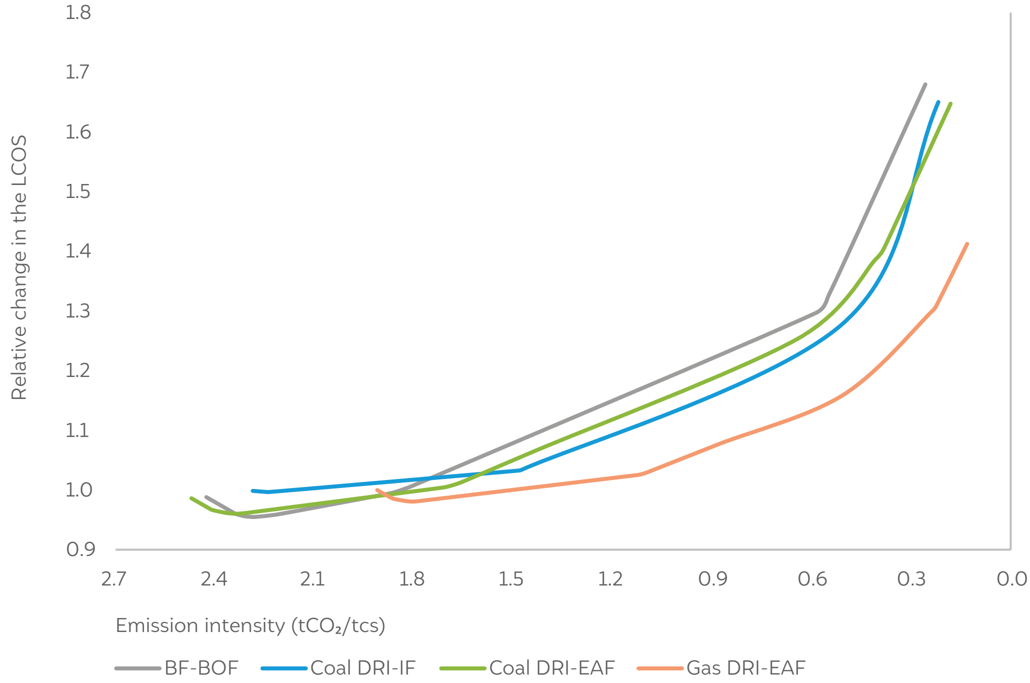
Source: Authors' analysis

While the absolute change in production cost based on the base case established in Figure 33 is discussed in Figures 34–37, it is important to also assess the change in relative costing given the varying extent of decarbonisation possible through various levers across different production processes. The relative change in production cost will impact the market share of various routes to steel production at varying emission intensities.

Figure 38 shows the change in the relative production cost of steel with respect to emission intensity across the four process options discussed in our report. For our analysis, irrespective of the actual production costs, we normalised the production cost across all processes at the same level to assess the impact of decarbonisation. The starting point for emission intensity represents the actual emission intensity for a particular route, which has been established in Section 1. For achieving the same emission intensity of 2.1 tCO_2/tcs, the cost of producing steel through the BF-BOF, coal DRI-IF, and coal DRI-EAF processes is expected to reduce by 13 per cent, 0.5 per cent, and 15 per cent, respectively.

However, for the BF-BOF and coal DRI-EAF routes, a higher amount of emission reduction can be achieved without increasing the price of steel. This implies that, in the initial phase, the decarbonisation of the coal DRI-IF sector will be significantly more expensive than the BF-BOF and coal DRI-EAF units. This is primarily because the coal DRI-IF process has limited gains from energy efficiency, whereas the BF-BOF and coal DRI-EAF processes have significant gains, possibly from the deployment of EE measures that reduce both the cost of producing steel as well as emission intensity from steel.

Figure 38 Comparison of increases in steel price as a function of emission intensity



Source: Authors' analysis

Below an emission intensity of 2.1 tCO_2/tcs, the cost of producing steel using the BF-BOF and coal DRI-EAF route increases faster compared with the coal DRI-IF and gas DRI-EAF routes. This is primarily due to the higher cost of mitigation for using alternative fuels, energy efficiency technologies such as CDQ and TRT, and renewable energy. Compared to the BF-BOF pathway, a significant reduction in emission intensity can be achieved just by switching to renewable energy in the DRI-EAF/IF routes. Therefore, the increase in the cost of steel is less steep in comparison with the BF-BOF pathway.

The gas DRI-EAF process has less of an increase in cost due to its lower power consumption compared to coal DRI-IF/EAF (due to the hot charging of DRI) and lower open access charges in states having gas-based capacity. However, for an emission intensity lower than 0.8 tCO_2/tcs, the cost of production increases steeply even for the gas DRI-EAF route due to the high mitigation cost associated with CCS and green hydrogen.

Below an emission intensity of 1.8 tCO_2/tcs, the cost of coal-based processes increases simultaneously. For emission intensity lower than 0.6 tCO_2/tcs, the cost of the BF-BOF process increases as these plants switch to CCU, which has a higher cost of abatement due to right-of-way issues related to setting up CO_2 pipelines for CCS.

6. Sensitivity analysis


Image: Sabarish Elango/CEEW

In the base case, we considered the long-term stable prices of fossil fuels to ensure that the cost of transition was not underestimated. However, the cost of coal and natural gas increased significantly in FY 2022–23 due to increased demand after the pandemic and changing geopolitical situations. The sensitivity analysis captures the impact of the higher prices of fossil fuels on the MAC curve. The MAC curves are also representative of the impact that a carbon tax on fuels will have. The sensitivity analysis is based on the assumptions given in Table 3, which were derived from industry inputs and import prices reported by the Department of Commerce (2023). We assumed a 30 per cent markup over the import prices to cover inland logistic costs.

Table 3 The sensitivity analysis took the high post-pandemic prices of commodities

Commodity	Base case price	Sensitivity case price	Unit
Imported coal	13,000	15,000	INR/tonne
Domestic coal	6,000	8,000	INR/tonne
Coking coal	13,800	35,000	INR/tonne
Iron ore	6,000	7,000	INR/tonne
Iron ore pellets	7,500	10,000	INR/tonne
Natural gas	11.6	22.0	USD/MMBtu
Green hydrogen	4.2	2.0	USD/kg

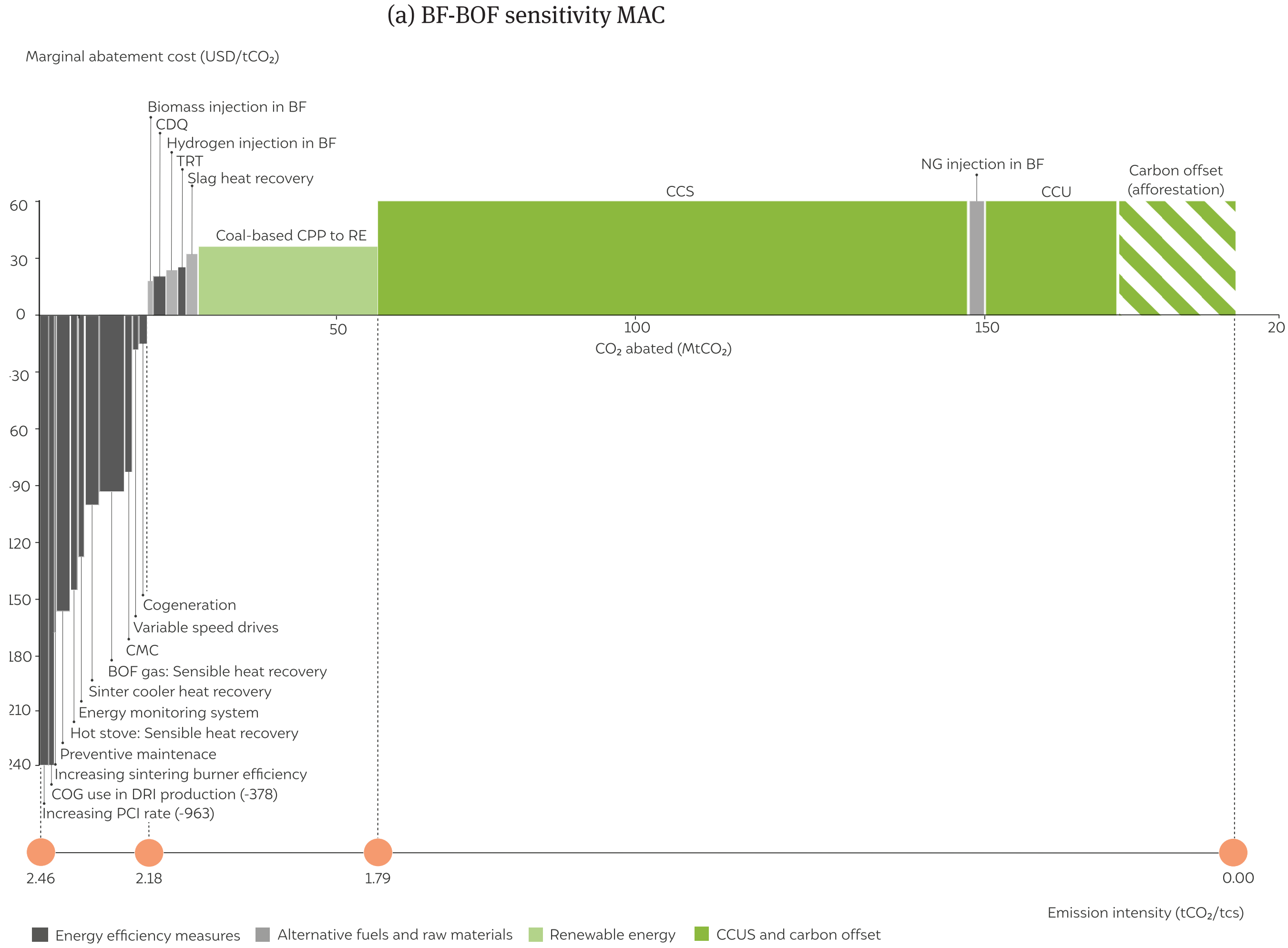
Source: Authors' analysis based on industry inputs and Department of Commerce (2023)

The base case reflects the need for CCU as a decarbonisation lever because the right-of-way for laying CO_2 pipelines is a critical challenge for the steel industry. However, it is expected that in the mid-to-long term, steel plants will have access to natural gas, and consequently, right-of-way for CO_2 pipelines will no longer be a critical challenge for the steel plants. Similarly, the cost of CCS is expected to reduce significantly in the future. In the sensitivity analysis, we considered a CCS cost of USD 50/tCO_2. We also considered a lower green hydrogen price of USD 2/kg to reflect the direction towards creating economies of scale.

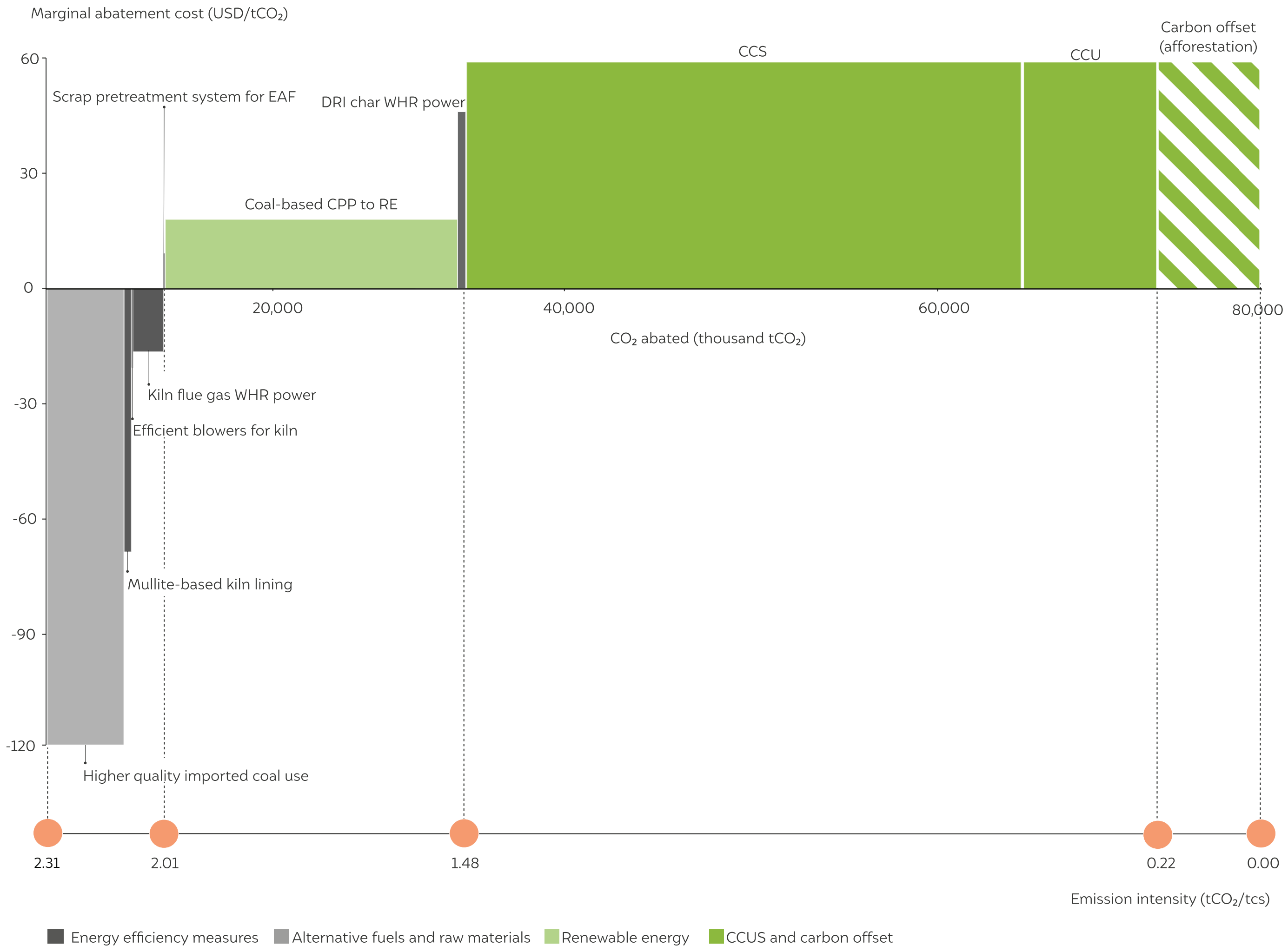
Figures 39 (a)–(d) show the revised MAC curves based on these sensitivity price assumptions. Unlike in the base case, where the pathways with the negative cost of mitigation can reduce the emission intensity only to 2.29 tCO_2/tcs for the BF-BOF route, here, the emission intensity can be reduced to 2.19 tCO_2/tcs.

In the case of coal DRI-IF and coal DRI-EAF, all decarbonisation pathways except slag waste heat recovery and CCS have a positive cost of mitigation. For the gas DRI-EAF pathway, only CCS has a positive cost of mitigation. Due to the cost-competitiveness of green hydrogen at USD 2/kg against natural gas at USD 22/MMBtu, a large share of decarbonisation is possible through fuel transition. When compared with the other routes, the role of CCS and carbon offsets is the smallest in the gas DRI-EAF pathway, demonstrating its more future-proof characteristics.

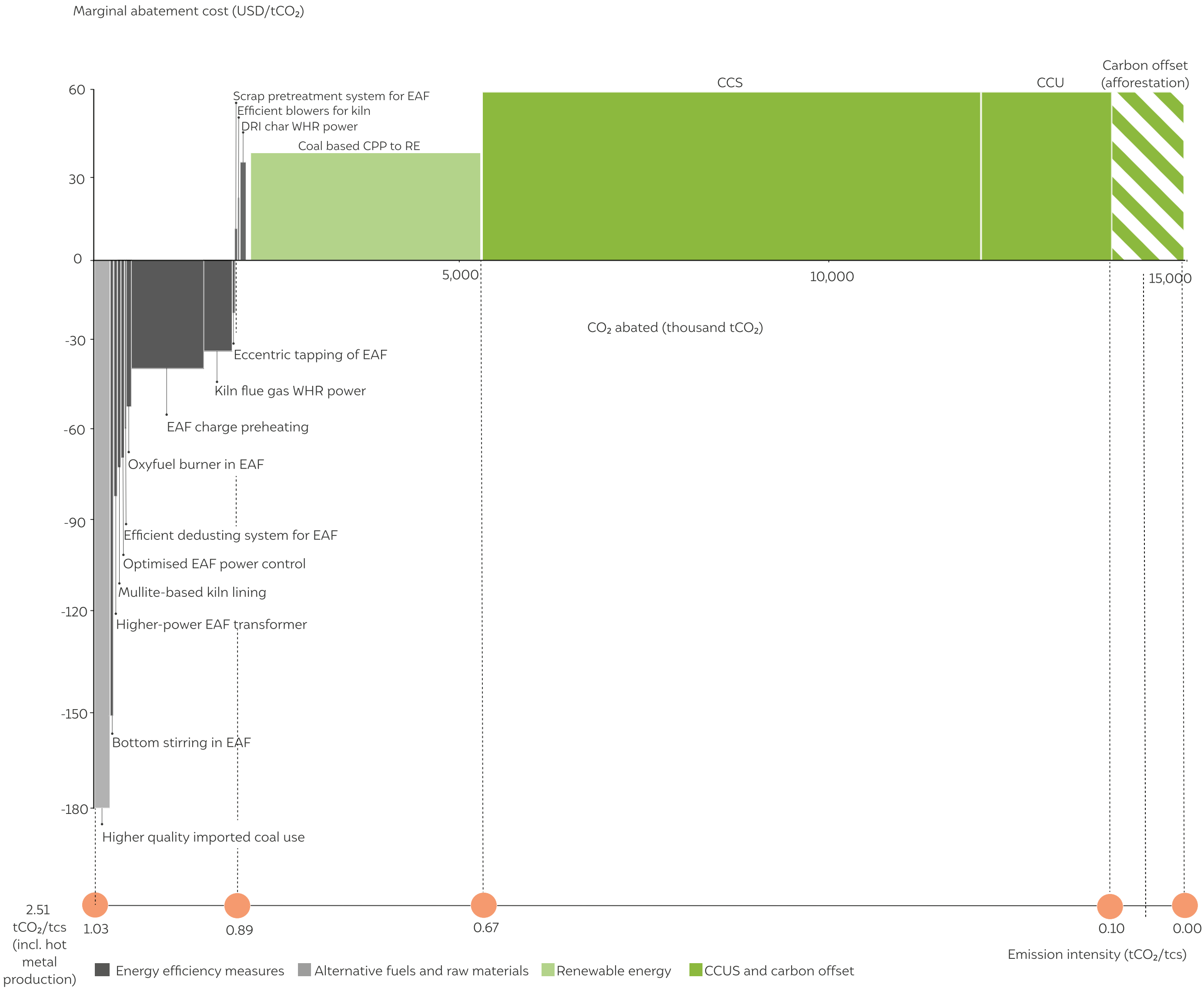
Figure 39 CCS and green hydrogen could become more accessible in the future



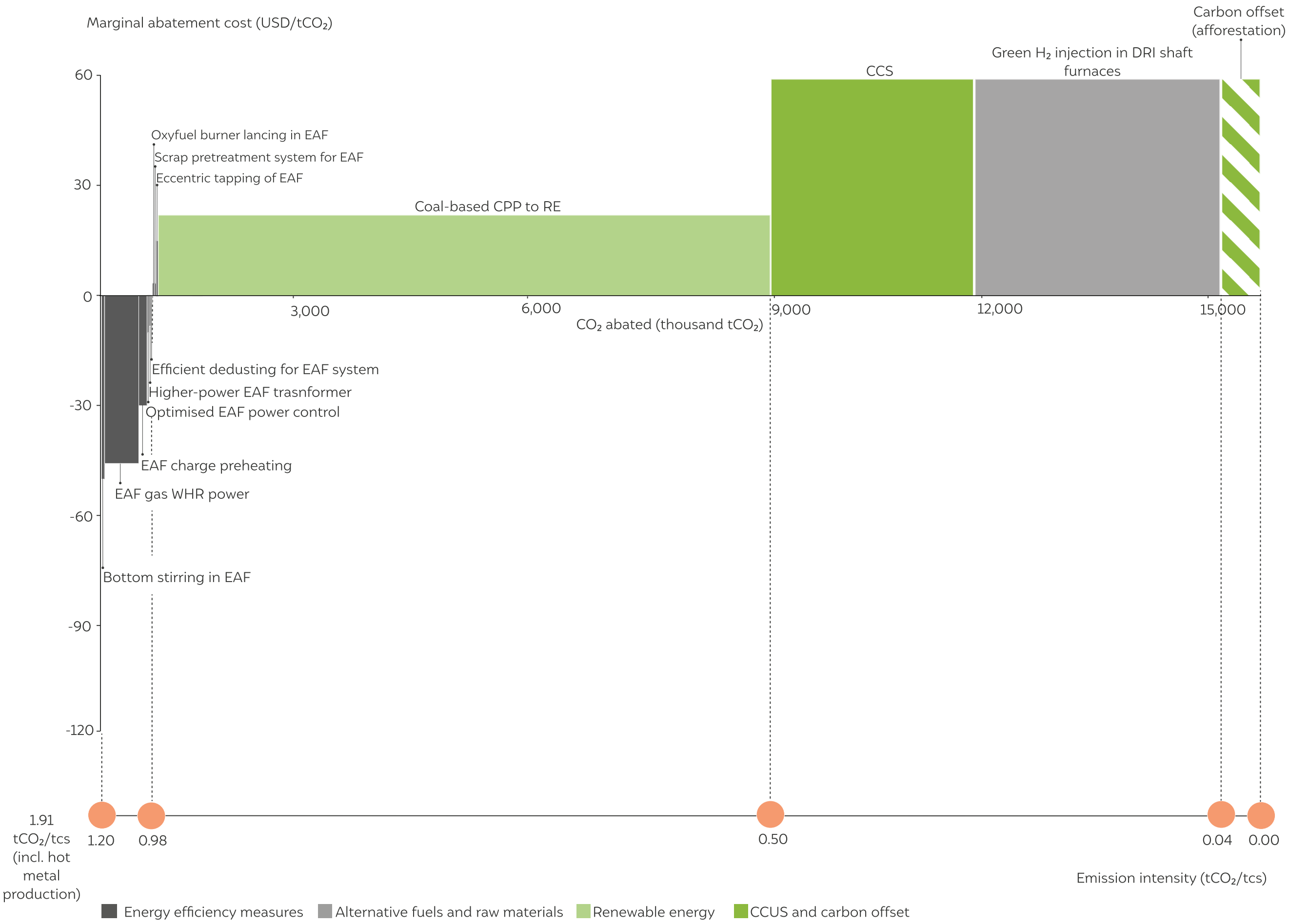
(b) Coal DRI-IF sensitivity MAC



(c) Coal DRI-EAF sensitivity MAC



(d) Gas DRI-EAF sensitivity MAC



Source: Authors' analysis

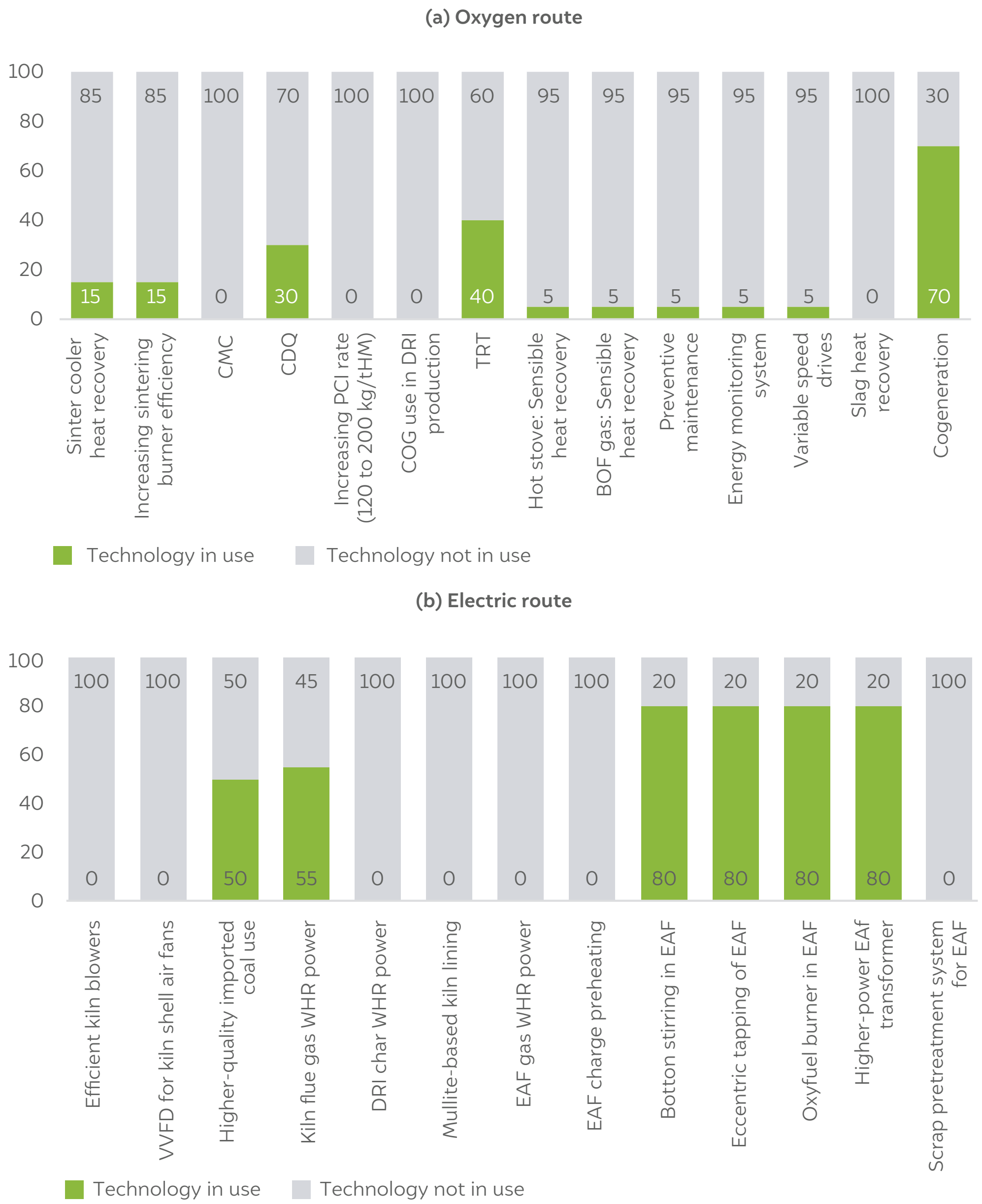
7. Uncertainty and challenges in analysis

Image: Sabarish Elango/CEEW

For the analysis presented in this report, the data regarding material consumption, emissions, and the use of efficient technologies at the plant level were not available in the open domain. We derived the level of penetration of energy efficiency measures, indicated in Figure 40, from various sources, including environmental clearance reports, annual sustainability reports of steel companies, and discussions with industry experts. The report does not consider practical constraints such as lack of space for setting up energy efficiency technologies and variance in gains due to different operating conditions. Additionally, some of the data points, such as coal and power consumption, are national or global averages, which may not adequately reflect the situation across all plants.

Similarly, the cost of energy efficiency technologies, renewable energy, and alternative fuels vary across India. This might significantly impact the capital investments required and the corresponding operating costs of mitigation measures at an individual plant level. Furthermore, plant-level fuel prices for steel plants and captive units were not available, necessitating the use of overarching assumptions for these parameters. Nonetheless, the MAC curve can be updated when plant-level data become available, enabling the development of a strategy for decarbonising the steel industry in India. Additionally, while the MAC curve may not be accurate for every plant in the country, the national-level estimates can be considered robust since the high- and low-end numbers at a plant level should nullify any extreme bias. Finally, the objective of the MAC curve is to inform national (and potentially state) policies for which these estimates are considered adequate.

Figure 40 **Penetration % of energy efficiency technologies is low in the Indian steel industry**



8. Policy recommendations and conclusions

Image: iStock

Our analysis flagged the different technology options available for the abatement of CO_2 emissions and their marginal abatement costs in the steel sector. Our study shows that the emission intensity in the steel sector can be reduced by approximately 10 per cent while also achieving a 1.2 per cent reduction in production costs. It further indicates that an approximately 21 per cent reduction in the emission intensity of steel can be achieved without any increase in production costs across various processes. Based on the MAC curves, we make the following policy recommendations to accelerate decarbonisation in the existing steelmaking capacity.

- **Incentivise the adoption of the best available EE technologies through the Indian Carbon Market:** Energy efficiency as a decarbonisation measure is a low-hanging fruit. All energy efficiency technologies discussed in this study, except slag waste heat recovery, measure TRL 11. Therefore, BEE, along with the Ministry of Steel, should conduct a survey to assess the penetration of various energy efficiency technologies in the steel sector. The energy/emission intensity targets to be set under the Indian Carbon Market regulations should be made higher than the reductions that can be achieved through energy efficiency technologies in each of the sectors. The coverage of the carbon market and future policy mechanisms that regulate energy consumption should also be extended to small-scale industries. State governments should support small-scale rotary kilns with power purchase agreements to ensure the installation of WHRBs. The government should also encourage new business models such as energy service companies for small-scale industries. Further, greenfield investments should be mandated by regional pollution control boards to adopt EE technologies to be eligible for environmental clearances.

The Indian Carbon Market will need to play a significant role in incentivising EE and RE in the steel industry

- **Incentivise RE as it will play a pivotal role in decarbonisation:** As per our estimation, steel plants need 5.9 GW of RTC RE to meet their power demands even after the adoption of energy-efficient technologies. This RTC RE includes wind and solar power capacities (oversized to account for variabilities; see Section 4.2). A major share of steel plants are in states that do not have optimal wind power potential. Therefore, the central government should provide long-term waivers on interstate open access charges for the steel industry. Further, state governments should support the steel industry in decarbonising by waiving or reducing open access charges for renewable power. More central transmission of unit-level connections must be provided to large industries to benefit from waivers on interstate open access charges. State governments should also prioritise giving right-of-way to industries for setting up their evacuation infrastructure for transmitting renewable power. Additionally, green finance must be made accessible for small-scale plants to offset the cost burden they need to bear in terms of open access charges.

- **Shaft furnaces as a means to decarbonise BF-BOF steelmaking:** For adding capacity to blast furnaces, gas DRI production with COG should be prioritised, thereby reducing the demand for natural gas. This approach will aid in reducing coal-based production while promoting the growth of gas-based processes, which are beneficial for transitioning towards the utilisation of green hydrogen.

- **Develop a robust MRV framework to estimate GHG emissions at a process, equipment, and plant level:** The Ministry of Steel should prioritise a robust measurement, reporting, and verification (MRV) framework for emissions monitoring to support the decarbonisation of the steel sector. The advent of carbon pricing makes this critical. The challenges related to MRV have become more important, especially the use of alternative fuels, such as biomass, which will have a significant role to play in the decarbonisation of the sector.

- **Develop a CCS ecosystem in India for full decarbonisation:** Our study shows that ~160 million tonnes of CO_2 have to be abated in the steel industry through the CCS pathway. Therefore, infrastructure and technologies related to CCS must be actively developed and deployed. The Government of India should develop a CCS policy that will lead to the development of an effective CCS ecosystem in India.

- **Formulate favourable policies to build a CCU ecosystem in the country:** CCU will be critical for the steel industry to achieve net-zero. However, CCU applications require green hydrogen, and their relative economics with CCS technology is yet to be proven. Therefore, the next phase of the *National Green Hydrogen Mission* should focus on creating a research and development ecosystem for CCU in India to evaluate its feasibility.
- **Provide access to large volumes of low-cost green finance:** Our analysis estimates that the steel industry will need a capital investment of INR 2,119 thousand crore to achieve net-zero emissions. Further, the industry also needs an extra INR 66,715 crore every year to meet the increased operational costs of decarbonisation. While the big steel players can raise money from the market based on their strong balance sheets, small-scale industries will need new financial solutions to decarbonise. The government must explore policies that enable priority lending and dedicated green bonds for such decarbonisation projects.
- **Build an R&D ecosystem for the steel industry:** There is a critical need for data and evidence generation on decarbonisation in the steel industry, especially concerning the use of alternative fuels. Therefore, pilot studies on green hydrogen injection in blast and shaft furnaces should be prioritised. Research is also needed to assess the potential for injecting alternative fuels in rotary kilns, as there is little research or evidence to support fuel transitions in DRI kilns. A robust R&D ecosystem, including pilot projects for CCUS across all geographies – depleted oil and gas wells and saline and basalt rock formations – and utilisation pathways must be nurtured.

References

ABC Techno Labs India. n.d. *Environmental Impact Assessment for Installation of Ethanol Plant from PSA Off-gases Ex-HGU Using Gas Fermentation Technology at Panipat Refinery, Haryana, of Indian Oil Corporation Limited*. Chennai: ABC Techno Labs India.

Bakshi, Tuli, Hemant Mallya, and Deepak Yadav. 2023. *Assessing India's CO_2 Storage Potential: A Critical Analysis of What Lies Beyond the Theoretical Potential*. New Delhi: Council on Energy, Environment and Water.

Biswas, Tirtha, Deepak Yadav, and Ashish Guhan Baskar. 2020. *A Green Hydrogen Economy for India: Policy and Technology Imperatives to Lower Production Cost*. New Delhi: Council on Energy, Environment and Water.

CEEW Centre for Energy Finance. 2023. *Advanced Open Access Landed Cost Calculator*. Accessed May 28, 2023. https://www.ceew.in/cef/intelligence/tool/open-access-advanced.

Department of Commerce. 2023. "Total Trade: Country-wise Top N Countries." Export-Import Data Bank. Last updated August 28, 2023. https://tradestat.commerce.gov.in/eidb/.

Fleischanderl, Alexander, Robert Neuhold, and Thomas Fenzl. 2018. "Tapping Hot Slag for Energy." *Primetals*, October 1, 2018. https://magazine.primetals.com/2018/10/01/tapping-hot-slag-for-energy/.

GenesisRay Energy. 2022. *Oil and gas database*.

GGGI and CSTEP. 2018. "Harnessing Waste Heat for Power Generation in Karnataka: Policy Note." Accessed June 19, 2023. https://www.cstep.in/drupal/sites/default/files/2018-12/CSTEP_PB_Harnessing_Waste_Heat_for_Power_Generation_in_Karnataka_Jan2016.pdf.

GHG Platform India. n.d. "GHG Emissions Estimates in India, 2018." Emission Estimates. Accessed May 25, 2023. https://www.ghgplatform-india.org/.

IEA. 2022. *CO2 Storage Resources and Their Development*. Paris: International Energy Agency.

———. 2020. *Iron and Steel Technology Roadmap*. Paris: International Energy Agency.

IBM. 2023. *Indian Minerals Yearbook 2021: Iron Ore*. Nagpur: Indian Bureau of Mines, Ministry of Mines.

———. 2011. *Iron and Steel Vision 2020*. Nagpur: Indian Bureau of Mines, Ministry of Mines.

IspatGuru. 2014. "Coke Oven Gas Injection in a Blast Furnace." *IspatGuru.com*, July 19, 2014. https://www.ispatguru.com/coke-oven-gas-injection-in-a-blast-furnace/.

Jin, Peng, Zeyi Jiang, Cheng Bao, Shiyu Hao, and Xinxin Zhang. 2017. "The Energy Consumption and Carbon Emission of the Integrated Steel Mill with Oxygen Blast Furnace." *Resources, Conservation and Recycling* 117(A): 58–65. https://doi.org/10.1016/j.resconrec.2015.07.008.

JPC. 2022b. *Annual Statistics 2021–22*. Kolkata: Joint Plant Committee.

———. 2022a. *The Indian Iron and Steel Database 2021–22*. Kolkata: Joint Plant Committee.

KERC. 2017. "OP No.26/2015." Bengaluru: Karnataka Electricity Regulation Commission. https://kerc.karnataka.gov.in/storage/repo/Dated%2009.11.2017%20-%20OP%2026%20of%202015%20-%20Sunvik%20Steel%20Pvt%20Ltd%20Vs%20KPTCL%20and%20others.pdf.

Midrex Technologies. n.d. "Providing Flexibility for Steelmaking." Uses of DRI. June 28, 2023. https://www.midrex.com/technology/direct-reduced-iron/uses-of-dri/.

Ministry of Steel. 2017. "National Steel Policy 2017." *The Gazette of India*, May 9, 2017. https://steel.gov.in/en/national-steel-policy-nsp-2017.

Morrow III, William R., Ali Hasanbeigi, Jayant Sathaye, and Tengfang Xu. 2014. "Assessment of Energy Efficiency Improvement and CO_2 Emission Reduction Potentials in India's Cement and Iron and Steel Industries." *Journal of Cleaner Production* 65: 131–141. https://doi.org/10.1016/j.jclepro.2013.07.022.

Mukherjee, Atanu, and Saurav Chatterjee. 2022. *Carbon Capture, Utilization and Storage (CCUS): Policy Framework and its Deployment Mechanism in India*. New Delhi: NITI Aayog.

Nduagu, Experience I., Deepak Yadav, Nishant Bhardwaj, Sabarish Elango, Tirtha Biswas, Rangan Banerjee, and Srinivasan Rajagopalan. 2022. "Comparative Life Cycle Assessment of Natural Gas and Coal-Based Directly Reduced Iron (DRI) Production." *Journal of Cleaner Production*, 347: 131196. https://doi.org/10.1016/j.jclepro.2022.131196

PFC. 2022. *Report on Performance of Power Utilities 2020–21*. New Delhi: Power Finance Corporation Ltd.

PIB. 2023. "Cabinet approves the Scheme titled Viability Gap Funding for Development of Battery Energy Storage Systems (BESS)." Press release, September 6, 2023. Accessed September 25, 2023. https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1955112.

———2022a. "Cabinet Approves India's Updated Nationally Determined Contribution to be Communicated to the United Nations Framework Convention on Climate Change." Press release, August 2, 2022. Accessed June 16, 2023. https://pib.gov.in/PressReleasePage.aspx?PRID=1847813.

———. 2022b. "Indian Steel Industry Reduces its Energy Consumption and Carbon Emissions Substantially with Adoption of Best Available Technologies in Modernisation and Expansions Projects." Press release, February 2, 2022. Accessed June 16, 2023. https://www.pib.gov.in/PressReleasePage.aspx?PRID=1794782.

———. 2021b. "National Statement by Prime Minister Shri Narendra Modi at COP26 Summit in Glasgow." Press release, November 1, 2021. Accessed June 16, 2023. https://pib.gov.in/PressReleasePage.aspx?PRID=1768712.

———. 2021a. "Per Capita Steel Consumption." Press release, March 17, 2021. Accessed June 16, 2023. https://pib.gov.in/PressReleasePage.aspx?PRID=1705404.

———. 2018. "Meeting of National Steel Consumers' Council of Ministry of Steel." Press release, June 29, 2018. Accessed June 16, 2023. https://pib.gov.in/PressReleasePage.aspx?PRID=1537143.

Pistorius, Petrus Christiaan, Jorge Gibson, and Megha Jampani. 2017. "Natural Gas Utilization in Blast Furnace Ironmaking: Tuyère Injection, Shaft Injection, and Prereduction." *The Minerals, Metals & Materials Series*, February 8, 2017, 283–292. https://doi.org/10.1007/978-3-319-51091-0_26.

Press Trust of India. 2021. "Cabinet Approves Ethanol Price Hike by up to 1.47 Per Litre for Mixing in Petrol." *NDTV*, November 10, 2021. https://www.ndtv.com/india-news/cabinet-approves-ethanol-price-hike-by-up-to-rs-1-47-litre-for-mixing-in-petrol-2605624.

———. 2022. "India exports 13.5 MT Finished Steel Worth Rs 1 Lakh Cr in FY22." *The Economic Times*, April 27, 2022. https://economictimes.indiatimes.com/industry/indl-goods/svs/steel/india-exports-13-5-mt-finished-steel-worth-rs-1-lakh-cr-in-fy22/articleshow/91123884.cms?from=mdr.

Ramakrishnan, N. 2018. "Cement Cos See Savings in Captive Power Plants." *The Hindu BusinessLine*, March 12, 2018. https://www.thehindubusinessline.com/economy/cement-cos-see-savings-in-captive-power-plants/article64106091.ece.

ReNew. 2021. "Renew Power Signs India's First Round-The-Clock Renewable Energy PPA" [Press Release]. Accessed June 16, 2023. https://renewpower.in/wp-content/uploads/2021/08/ReNew_Power_PPA_SECI_RTC_V6-NJ.pdf.

Sato, Michitaka, Koichi Takahashi, Taihei Nouchi, and Tatsuro Ariyama. 2015. "Prediction of Next-Generation Ironmaking Process Based on Oxygen Blast Furnace Suitable for CO_2 Mitigation and Energy Flexibility." *ISIJ International* 55 (No. 10): 2105–2114. http://dx.doi.org/10.2355/isijinternational.ISIJINT-2015-264

Selvaraj, Kurinji, and Srish Prakash. 2021. *Why Paddy Stubble Continues to be Burnt in Punjab? Meeting Challenges with Solutions*. New Delhi: Council on Energy, Environment and Water.

Srinivasan, Vivek, Max Temminghoff, Sebastian Charnock, and Anthea Moisi. 2021. *CO_2 Utilisation Roadmap*. Canberra: Commonwealth Scientific and Industrial Research Organisation.

JISF. n.d. "Technologies Customised List." Reference Information. Accessed June 16, 2023. https://www.jisf.or.jp/en/activity/climate/Technologies/.

US EPA. 2012. *Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Iron and Steel Industry*. North Carolina: United States Environment Protection Agency.

———. n.d. "Greenhouse Gas Reporting Program (GHGRP)." Home page. Accessed June 16, 2023. https://www.epa.gov/ghgreporting#:~:text=EPA's%20Greenhouse%20Gas%20Reporting%20Program,emissions%20in%20the%20United%20States.

Wang, Chuan, Pelle Mellin, Jonas Lövgren, Leif Nilsson, Weihon Yang, Hassan Salman, Anders Hultgren, and Mikael Larsson. 2015. "Biomass as Blast Furnace Injectant – Considering Availability, Pretreatment, and Deployment in the Swedish Steel Industry." *Energy Conversion and Management* 102: 217–226. https://doi.org/10.1016/j.enconman.2015.04.013.

Worldsteel. 2022. *Sustainability Indicators 2022 Report*. Brussels and Beijing: World Steel Association.

———. 2023. *Wordsteel in Figures 2023*. Brussels and Beijing: World Steel Association.

Yadav, Deepak, Ashish Guhan, and Tirtha Biswas. 2021. *Greening Steel: Moving to Clean Steelmaking Using Hydrogen and Renewable Energy*. New Delhi: Council on Energy, Environment and Water.

Yilmaz, Can, Jens Wendelstorf, and Thomas Turek. 2017. "Modelling and Simulation of Hydrogen Injection into a Blast Furnace to Reduce Carbon Dioxide Emissions." *Journal of Cleaner Production* 154: 488–501. doi.org/10.1016/j.jclepro.2017.03.162.

Acronyms

Bcm	billion cubic metres
BEE	Bureau of Energy Efficiency
BF	blast furnace
BOF	basic oxygen furnace
CAPEX	capital expenditure
CDQ	coke dry quenching
CCS	carbon capture and sequestration
CPP	captive power plant
COG	coke oven gas
CCU	carbon capture and utilisation
CCUS	carbon capture and utilisation/sequestration
DRI	direct reduction of iron/direct-reduced iron
EAF	electric arc furnace
EE	energy efficiency
ESCO	energy service company
IF	induction furnace
ISP	integrated steel plant
JISF	The Japan Iron and Steel Federation
JPC	Joint Plant Committee
MAC	marginal abatement cost
MMBtu	million British thermal units
$MtCO_2$	million tonnes of CO_2
Mtpa	million tonnes per annum
NG	natural gas
OPEX	operating expenditure
PCI	pulverised coal injection
PIB	Press Information Bureau
RE	renewable energy
RTC	round-the-clock
tcs	tonnes of crude steel
tDRI	tonnes of direct-reduced iron
tHM	tonnes of hot metal
TRL	technology readiness level
TRT	top-pressure recovery turbine
US EPA	United States Environment Protection Agency
VVFD	variable voltage and frequency drive
WHR	waste heat recovery
WHRB	waste heat recovery boiler

The authors

Sabarish Elango
sabarish.elango@ceew.in

Sabarish is a Programme Associate at CEEW working on industrial energy transitions and decarbonisation. His work revolves around transition and adaptation pathways for key industries and natural gas systems. Sabarish holds a master's degree in Sustainable Energy Engineering from KTH Royal Institute of Technology, Sweden and a bachelor's degree in Mechanical Engineering from Anna University, Chennai.

Kartheek Nitturu
kartheek.nitturu@ceew.in

Kartheek Nitturu is a thermal engineer and a Programme Associate at CEEW. He has over 12 years of experience in thermal system design, simulation, and selection. Kartheek completed his post-graduation in Thermal and Fluids Engineering from the Indian Institute of Technology, Bombay (IIT-B) and graduated in Mechanical Engineering from Jawaharlal Nehru Technological University, Anantapur.

Deepak Yadav
deepak.yadav@ceew.in

Deepak is a Programme Lead at CEEW and has expertise in green hydrogen, carbon capture and utilisation and the steel sector. He has 8+ years of experience in renewable energy, alternative fuels and industrial sustainability. He is also a BEE-certified energy auditor and has published his research in leading international journals and conferences. Deepak holds a Doctorate and a Master's degree from the Department of Energy Science and Engineering, IIT Bombay.

Pratheek Sripathy
pratheek.sripathy@ceew.in

Pratheek is a mechanical engineer and a Research Analyst at CEEW. He currently focuses on research topics related to hydrogen and the decarbonisation of heavy industries and has been working at CEEW for nearly a year. He holds a Master's degree in Energy Science from the University of Groningen, The Netherlands and a bachelor's in mechanical engineering from PES Institute of Technology, Bengaluru.

Rishabh Patidar
rishabh.patidar@ceew.in

Rishabh is a chemical engineer and a Research Analyst at CEEW. He has nearly three years of experience , and his current research focuses on the techno-economic assessment of pathways for CO_2 utilisation and green hydrogen technologies. Rishabh holds an MTech in Chemical engineering from IIT Gandhinagar, Gujarat, and bachelor's degree in Chemical Engineering from Ujjain Engineering College, MP.

Hemant Mallya
hemant.mallya@ceew.in

Hemant is a Fellow at CEEW and leads the Industrial Sustainability team. Hemant leads the team in four broad areas–energy transition and industrial decarbonisation; carbon management; circular economy and innovation; and R&D. He has nearly 20 years of experience in energy, environment, and climate change-related issues. Hemant holds a dual M.S. in Industrial Engineering and Operations Research from Pennsylvania State University, USA, and B.E. from Mumbai University.

COUNCIL ON ENERGY, ENVIRONMENT AND WATER (CEEW)

ISID Campus, 4 Vasant Kunj Institutional Area
New Delhi - 110070, India
T: +91 11 4073 3300

info@ceew.in | ceew.in | @CEEWIndia | ceewIndia