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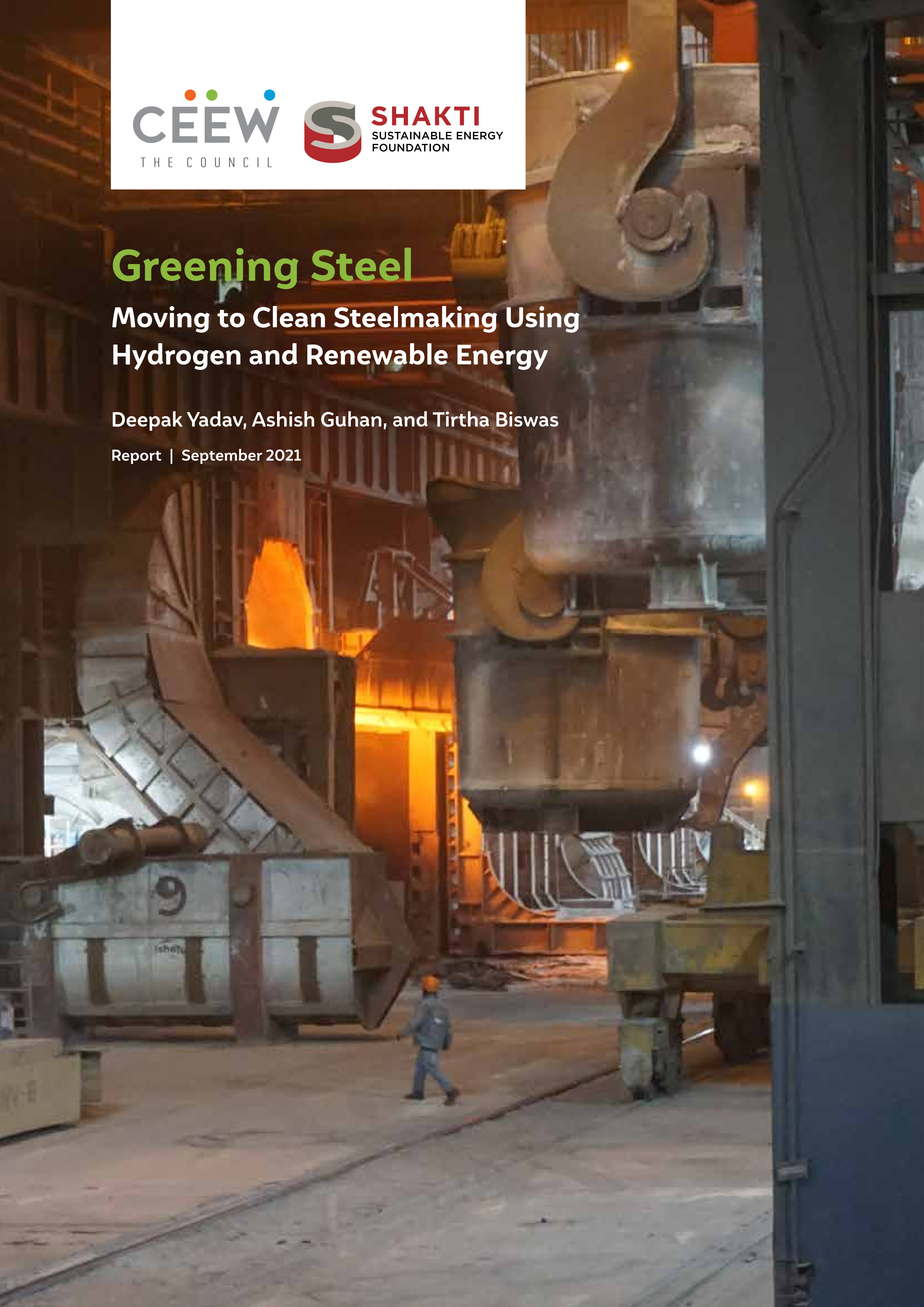
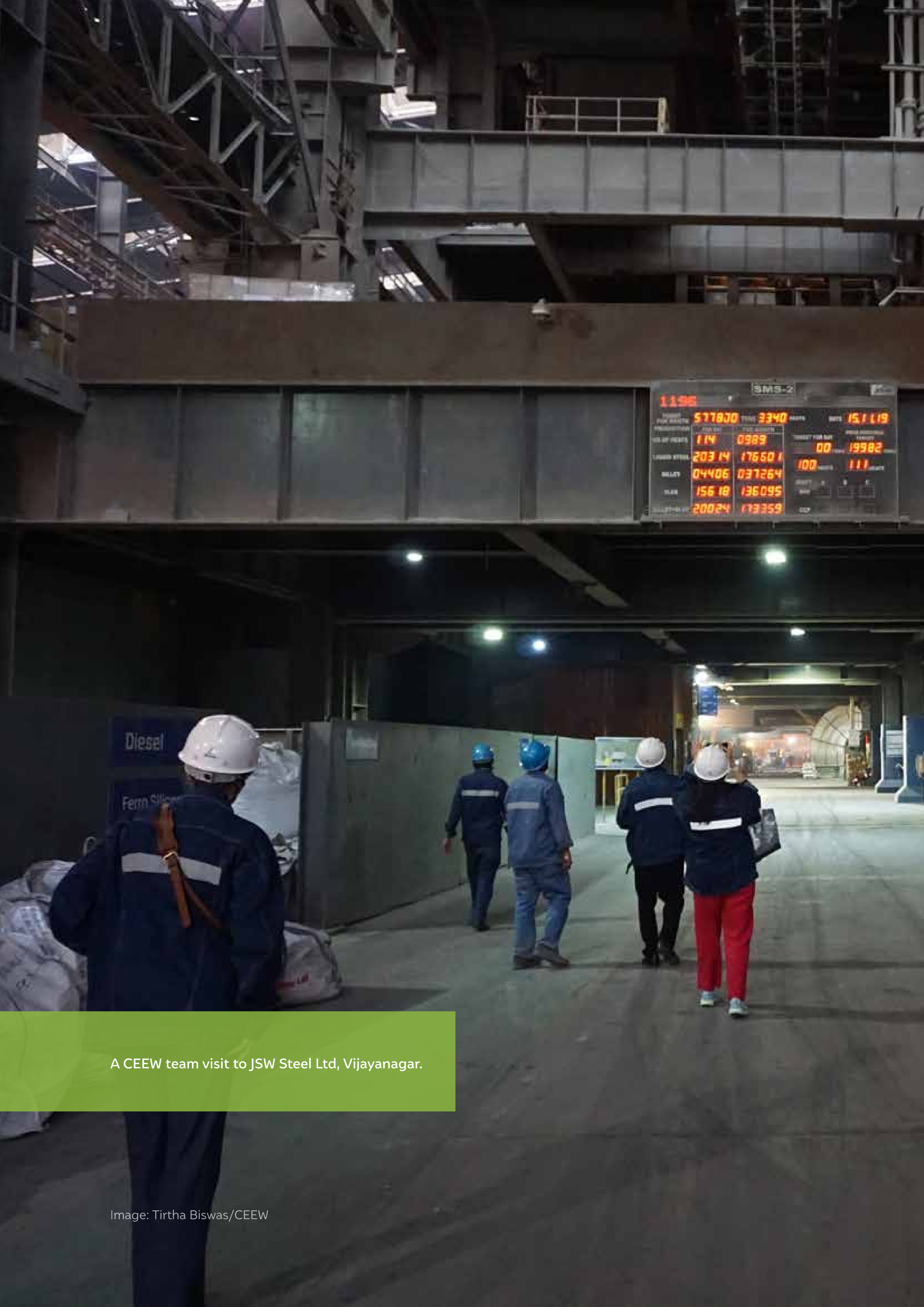


Greening Steel

Moving to Clean Steelmaking Using Hydrogen and Renewable Energy

Deepak Yadav, Ashish Guhan, and Tirtha Biswas

Report | September 2021



A CEEW team visit to JSW Steel Ltd, Vijayanagar.

Image: Tirtha Biswas/CEEW

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Shakti Sustainable Energy Foundation seeks to facilitate India's transition to a sustainable energy future by aiding the design and implementation of policies in the following areas: clean power, energy efficiency, sustainable urban transport, climate change mitigation and clean energy finance.

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"Fossil-free steelmaking is a utopia that comes with a very high price tag. Indian steelmaking can benefit from blending grey with green hydrogen and grid power with renewable power to significantly reduce costs at the expense of a marginal increase in emissions. Hydrogen-based steelmaking is promising. It is now important to indigenise the process and develop pilots to meet our shared ambitions on Aatmanirbhar Bharat and climate change."

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Ashish is an energy engineer striving to find solutions for widespread renewable energy (RE) utilisation, and thereby, for RE energy transition. He holds a master's degree in sustainable energy engineering from KTH Royal Institute of Technology, Sweden.

"Hydrogen provides an opportunity to electrify the primary steelmaking process by replacing carbon as the reducing agent. This can kick-start a green hydrogen economy that will lower the production costs across the value chain and unlock demand in other emerging applications. Hydrogen is the torchbearer of the potential solutions for decarbonising hard-to-abate end-use sectors globally."

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Tirtha is a policy analyst working on the development of sustainable and competitive pathways for Indian industry to support its low-carbon growth aspirations. At The Council, his research involves mineral resource security, greenhouse gas emissions and clean energy solutions, and energy efficiency of the domestic industrial sector in India. He holds a dual degree from the Indian Institute of Technology (Indian School of Mines), Dhanbad, with an undergraduate degree in Mineral Engineering and a master's degree in Mineral Resource Management.

"Hydrogen energy has a critical role to play in decarbonising steel production, which is currently responsible for nearly half of the manufacturing sector's greenhouse gas emissions. The findings from this study indicate the feasibility of such processes and aim to incentivise the industry and government towards early investments in pilots and demonstration projects for commercial scale deployment."

Green hydrogen offers the opportunity to indirectly electrify the energy and emissions intensive ironmaking step.

Image: iStock

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Acronyms

AE	alkaline electrolyser
AMRUT	*Atal Mission for Rejuvenation and Urban Transformation*
BAT	best available technology
BEE	Bureau of Energy Efficiency
BF-BOF	blast furnace-basic oxygen furnace
BoP	balance of plant
CAPEX	capital expenditure
CCUS	carbon capture utilisation and storage
CEEW	Council on Energy, Environment and Water
CEF	CEEW Centre for Energy Finance
CS	crude steel
DRI	direct reduced iron
EAF	electric arc furnace
GHG	greenhouse gas
H-DRI	hydrogen-based direct reduced iron
HHV	higher heating value
HYBRIT	Hydrogen Breakthrough Ironmaking Technology
kW·h	kilowatt-hour
LCOH	levelised cost of hydrogen
LCOS	levelised cost of steel
MMBtu	metric million British thermal unit
MOE	molten-oxide electrolysis
MT	million tonnes
MW	megawatt
mW·h	megawatt-hour
NG	natural gas
OPEX	operating expenditure
PC	power converter
PEMFC	proton-exchange membrane fuel cell
PV	solar photovoltaic
R&D	research and development
RK	rotary kiln
RE	renewable energy
SEC	specific energy consumption
SMR	steam methane reforming
SOEC	solid oxide electrolyser cell
TCS	tonnes of crude steel
THM	tonnes of hot metal
VRE	variable renewable energy
WHR	waste heat recovery
WSH	wind-solar hybrid

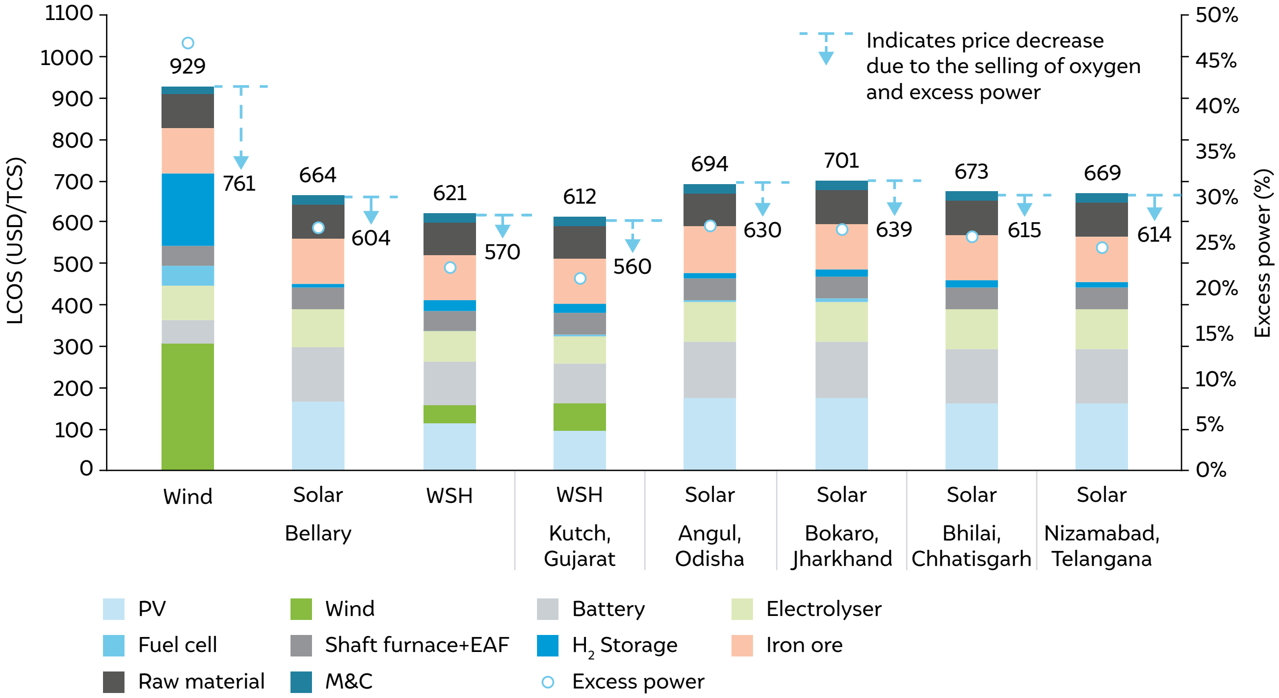
Executive summary

Image: iStock

Hydrogen has the potential to decarbonise steel manufacturing—a process that currently occupies the lion's share (35 per cent) of the greenhouse gas (GHG) emissions from India's manufacturing sector. Hydrogen-based steel has received global attention across several industry collaborations and partnerships. A joint venture founded by Swedish companies SSAB, Luossavaara-Kiirunavaara Aktiebolag (LKAB), and Vattenfall initiated the Hydrogen Breakthrough Ironmaking Technology (HYBRIT) project to achieve 100 per cent fossil-free steelmaking by 2035 (HYBRIT 2017). At the same time, Voestalpine, an Austrian steel company, in partnership with Siemens and VERBUND, has installed a 6 MW electrolyser in their steelmaking plant at Linz (H2Future 2019a).

Here, we evaluate the feasibility of green hydrogen-based steelmaking (hydrogen-based direct reduced iron (H-DRI) + electric arc furnace (EAF)) in India by providing insights into the techno-economics and associated environmental benefits. Figure ES1 shows the cost break-up of an optimised green steel plant configuration at various locations in India. Depending on the renewable energy (RE) mix, the levelised cost of steel (LCOS) in 2020 varies between 612 and 929 USD/TCS – currently 50-127 per cent higher than the average cost of the conventional blast furnace-basic oxygen furnace (BF-BOF) process. The variation in cost is primarily due to renewable intermittency, which increases as the renewable profiles shift away from a wind-solar hybrid (WSH) towards either solar- or wind-only profiles. The wind profiles in Bellary exhibit strong seasonal variability. Hence, a larger buffer of hydrogen storage is required to ensure continuous operation during the low generation months.

Figure ES1 WSH locations have the lowest levelised cost of steel (LCOS) in 2020



PV – Solar photovoltaic cost; M&C – Maintenance and operation costs; H_2 storage – Hydrogen storage cost
Source: Authors' analysis

Similar oversizing of the system is observed in other locations. However, the magnitude is several times lower when compared to a wind-only operation. The oversized system also produces excess electricity. Figure ES1 indicates that the excess electricity is approximately 45 per cent of the total electricity produced for wind-only operation, whereas for other locations, the excess electricity ranges between 21 to 26 per cent. If additional revenues from the sale of electricity (at levelised cost of electricity (LCOE) prices) and oxygen are considered, LCOS ranges between 560-7611 USD/TCS. However, a challenge with selling the excess power is that the excess solar and wind electricity are available only during peak solar and wind availability periods. The excess power is significantly higher for the solar plant during the daytime, with reduced generation during early afternoon or evening hours. Similarly, for the wind plant, we see very high availability during the months of peak wind. During the lean months, the excess power from the wind plant decreases significantly. Therefore, it is important to ensure that the power evacuation infrastructure is ready and flexible enough to support the large-scale deployment of hydrogen-based steelmaking.

In 2020, LCOS of green steel is 612-929 USD/TCS–50-127% higher than the BF-BOF process

Key findings

Access to both wind and solar resources is imperative for achieving the lowest production cost

Figure ES2 illustrates the mid- and long-term production costs estimates for all RE mixes. The estimates only consider revenues from selling oxygen. The results indicate that the green hydrogen-based process requires *a **favourable RE mix*** to break even with the conventional production process. Availability of wind and solar resources is a prerequisite to minimise the renewable intermittency cost and reduce the production cost by 8 to 13 per cent in the near to medium term. In 2050, with an aggressive decline in electrolyser and storage costs, the intermittency costs also reduce. Hence, the cost differential between these locations further reduces to 4 to 7 per cent.

In 2040, only the WSH locations (Bellary and Kutch) become competitive with the blast furnace production costs. However, our estimates indicate that the solar-only locations can break even with natural gas (NG)–based DRI costs (with NG price of $13.5/MMBtu) by 2040, and with blast furnace costs, only in 2050.

In 2040, only the wind-solar hybrid locations become competitive with the blast furnace production costs

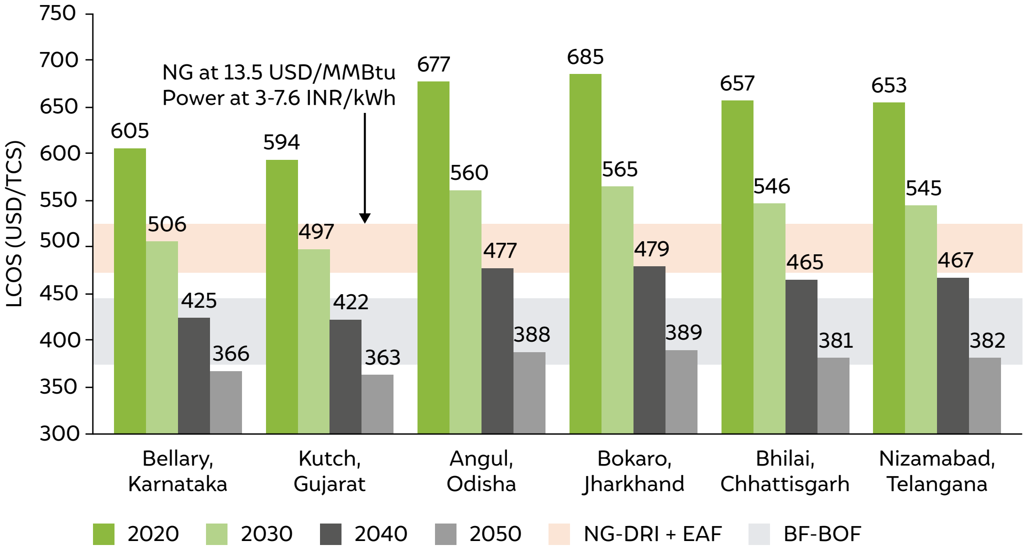


Figure ES2
WSH locations break even with NG-DRI by 2030, and with blast furnace costs by 2040

Source: Authors' analysis

Develop robust grid infrastructure to support large-scale deployment of green hydrogen-based steel production

A 0.5 million tonnes per annum (MTPA) production capacity in Bellary will require 1157 MW of solar photovoltaic (PV) and 207 MW of wind capacity. Further, the oversized system will also generate 580 GWh of excess electricity. The magnitude of excess electricity in a year is equivalent to annual power generation from 277 MW PV and 35 MW wind plants. However, the fact that the excess generation is available only during the peak hours of renewable generation increases the challenge of absorbing this power in the grid. For the solar plant, excess electricity is generated during the afternoon. Similarly, we see very high excess generation for the wind plant during the months of peak wind generation. Therefore, as green steel production scales up, it is important to ensure that the grid infrastructure is flexible enough to maintain the future electricity demand-supply balance.

Blending grey with green hydrogen and renewable power with grid electricity will accelerate the transition to green hydrogen-based steel production in India

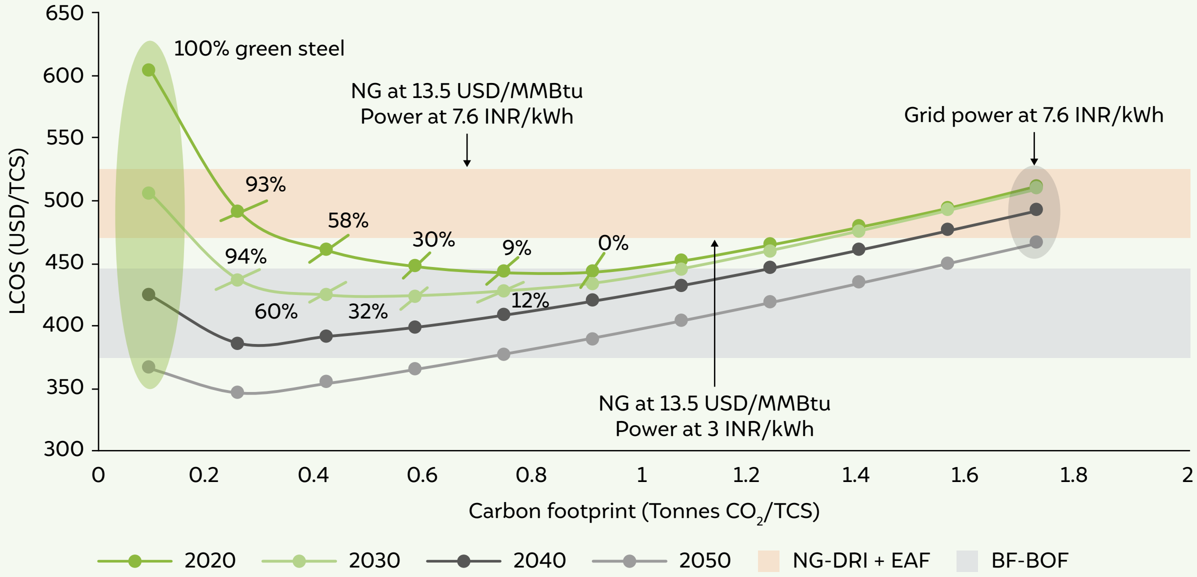
An overnight transition to fossil-free steelmaking will be highly expensive. In 2030, the lowest cost of producing green steel is still 22 per cent higher than the blast furnace process. Renewable intermittency contributes to a significant share of the costs of fossil-free steel production. Hence, the overall cost of production can be reduced by blending grey hydrogen (flexibly produced from NG during periods of low renewables generation) with green hydrogen and grid electricity with renewable power (for auxiliary electricity demand).

Box ES1

Blending grey hydrogen and grid power with renewable energy significantly reduces costs with a marginal increase in emissions footprint

Figure ES3 illustrates the optimal blend configuration for WSH operation and the associated production cost for various CO_2 emissions targets. The figure also shows the high marginal abatement cost of carbon emissions, especially when moving towards a 100 per cent green hydrogen operation. We consider an NG price of 13.5 USD/MMBtu. We also consider a grid power cost of 7.6 INR/kWh and the time-of-day tariff currently imposed in Bellary, Karnataka.

Figure ES3 Transition pathways for blending green and grey hydrogen in steelmaking in Bellary, Karnataka



Source: Authors' analysis

Note: 1) The values in percentage indicate the share of green hydrogen. 2) The SMR unit is not needed in 2040 and 2050.

Table ES1 shows a summary of infrastructure and energy required for green steel production.

Table ES1 Infrastructure and resource requirement for green steel production

	Land	Water	Electricity
Consumption intensity	30630 acres per MTPA	2.93 tonnes/TCS	5.3 MWh/TCS
To produce 111 MTPA of green steel (equivalent to India's steel output in 2019)	3.4 million acres	325.3 MTPA	264 GW of solar
	7 per cent of Gujarat's land area	16 per cent of Gujarat's annual supply	59 per cent of India's 450 GW target by 2030

Source: Authors' analysis

In 2020, the emission footprint of steel can be reduced from 1.75 tonnes CO_2/TCS to 0.91 tonnes CO_2/TCS just by co-locating the steel plant with a location having access to captive wind and solar energy. In this scenario, RE is used to meet only the plant auxiliary demand without producing any green hydrogen. The emission footprint of coal and natural gas-based processes are 2.3-2.4 tonnes CO_2/TCS and 1.3 tonnes CO_2/TCS. We see that in 2020, hydrogen-based steelmaking just about breaks even with the upper range (442 USD/TCS) of blast furnace cost for an emission footprint of 0.75 tonnes CO_2/TCS using 9 per cent green hydrogen (on an annual basis) in the plant. The cost of steel obtained from the coal DRI + EAF process is 300-451 USD/TCS. By 2030, hydrogen-based steelmaking becomes competitive (with an LCOS of 424 USD/TCS), with an average blast furnace cost for an emission footprint of 0.41 tonnes CO_2/TCS by using 60 per cent green hydrogen. Subsequently, when the costs across the hydrogen value chain decrease to the 2040 and 2050 levels, the steel units can reduce emissions without the need of a steam methane reforming (SMR) unit. In this scenario, the emission constraint at minimum cost value (0.25 tonnes CO_2/TCS) is met by using a blend of grid electricity and RE to power the electrolyser.

Planning the future infrastructure for raw material and energy transportation is critical for scaling up green hydrogen–based capacities

The majority of the existing steel plants are currently located close to iron ore and coal mines. However, most of these locations do not have access to favourable renewable resources. Our analysis indicates that the three states in the east (Odisha, Chhattisgarh, and Jharkhand) have no wind installations and only 1.8 per cent of India's total solar installed capacity but caters to 45% of national steel demand (PIB, 2019). For green hydrogen-based production, these plants have the following options: a) transporting hydrogen and wheeling RE power for meeting auxiliary load, b) wheel power from RE-rich areas (to produce hydrogen locally and meet auxiliary power demand), and c) shift their production base to RE-rich areas and transport iron ore instead.

Table ES2 shows the various transport cost scenarios for a steel plant located in Angul, Odisha. The source of hydrogen or renewable power is Kutch, Gujarat. Across these scenarios, the increase in steel production cost is the highest for liquid hydrogen transport. The transportation costs for hydrogen using large-scale pipelines (~500 TPD) while wheeling RE power to meet auxiliary load or wheeling electricity alone to meet the entire plant power requirement using open access are comparable. However, we find out that transporting iron ore through railways is the cheapest option.

Transporting iron ore from Angul to Kutch is cheaper than moving power and hydrogen from Kutch to Angul

Each of the three scenarios has several limitations associated with them. Setting up hydrogen pipelines is highly capital intensive and will require off-take guarantees well before the project's construction. Similarly, several policy barriers and price uncertainties are limiting the open-access volumes in the current electricity sector. While transporting iron ore is the cheapest option, the rail infrastructure in the country can constrain the annual capacity that can be transported. Setting up steel plants within the RE-rich areas in the western part of the country can also lead to a future increase in iron ore imports. Nevertheless, we expect the price of green steel to roughly increase by 10-15 per cent due to the logistical challenges in moving iron ore and renewable power/hydrogen.

Table ES2
Green steel plants located near the favourable RE locations will have the lowest logistics cost

Sr. No.	Transport medium	Sourced from	Delivered to	Transport tariff	Consumption	Total transport costs (USD/ TCS)*
1.a	H_2 (Liquid) + RE power (Open access)	Kutch	Angul	2.57 USD/kg H_2 +1.65 INR/kWh	50 kg H_2/TCS + 1.6 MWh/TCS	163
1.b	H_2 (Pipeline) + RE power (Open access)	Kutch	Angul	1.20 USD/kg H_2 +1.65 INR/kWh	50 kg H_2/TCS + 1.6 MWh/TCS	95
2	RE power (Open access)	Kutch	Angul	1.65 INR/kWh	4.1 MWh/TCS	90
3	Iron ore (Railways)	Angul	Kutch	41.2 USD/t-Ore	1.4 t-Ore/TCS	58

** Assuming USD to INR conversion of 75*

Source: Authors' analysis

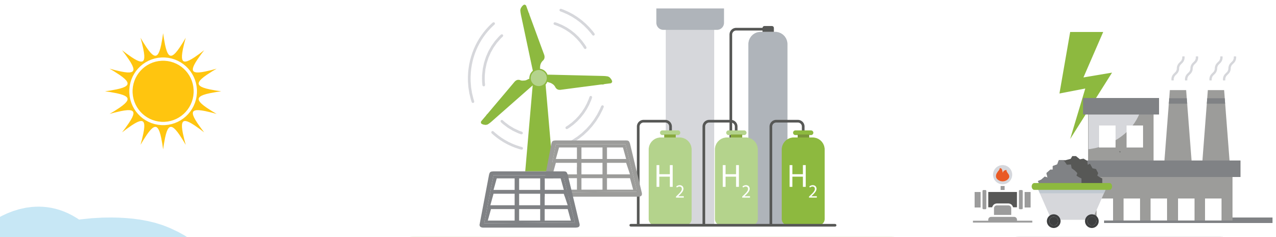
Conclusion

Our study finds that hydrogen can be a promising candidate to decarbonise the growing domestic steel industry. However, we see that a 100 per cent green hydrogen operation will only become viable in the next two decades. We also find that access to favourable renewable resources is critical towards achieving an early break-even. Producing green steel using only solar resources (which is true for most locations in the country) will push back the break-even period to 2050. We propose a faster way to incentivise the transition: blending green hydrogen with conventional grey hydrogen (produced from SMR) and RE power with grid power. The high renewables intermittency costs of 100 per cent fossil-free operation can be significantly reduced by blending 7 per cent grey hydrogen while marginally increasing the emissions footprint of the process. At today's prices, blending ~9 per cent of green hydrogen (with grey hydrogen) is competitive with the upper range of BF-BOF costs.

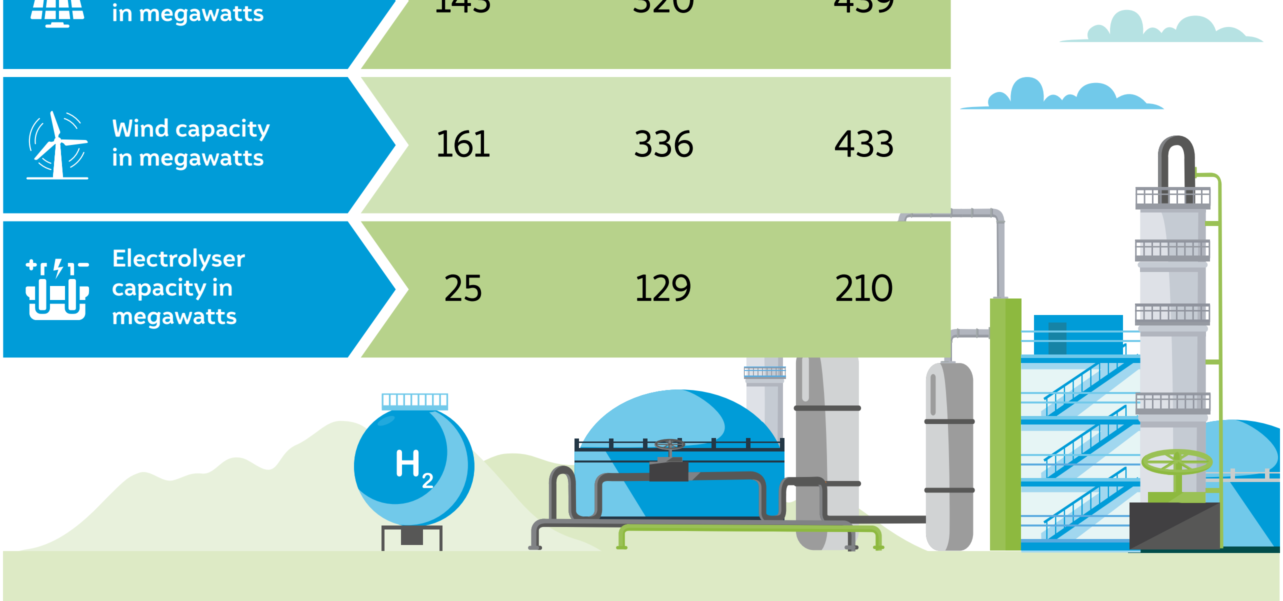
We also highlight the major challenges in transitioning to green hydrogen-based steel production. A green steel plant will need investments to the tune of USD 3 Billion per MTPA – more than three times the conventional BF-BOF route. With the thin research and development (R&D), and innovations investments by steelmakers (less than 1 per cent of their annual turnover), the transition may be extremely challenging. Further, converting the current steelmaking capacity to green hydrogen-based production will require 264 GW of solar capacity and annual water consumption representing ~16 per cent of the annual water supply in the state of Gujarat. A detailed evaluation of raw-material and energy (including hydrogen) delivery infrastructure will help identify the optimal locations of future investments and evaluate the potential impact on jobs and revenues from shifting existing supply chains. The recommendations of this study are aimed at strengthening the *National Hydrogen Energy Mission* and *National Steel Policy, 2017* to support a transition to green hydrogen and make our steel industry *Aatmanirbhar*.

A green steel plant needs investments of USD 3 Billion per MTPA – more than three times the BF-BOF route

Transition pathways for blending green and grey hydrogen in steelmaking



	Designing a hydrogen direct reduced iron (H-DRI) and electric arc furnace (EAF) steel plant of 0.5 million tonnes per annum (MTPA) capacity			Equivalent blast furnace - basic oxygen furnace (BF-BoF)
	2020	**2030**	**2040**	**BF-BoF**
Green H_2 blend in the process	9%	60%	100%	N/A
Production cost in USD per tonne of crude steel	443	424	386	408
Emissions footprint in tonnes CO_2 per tonne of crude steel	0.74	0.41	0.25	2.3
Capital investments in million USD (2020 prices)	538	685	694	366
Land footprint in acres	5259	11553	15641	200
Solar capacity in megawatts	143	320	439	
Wind capacity in megawatts	161	336	433	
Electrolyser capacity in megawatts	25	129	210	



Source: Authors' analysis

India should prioritise investments in hydrogen-ready technologies. Any investment in blast furnaces today will lock in imported coal demand for mid-century and beyond.

Image: iStock

1. Introduction

The iron and steel industries are significant economic contributors in India. The current annual installed capacity of ~130 million tonnes (MT) (IBM 2018) can only support a per capita steel consumption of ~70 kilograms compared with a global average of 224 kilograms (MoS 2019). Economists often use per-capita steel consumption as an indicator of socioeconomic development and the income levels of a country. The *National Steel Policy 2017* aims to bridge the gap by supporting additional investments to boost the domestic production capacity to 300 MT by 2030 (MoS 2019). Whilst the policy promotes economic development, it does very little to incentivise investment in mitigating the additional environmental effect from the over two-fold increase in production (capacity).

The steel sector is the single largest energy consumer, roughly accounting for 45 per cent of total industrial consumption in 2016. The sector's energy mix is dominated by coal and its derivatives that cater to 90 per cent of the demand. Coal has a significantly higher emissions footprint, with the resultant emissions from the sector representing ~42 per cent of India's overall industrial greenhouse gas (GHG) emissions. Between 2010 and 2017, the share of coal-based production increased from 73 per cent to 87 per cent, despite the presence of coal, gas, and electricity-based production assets (Gupta et al. 2019). Limited availability of domestic gas supply and high cost of imports are gradually pushing industries to rely on coal instead. Thus, potentially offsetting the gains made through the programmatic pursuit of energy efficiency. There is a need for a clear policy that looks beyond the incremental process efficiency gains and aims for the deep decarbonisation of industrial energy use.

The steel sector accounted for 45% of total industrial energy consumption in 2016

Green steelmaking can reduce our import dependence on coking/ non-coking coal and make us *Aatmanirbhar*.

Image: iStock

2. Technology pathways for decarbonising steelmaking

The primary ironmaking process uses three reducing agents: carbon, hydrogen, and electricity. Figure 1 shows the ternary diagram of technology pathways to decarbonise the iron and steel sector. The objective of any clean processes will be to move away from carbon towards hydrogen and/or electricity. In the past, conventional ironmaking in blast furnaces relied heavily on coke (obtained from coking coal). However, blast furnaces moved from the coke-only operation over the years and started co-injecting pulverised coal thereby, reducing carbon emissions and operating costs. Upcoming technologies like HIsarna (Stel et al. 2018), which can potentially reduce the carbon footprint of steel by at least 20 per cent (TSL 2020), rely on a smelting process that produces pig iron from coal without consuming coke. The rotary kiln (RK) process also produces direct reduced iron (DRI) from only coal (without consuming coke).

A potential pathway for the steel industry to move away from coke/coal is by using two reducing agents – carbon (monoxide) and hydrogen – with a progressively increasing share of hydrogen. In this regard, technologies like coal gasification can be integrated with shaft furnaces for producing sponge iron (Mittal 2020). In the transition away from coal, NG in shaft furnaces is already a proven technology that can significantly reduce emissions from sponge ironmaking. However, the ultimate goal of the transition away from fossil fuels would be to produce steel using only hydrogen (obtained from renewable sources) as the reducing agent.

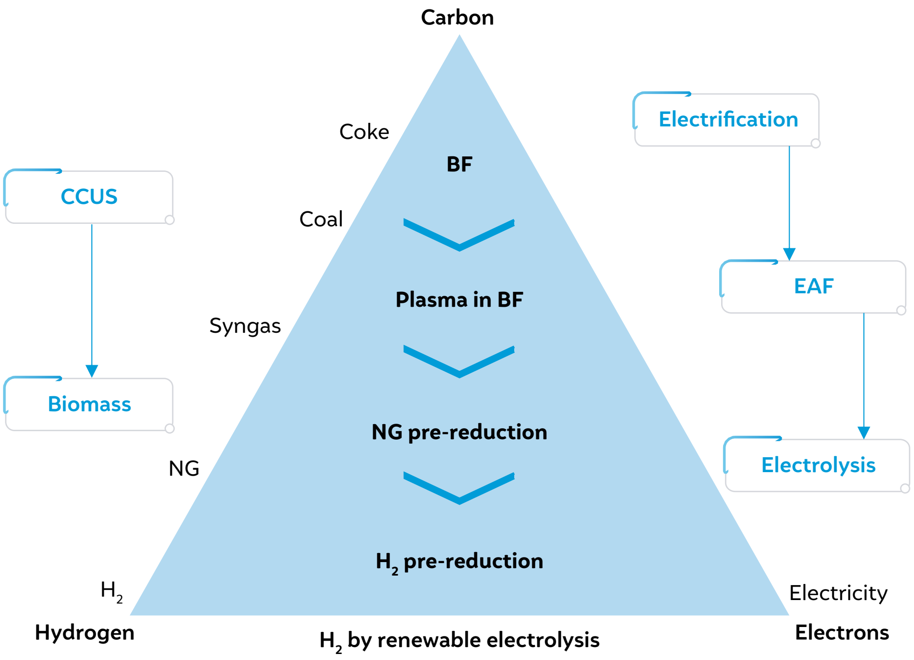
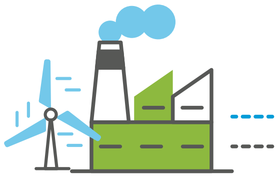


Figure 1
Green hydrogen offers the opportunity to indirectly electrify the ironmaking process

Source: Pasquale (2019).

The pathway from carbon to hydrogen can be made cleaner by using biomass and carbon capture utilisation and storage (CCUS) technologies. Biomass can be used to mitigate emissions by replacing coke and coal consumption in the existing sectors. Biomass-derived charcoal can substitute the coke used in blast furnaces (Wang et al. 2020). Similarly, biomass can be directly used in an RK, HIsarna, or converted into syngas/hydrogen for shaft furnaces. The emissions from existing processes can be mitigated by CCUS technologies that can produce synthetic fuels (ArcelorMittal 2018) for use in various sectors of the economy. The application of green hydrogen (produced from the electrolysis of water by using solar and wind power) for reducing iron ore provides an option to indirectly electrify the ironmaking step. Other upcoming technologies like molten oxide electrolysis (MOE) (Boston Metal 2021) and electrowinning (ArcelorMittal 2017) are based on direct electrolysis of iron ore to yield iron. A challenge with the direct electrolysis routes is the low technology readiness level (TRL). The ULCWIN pilot plant, based on electrowinning technology, is currently at TRL 4 and has produced only 4 kg of iron so far. The MOE technology has produced more than 1 tonne of iron, and efforts are underway to demonstrate this technology on a pilot scale (WorldSteel 2021). In the net-zero emissions scenario by 2050, the share of hydrogen and direct electrolysis-based technologies is expected to be 29 per cent and 13 per cent, respectively (IEA 2021). Nevertheless, until over-the-horizon technologies like direct electrolysis are fully developed and commercialised, renewable hydrogen offers the opportunity to indirectly electrify, and hence, significantly mitigate emissions from the primary steelmaking sector.



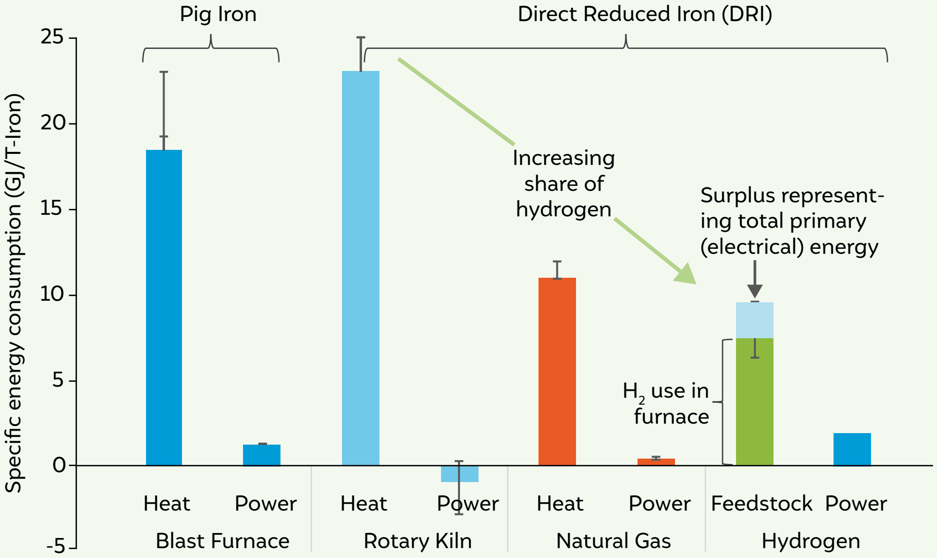
Green hydrogen offers the opportunity to indirectly electrify the ironmaking process

Box 1 The power of using hydrogen as a reducing agent

Figure 2 shows the specific energy consumption (SEC) for producing iron using blast furnaces, RK, NG, and hydrogen in shaft furnaces. The energy consumption is split based on the nature of energy use: heat and power. While the electricity use in the iron production stage can be made green by using renewable power, the critical challenge is in replacing thermal energy obtained from fossil fuels with RE.

The thermal SEC of blast furnace (including coke making and sintering units) ranges from 17.6-23 GJ/tonne of hot metal (THM) with a global best available technology (BAT) of 16.7 GJ/THM (Gupta 2014). The power consumption in the blast furnaces and associated components is 356 kWh/THM (Fan and Friedmann 2021). The thermal SEC of the RK process is estimated to be 23 GJ/T-DRI (Agrawal, Sahoo, and Mohanty 2015) with a global BAT of 18.8 GJ/T-DRI (Gupta 2014). The RK process can also generate surplus power using kiln off-gas. The typical power generation ranges from (-) 85 kWh/T-DRI (if no captive generation) to 524 kWh/T-DRI (Worrell et al. 2008). The NG-based shaft furnace consumes approximately 267 normal cubic metres of NG/T-DRI (Fan and Friedmann 2021), which implies an SEC of 10.9 GJ/T-DRI. The typical power consumption in a shaft furnace is 120 kWh/T-DRI (Chatterjee 2012). Notably, with the use of NG, the SEC of DRI production decreases by more than 50 per cent compared to the RK process. Note that the share of electricity use in coal and NG-based processes is not significant.

Figure 2 Specific energy consumption (higher heating value) of the blast furnace, rotary kiln, natural gas, and hydrogen-based sponge iron production processes



Source: Authors' analysis

Green hydrogen provides a unique opportunity to indirectly electrify the iron production process by replacing coal and NG. The hydrogen consumption in the shaft furnace ranges from 47-68 kg of H_2/T-DRI (IEA 2020a). With a conservative estimate of 53 kg of H_2/T-DRI (Hölling and Gellert 2018) (HYBRIT 2017), the SEC of feedstock-related energy consumption is 7.5 GJ/T-DRI (based on a higher heating value (HHV) of 142 MJ/kg). Assuming an electricity consumption of 50 kWh/kg of hydrogen in the electrolyser, the total primary energy for the electrolytic production of H-DRI is 9.57 GJ/T-DRI. Besides the electricity consumed for producing hydrogen, the hydrogen-based sponge iron production consumes power for heating the iron ore and hydrogen to the reaction temperature. Electricity is also needed to drive the endothermic reaction for reducing iron ore to sponge iron. Hence, the power consumed in the hydrogen-based processes is significantly higher than coal- and gas-based technologies. Nevertheless, we see a declining trend for the thermal or feedstock-related energy consumption in moving from coal to NG and from NG to hydrogen. This shows the effect of using a more potent reducing agent – hydrogen – for producing iron.

India should prefer incremental blending of green hydrogen in steelmaking rather than aiming for fossil-free steel production.

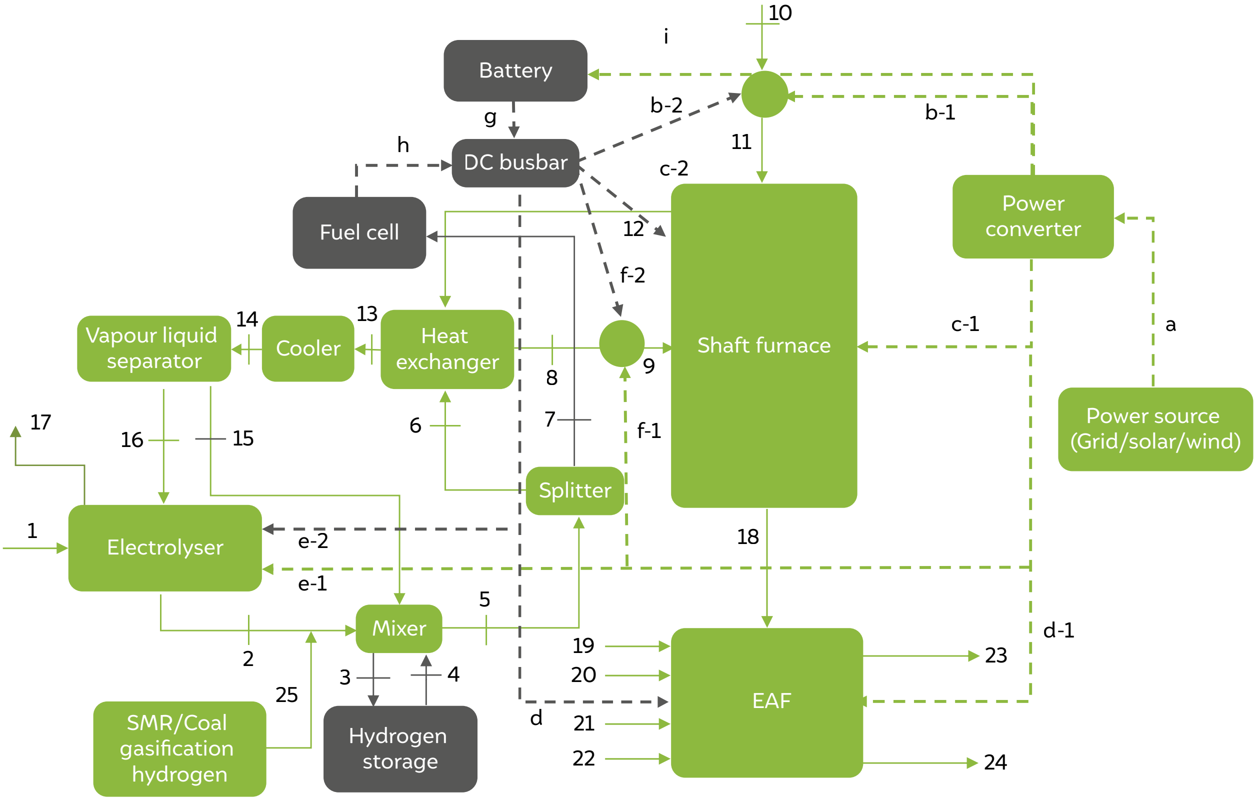
Image: iStock

3. Process description

Figure 3 illustrates the process flow sheet of the model. The dotted lines indicate the flow of power, whereas the solid lines indicate the material flow. The orange lines connect the components (shown in the orange text box) used to manage the RE intermittencies, while the blue lines indicate the material and power flows without any intermittencies. The material and power flows are identified by numbers and alphabets, respectively. These identifiers are used to highlight the material-energy and power balances in Annexure I and Annexure-II, respectively.

The hydrogen-based steel plant consists of three major units: 1) the hydrogen production and storage system, 2) the iron and steel production unit, and 3) the RE storage systems. The hydrogen production plant consists of an alkaline electrolyser (AE) that produces hydrogen (2) and oxygen (17) from fresh (1) and recycled water (16). In our analysis, we assume that the electrolyser can ramp instantaneously and is capable of handling RE intermittencies. Studies indicate that modern AEs now have the capacity to ramp up/down at a rate of ±20 per cent per second (IRENA 2018). For the AE, we consider a turndown (minimal load) ratio of 10 per cent.

Figure 3 Process flow diagram of green hydrogen-based steel production



Source: Authors' analysis

The hydrogen generated in the electrolyser (2) mixes with the unreacted hydrogen from the shaft furnace (15). We also consider a scenario where grey/black hydrogen obtained from steam methane reforming (SMR) or coal gasification is blended with hydrogen produced by the electrolyser. If the total hydrogen availability exceeds the demand of the shaft furnace, then the additional hydrogen is stored (3) in the hydrogen storage system. We consider that hydrogen is stored in underground piped storage facilities (Ahluwalia et al. 2019). If the hydrogen production from the electrolyser is less than the demand in the shaft furnace, then the desired hydrogen is obtained (4) from the storage facility. The hydrogen from the storage/electrolyser unit is fed (5) to a splitter that diverts it to a heat exchanger (6) and fuel cell (FC) (7). The hydrogen is pre-heated (8) in the heat exchanger by utilising the heat from the steam/hydrogen mixture coming from the shaft furnace. The preheated hydrogen is then further heated to the shaft temperature in an electric heater (9). Based on the literature (Vogl, Åhman, and Nilsson 2018), we consider that 62 per cent excess hydrogen (over the stoichiometric demand) is fed to the shaft furnace to ensure complete reduction of iron ore. We also account for hydrogen loss in the shaft furnace by considering 17 per cent additional hydrogen (over the stoichiometric demand) consumption (Hölling and Gellert 2018). After the reduction reaction, the unreacted hydrogen and steam mixture (12) is first used to pre-heat the incoming hydrogen in a heat exchanger. The hydrogen/steam mixture (13) is then cooled in a cooler to the ambient temperature, following which the hydrogen (15) is separated from water (16) in a vapour-liquid separator (14).

The steel production unit consists of the shaft furnace and the electric arc furnace (EAF). In the shaft furnace, as indicated in the equations in Annexure III, hydrogen (9) reacts with the iron ore (10) to produce DRI (18) and hydrogen/steam mixture (12). The iron ore fines are preheated from ambient temperature (10) to reaction temperature (11) in an electric heater before introducing them in the shaft furnace. Based on the literature (IEA 2020a), we assume that the shaft furnace has a flexibility of 20 per cent (ramping down to 80 per cent of the design capacity), and can ramp up and down at the maximum rate of 10 per cent per hour of the design capacity. Technology providers indicate that the shaft furnace can ramp down to even 30 per cent of the design capacity (Midrex 2018). We assume that the furnace and EAF units have a continuous operation (shaft furnace continuously feeding to the EAF with a tap-to-tap time of 45-60 minutes). Besides the DRI obtained from the shaft furnace, the EAF also consumes raw materials such as steel scrap (19), lime (20), carbon (21), and ferroalloys (22). The outputs from the EAF unit are slag (23) and liquid steel (24). In this report, we model the process of producing only crude steel (CS). However, in industry, CS is further processed in secondary steelmaking to yield finished products, which has not been covered in this report.

We assume that the only renewable electricity from solar and wind energy is used to produce green steel in the base case. The variable renewable energy (VRE) sources meet the power requirement of the iron ore heater (b), shaft furnace (c), EAF unit (d), electrolyser (e), and hydrogen heater (f). We do not consider any credits from the excess (or curtailed) power generated by the system. However, credits from selling oxygen are considered in the analysis. For the transition story, we also consider that the system can obtain energy from two sources: grid power for meeting the plant auxiliary load and NG/coal gasification for providing grey/black hydrogen to the shaft furnace.

To manage the RE intermittencies, we consider a proton-exchange membrane fuel cell (PEMFC) unit and battery storage. Based on the relative cost, life, and efficiencies of these systems, the model sizes the FC (including the associated components like a storage tank and electrolyser) and the electrochemical storage. If renewable supplies exceed the total power requirement of the system, then the excess power is stored in these energy storage systems. During times of low RE availability, the energy storage unit provides power to meet the plant auxiliary load. In a real system, the energy storage units and the RE are connected to a common bus bar. However, for the sake of explanation and readability, we indicate the power from RE (in green) and from energy storage (in grey) separately.

The model has 59 constraints, 52 decision variables and 107 parameters

3.1 Method

The H-DRI + EAF route for steelmaking is modelled as a linear programme in Python. The model is developed to enable the variation of key inputs parameters, and to subsequently analyse their impact on the cost of production of CS and the associated carbon footprint. When provided with hourly RE (both solar and wind) availability profiles, the model optimises the size of various components like solar and wind plant, battery storage, electrolyser, hydrogen storage, and FC to produce the desired annual output of CS. The model has 59 constraints, 52 decision variable and 107 parameters.

The model consists of various sub-models that are directly adopted from the literature. The material-energy balance of the shaft furnace and the EAF are modelled based on literature (Vogl, Åhman, and Nilsson 2018). To keep the model linear, only major chemical reactions are considered. The reactions inside the EAF are neglected and replaced with a linear mass and energy balance equation. Similarly, in the DRI production, the reduction reaction is not considered to be equilibrium in nature. Instead, the reduction is modelled as hematite reduces to free iron and wüstite (FeO). The ratio between free iron and wüstite (FeO) formed during the reduction process depends on the degree of metallisation. For the current analysis, a degree of metallisation of 0.92 has been assumed. This means that the quantity of FeO is negligible compared to the free iron. Hence, the reaction enthalpies for the hematite (Fe_2O_3) reduction to FeO is neglected. The detailed chemical reactions are provided in Annexure III. The operating temperatures have a direct implication on the energy requirement in the reactions. The dynamics of the shaft furnace are not modelled. We assume that the DRI operates in a steady state at 800 °C.

The hydrogen production rate is considered a linear function of the power input to the AE, notwithstanding the minor variation due to higher efficiency at part-load conditions. This is a valid assumption, as observed in the literature (Ulleberg 2003; IRENA 2018), and consistent with other studies (Mallapragada, et al. 2020; Nayak-Luke and Bañares-Alcántara 2020). Similarly, we consider constant efficiency for the FC, implying that the power output varies linearly with the hydrogen consumption (Santangeloa and Tartarini 2018). The heat exchanger is modelled by considering the standard method for sizing the heat exchanger (Yadav and Banerjee 2018). The solar and wind energy hourly power output profiles are obtained from renewable ninja for 2019 (Pfenninger and Staffell 2016; Renewable Ninja 2020). The model does not consider any material and energy losses in mixers, splitters, vapour-liquid separators, and electrical bus bars to avoid complexity. In a practical case, there will be water losses in the vapour-liquid separator, which has been separately considered to estimate the water consumption in the plant. As discussed earlier, we also consider hydrogen losses in the shaft furnace.

The cost of various components is computed by annualising the capital expenses (CAPEX) of the components. The operating expenses comprise of the periodic maintenance cost of every component as a percentage of CAPEX, cost of consumable resources (ore, scrap, lime, alloys, graphite electrodes), electricity cost, and other variable costs. The by-products like oxygen produced in the electrolyser and surplus electricity are the sources for additional revenue.

The objective of the model is to minimise the levelised cost of crude steel CS. While we consider the credits from selling oxygen in the objective function, the possible benefits from the sale of surplus power are externally computed outside the model.

As discussed earlier, the model has the flexibility to blend green hydrogen and renewable electricity with grey hydrogen (hydrogen from NG and coal gasification) and grid power, respectively. We assume that the SMR and coal gasification units have 50 per cent flexibility (Rajesh et al. 2000) without any constraints on the ramping rate. For grid power, we also consider the effect of the time-of-day tariff as an input to optimise the system configuration. The use of non-renewable sources of hydrogen and electricity have their respective CO_2 emissions, which are used to estimate the carbon emissions from the plant. For the transition story, based on the carbon emissions of grid power, SMR, and coal gasification units, the model sizes the plant and computes the minimum cost for a given carbon constraint.

The model has the flexibility to blend green hydrogen and renewable electricity with grey hydrogen (hydrogen from NG and coal gasification) and grid power, respectively

3.2 Modelling assumptions

In the analysis, we consider four time horizons: 2020 (current), 2030 (medium-term), and 2040 to 2050 (long-term). The costs of various components for the future years are obtained based on the literature and learning rate effects (discussed in Annexure-IV). In the 2050-time horizon, the costs of all major components reach the lowest limit and efficiency/life reach the optimal values. Thus, the 2050 costs essentially indicate the lowest possible production cost of green steel.

Table 1 lists the trends of the cost, efficiency, and operating life of key components across the time horizons. The assumptions related to the specific material consumption and their associated costs are listed in Annexure-IV. We make simplistic and conservative assumptions regarding the life of components like electrolysers and fuel cells. For example, even though we represent the life of these components in hours in the table, the model considers the life in years by assuming that these components operate for 8760 hours in a year. Across all cases, we consider fixed-tilt solar photovoltaic (PV) system inclined at an angle equal to the latitude. We do not consider direct current oversizing of the PV system and its effect is reflected in the capital cost of the solar plant. We validate our solar and wind levelised cost of electricity (LCOE) with the tariffs discovered in the market (Shah et al. 2021). The costs of the shaft furnace and the EAF units are obtained from the literature and validated with industry consultation. In industrial applications, the shaft furnace cost is inclusive of the gas reformer, which significantly contributes to the overall system cost. A shaft furnace that uses only hydrogen as the reducing agent does not need the gas reforming unit. However, we consider the prices available in the literature for our analysis in the absence of any accurate estimates. The costs and life of other components are directly obtained from the literature.

Table 1 Cost, efficiency, and life of various components of the hydrogen-based direct reduced ore + electric arc furnace plant

Capital cost	Unit	2020	2030	2040	2050	Source
Capital cost assumptions						
Solar PV	USD/kW	405	317	281	165	Biswas, Yadav, and Guhan (2020)
Wind	USD/kW	848	642	534	534	
AE	USD/kW	750	625	450	200	IRENA (2020); IEA (2019)
Power converter	USD/kW-ac	60	60	60	60	Fu, Feldman, and Margolis (2018)
Hydrogen storage	USD/kg	516	345	104	104	Ahluwalia et al. (2019); Schoenung (2011); Von Colbe (2019)
Shaft furnace	USD/tonne	228	228	228	228	IEA (2010); Duarte (2004)
EAF	USD/tonne	127	127	127	127	IEA (2010); Steelonthenet (2021)
Battery (Power)	USD/kW	600	380	320	280	Frazier and Will (2019)
Battery (Energy)	USD/kWh	175	120	100	80	Frazier and Will (2019)
PEMFC	USD/kW	1600	830	628	425	IEA (2015); IEA (2019)
Component life						
Solar life	Years	25	25	25	25	Chawla, Aggarwal, and Dutt (2020)
Wind life	Years	25	25	25	25	Chawla, Aggarwal, and Dutt (2020)
AE stack life	'000 hours	75	95	125	150	IEA (2019)
AE balance of plant (BoP) life	Years	30	30	40	50	Buttler and Spliethoff (2018)
Hydrogen storage	Years	30	30	30	30	Ahluwalia et al. (2019)
Battery storage	Years	12.5	12.5	12.5	12.5	IRENA (2017)
PEMFC - Stack	'000 hours	60	80	80	80	IEA (2015)
PEMFC - BoP	Years	15	15	15	15	IEA (2015)
Performance parameters						
AE efficiency	%	66.5	68	75	80	IEA (2019)
Battery round trip	%	85	85	85	85	NREL (2019)
PEMFC	%	43	54	56	57	IEA (2015)
Financial parameters						
Discount rate	%	10	10	10	10	Authors' assumption

Source: Authors' compilation

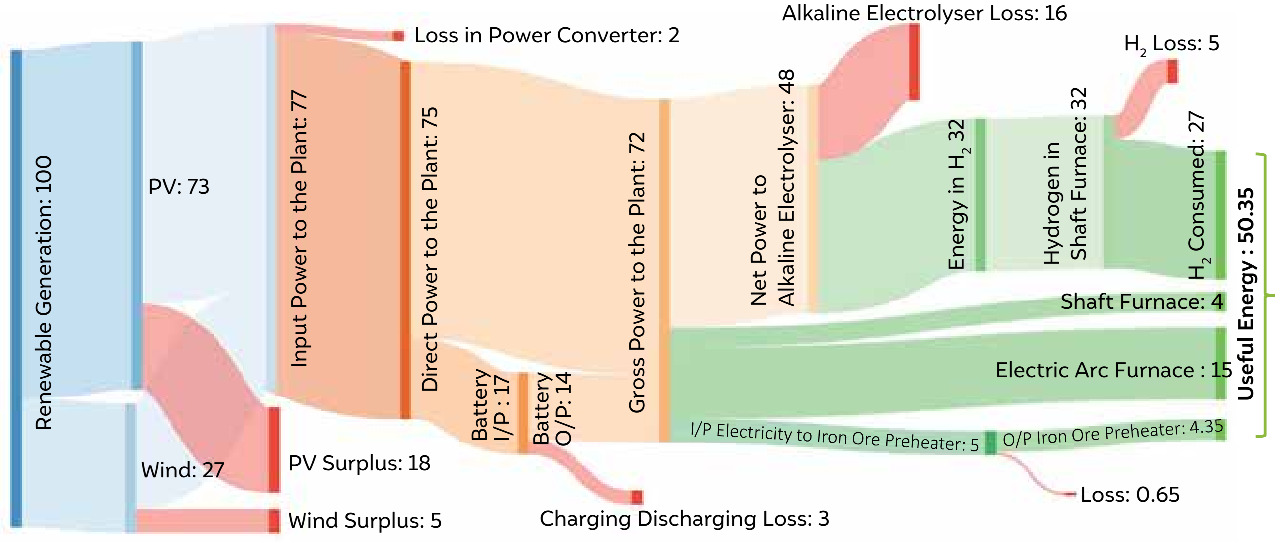
India is the second largest producer of crude steel in the world today. The national steel policy aims to double the production capacity by 2030.

Image: iStock

4. Results

Figure 4 shows the energy flow in the green steel plant that uses a WSH profile in Bellary, Karnataka, for the year 2020. The graph has been normalised for an energy input of 100 units from the solar and wind systems based on the annual performance of the green steel plant. Approximately 23 per cent of the power generated by the RE plants is surplus or excess, and will be curtailed if not off taken by the grid. There are losses in the power converter and in the batteries during the charging and discharging cycles. The AE has an efficiency of 66.5 per cent, implying that 1/3rd of the total power input is lost due to system inefficiencies. Finally, based on the literature (Hölling and Gellert 2018), we assume that 17 per cent of the hydrogen input to the shaft furnace is lost due to various inefficiencies. Note that the power input to the EAF unit is inclusive of energy input to the DRI and losses in the furnace. However, we do not separately indicate a detailed breakup of energy flow in the EAF unit in the current analysis. On a system level, we expect that 49 per cent of the total energy generated by the plant is lost due to curtailment and component inefficiencies.

Figure 4 About 49 per cent of the total power produced by the RE system is lost



Source: Authors' analysis

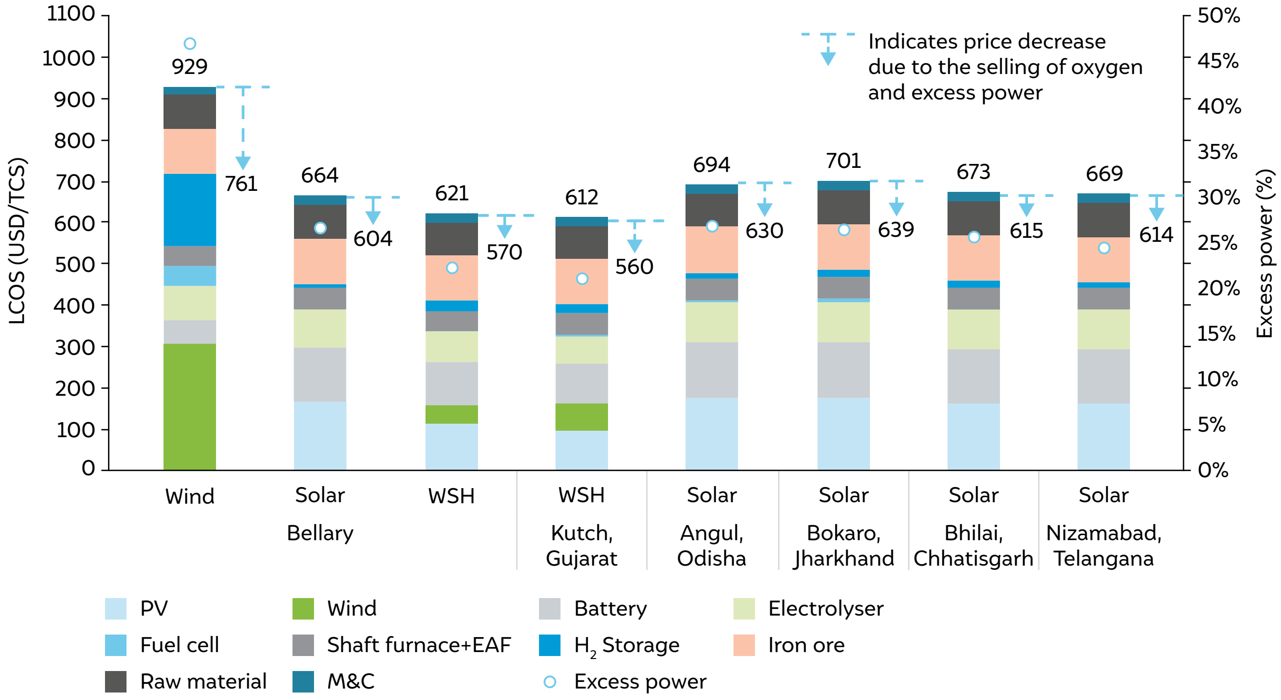
Figure 5 shows the variation in LCOS with solar, wind, and WSH profiles at Bellary, Karnataka. The effect of locating the steel plant in different geographies with WSH potentials like Kutch, Gujarat, and iron-ore rich regions with only solar potential like Angul in Odisha, Bokaro in Jharkhand, and Bhilai in Chhattisgarh is also indicated. However, our data indicate that these three states (Odisha, Jharkhand, and Chhattisgarh) do not have significant solar capacity. Therefore, we also consider a representative case of Nizamabad, Telangana, with substantial solar capacity located close to the steel hub on the east coast. We indicate the LCOS for an islanded system that curtails any excess power generated by the RE plants for the base case. In the stacked chart, we also do not consider any credits obtained by selling the by-product oxygen. These credits (obtained by selling oxygen and excess power) are indicated separately in the graph with an inverted arrow.

The levelised cost of steel (LCOS) in 2020 ranges between 612 and 929 USD/TCS, depending on the RE mix. The variation in cost is primarily due to renewable intermittency. It increases as the renewable profiles shift away from a WSH towards either solar-only or wind-only profiles. The wind profiles in Bellary indicate seasonal intermittencies. Hence, an additional buffer of hydrogen storage is required to ensure continuous operation during the low generating months. For certain months, when the available energy falls below the point needed for plant operation, the FC kicks in. Of note is the hydrogen storage size, which is significantly higher for the wind-based hydrogen production systems due to strong seasonality. The wind-based steel plant generates more than 46 per cent excess electricity. Therefore, if this power is off-taken at LCOE prices and the additional benefits due to the selling of oxygen are considered, the cost of steel reduces to 761 USD/TCS.

The overall efficiency of the green steelmaking process is less than 51%

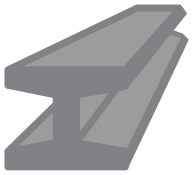
In contrast to wind-based steel production, the impact of seasonality is mitigated with solar-only profiles. Therefore, the hydrogen storage size decreases and there is a need for a relatively small capacity FC. However, the battery size increases in solar-alone operation to run the system at night. The magnitude of excess electricity decreases from 46 per cent in wind-alone systems to 26 per cent in solar-only operation. For a WSH, the share of wind-based electricity is 28 per cent in Bellary and 40 per cent in Kutch. This is because the wind profile in Bellary has a significant seasonality that disincentives the build-up of large wind capacities. Nevertheless, we expect the lowest production cost in Kutch, Gujarat, amongst all locations considered in the analysis. Due to low solar availability and the absence of any wind resources in iron ore-rich areas of Odisha, Jharkhand, and Chhattisgarh, the cost of producing steel is significantly higher than Bellary and Kutch.

Figure 5 WSH locations have the lowest levelised cost of steel (LCOS) in 2020



Source: Authors' analysis

By selling the oxygen obtained as a by-product during the electrolysis step, the LCOS decreases by ~16 USD/TCS (except for wind-only operation in Bellary). This corresponds to a nominal 2.5 per cent decrease in the overall costs. Further reduction can be achieved if the excess electricity is sold to the grid. For our analysis, we consider a case where the excess electricity is sold at levelised costs. If the excess power is monetised, the steel costs further reduce by 40-46 USD/TCS for solar, 34-35 USD/TCS for hybrid profiles, and 143 USD/TCS for wind-only locations. This corresponds to a decrease of 6-15 per cent in the cost of green steel.



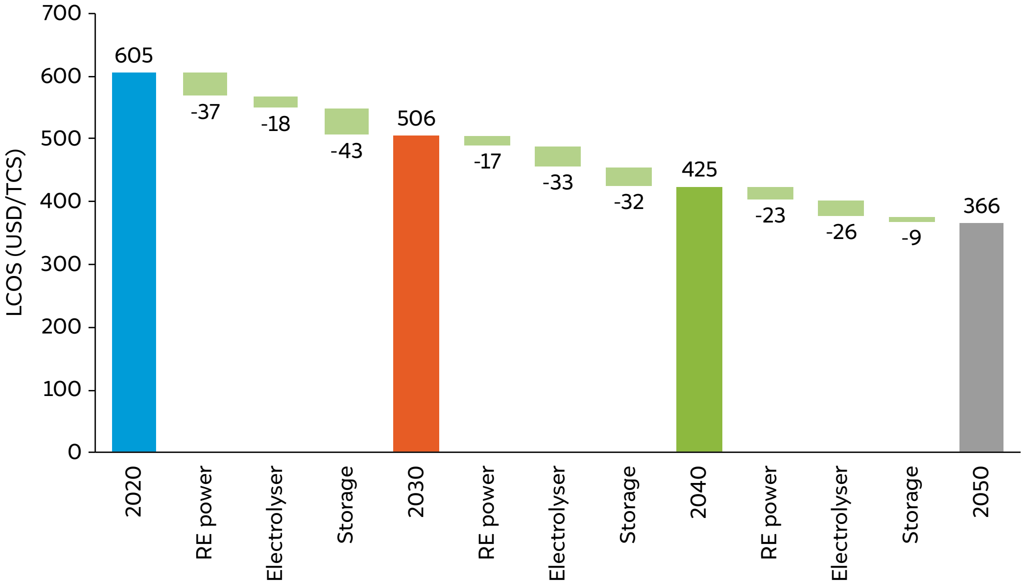
612-929$

The levelised cost of steel (LCOS) in 2020 ranges between 612 and 929 USD/TCS

4.1 Long-term cost trajectories

Figure 6 illustrates the waterfall chart for the decrease in steel cost with the reduction in capital costs of equipment and improvement in the process parameters. To indicate the price of steel across various temporal scenarios, we consider the benefit of selling the by-product oxygen but do not consider any perceived gains obtained by selling the excess electricity. We group the cost decrease into three significant components for ease of representation: renewable power, electrolyser, and storage. The cost decrease from electrolyser considers the gains from reducing capital costs and increasing stack efficiency and life. Similarly, the reduction in battery and hydrogen storage prices, and the increase in efficiency and life are grouped under a single entity named storage.

We expect that between 2020 and 2030 (mid-term), the optimal cost of steel will decrease by ~98 USD/TCS. We see that the cost reduction is primarily due to a decrease in RE and storage costs. We expect solar electricity prices to decrease from 30 USD/MWh in 2020 to 23 USD/MWh in 2030. Similarly, wind power costs are expected to drop from 32 USD/MWh in 2020 to 25 USD/MWh in 2030. The electricity prices indicated above represent the levelised cost, and do not consider any increase due to profits and taxes.



Note: Values rounded to nearest decimal

Figure 6
Decreasing trend in levelised cost of steel (LCOS) across various scenarios for Bellary, India

Source: Authors' analysis

A decrease in electrolyser CAPEX and its performance improvement can potentially decrease the cost of production by ~18 USD/TCS during the period. Based on the industry estimates and literature reviews, we assume that the CAPEX of the electrolyser will decrease from 750 USD/kW to 625 USD/kW. The electrolyser performance during the period is indicated by an increase in efficiency (66.5 per cent to 68 per cent) and the operating life (75000 hours to 95000 hours).

Finally, the decrease in hydrogen storage, electrochemical storage, and FC reduces production costs by 43 USD/TCS. These cost reductions consider the improvements in both efficiency and life of these components, and the decrease in capital costs across significant plant components. In the subsequent temporal scenarios, the impact of a decline in storage cost flattens out, and cost reductions are achieved essentially due to the decrease in RE and electrolyser costs.

Green steelmaking at WSH locations becomes competitive by 2040 and at solar-only locations only in 2050

During the mid- (2030) to long-term (2040) period, the optimal cost of production is estimated to further decrease by 82 USD/TCS. The LCOE of solar and wind power is expected to be ~20 USD/MWh. A significant share of the cost reduction is primarily driven by the improvements in electrolyser performance, stack life, and costs. The long-term CAPEX cost, efficiency, and life of electrolyser are assumed to be 450 USD/kW, 75 per cent, and 125000 hours, respectively. The hydrogen storage and battery cost are estimated to fall to 104 USD/kg and 100 USD/kWh, respectively.

In the long-term (2040 to 2050) period, the price of green steel is expected to be 366 USD/TCS, which is well within the cost range of fossil-based steel production. The cost reductions are primarily driven by the decrease in costs of RE and improvements in electrolyser technology. Nevertheless, green steel technology can become competitive with the fossil-based steelmaking process in the long term. The year in which green steel breaks even with the blast furnace route will essentially depend on the cost reductions achieved for various components of the green steel plant.

Figure 7 shows the plot of the LCOS across the four temporal scenarios for six locations in India. The estimates only consider revenues from the sale of oxygen. The range of blast furnace costs is shown in shades. The cost for NG + EAF route is indicated in orange for a gas price of 13.5 USD/MMBtu. The cost range is obtained for an electricity price of 3 INR/kWh (40 USD/MWh) to 7.6 INR/kWh (102 USD/MWh). The WSH (Bellary and Kutch) locations have approximately 7-13 per cent lower costs across all locations than solar-only locations in 2020. However, the cost difference progressively decreases to 4–7 per cent by 2050. Green steel is expected to become competitive for WSH locations with the upper range of blast furnace costs by 2040. However, the solar-only locations demonstrate higher prices than the blast furnace route, even in 2040. The benefit from the offtake of excess electricity can further reduce the costs by 35-46 USD/TCS, 26-32 USD/TCS, 17-19 USD/TCS, and 9-14 USD/TCS in 2020, 2030, 2040, and 2050, respectively. Nevertheless, green steelmaking breaks even with the blast furnace route in the long term (2050) and is a promising route to decarbonise the steel industry in the future.

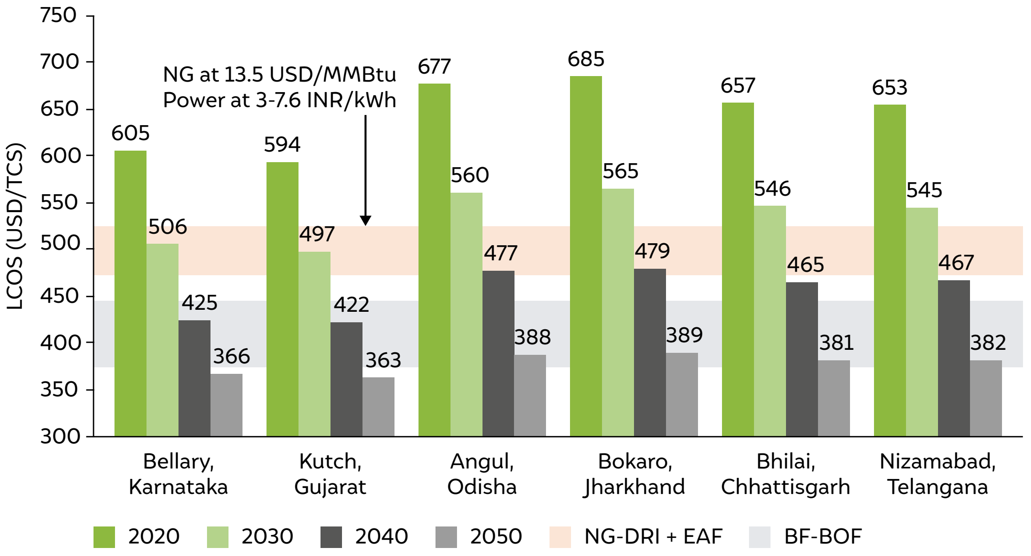


Figure 7
WSH locations (Bellary and Kutch) can break-even with NG DRI + EAF by 2030 and BF-BOF costs by 2040

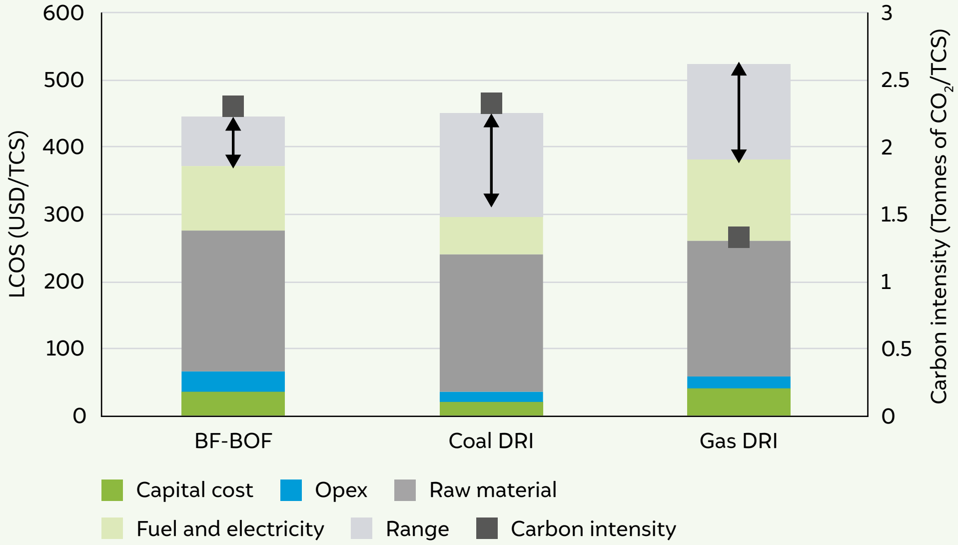
Source: Authors' analysis

Box 2

A comparison of costs and emissions footprint across conventional steel production technologies

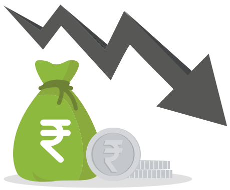
Figure 8 shows the cost and emission intensity of producing steel from the BF-BOF, coal, and NG-based DRI + EAF processes. The lower and higher range of costs are obtained using the lowest and highest values of SEC, fuel, and electricity prices (Annexure V). The coal DRI + EAF process has the largest variation in costs. This is primarily due to a wide variation in the SEC (18.70 to 26.11 GJ/tDRI) and coal prices (2.2 to 5.9 $/GJ). A more efficient operation allows the blast furnace to have the lowest operation cost despite having higher capex and energy costs compared to the coal DRI + EAF process. In contrast, the NG DRI + EAF process has the highest cost of production primarily due to high energy costs. The variation in production costs primarily reflects the variation of NG price (6.7 to 13.5 $/MMBtu). The underlying costs assumptions are presented in Annexure V.

Figure 8 Steel production costs and emissions from fossil-based routes



Source: Authors' analysis

The carbon emissions from the BF-BOF route are estimated to be 2.3-2.4 tonnes CO_2/TCS, based on industry sustainability reports (TSL 2019; JSW 2019) and published literature (IEA 2020a). Based on industry data, the emission intensity of the coal-based DRI + EAF route is estimated to be 2.4 tonnes of CO_2/TCS (Agrawal, Sahoo, and Mohanty 2015). The gas-based DRI + EAF process has the lowest emissions footprint of 1.3 tonnes CO_2/TCS. The underlying specific NG consumption and electricity demand are obtained from the literature (Fan and Friedmann 2021; IEA 2020a).

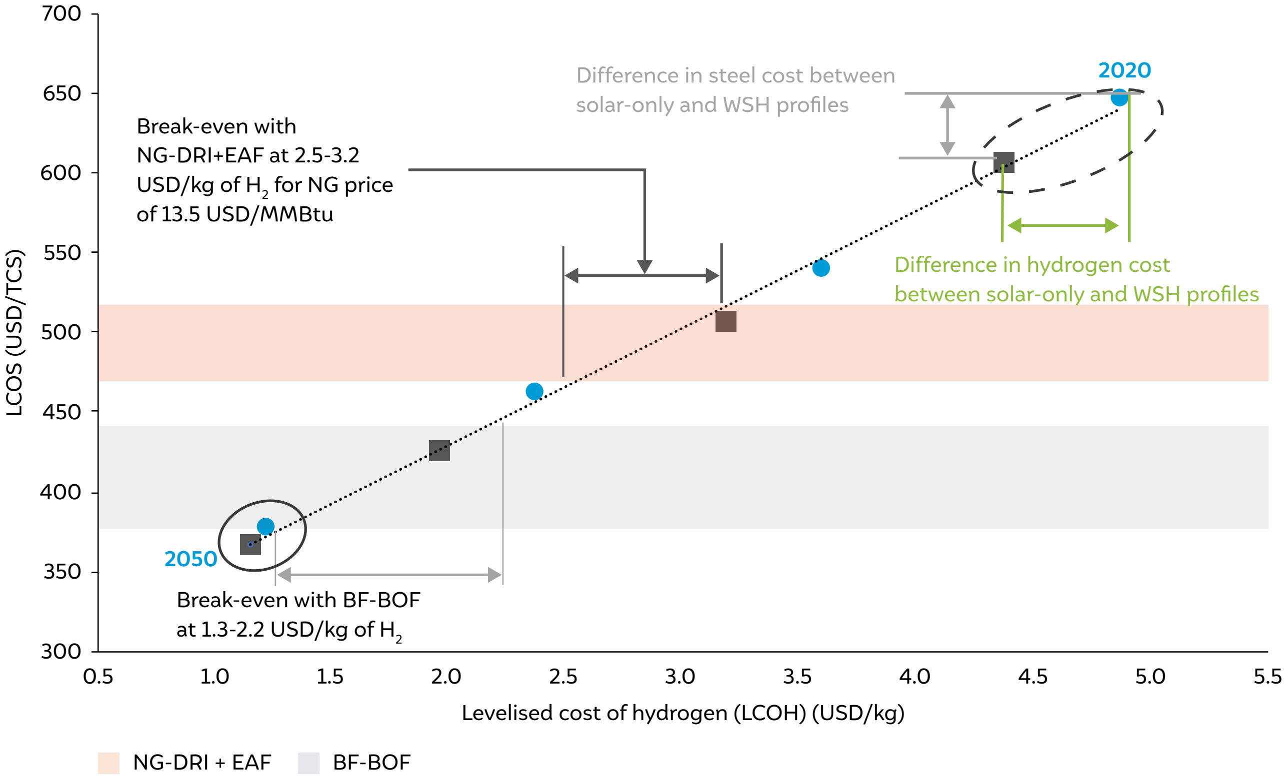


Green steelmaking breaks even with BF-BOF process at hydrogen price of 1.3-2.2 USD/kg

4.2 Linking steel cost with hydrogen production costs

Figure 9 shows the steel production costs as a function of the green hydrogen cost. We illustrate the relationship for Bellary, Karnataka, with WSH (black squares) and solar-only (blue circles) profiles. The data points indicate the cost of producing steel and hydrogen across various temporal scenarios starting from 2020 (top right) to 2050 (bottom left). The rate of hydrogen production in the green steel plant varies with time. Therefore, to relate the steel and hydrogen costs, we use the hydrogen generation profile of the green steel plant as an input to the green hydrogen production model (Biswas, Yadav, and Guhan 2020). For the same year, we observe that the steel and hydrogen production costs are higher for the solar-only profile (blue circles) compared to the WSH (orange squares). We expect the green steelmaking process to be competitive with the upper range of blast furnace costs for a hydrogen price of ~1.3-2.2 USD/kg, to break even with gas-based technologies at a hydrogen price of 2.5-3.2 USD/kg.

Figure 9 **Green steelmaking breaks even with BF-BOF processes if green hydrogen can be delivered at prices between 1.3 to 2.2 USD/kg**



Source: Authors' analysis

5. Accelerating green hydrogen-based steelmaking in India – key policy and technology imperatives

Image: iStock

The iron and steel industry already contributes to the lion's share (35 per cent) in the greenhouse gas emissions from the domestic manufacturing sector. An additional two-fold increase in the production capacity by retaining the existing fuel mix and technology choices will significantly affect India's future greenhouse gas emissions. It is imperative to ensure that any additional investment made in the sector does not lead to a technology lock-in, thus allowing a seamless transition to H-DRI as it becomes competitive. While the BF-BOF process remains the main workhorse of the industry, it has a limited technical potential to substitute coal with hydrogen. Further, any investments made in BF-BOF today will be recovered over the next 30-40 years.

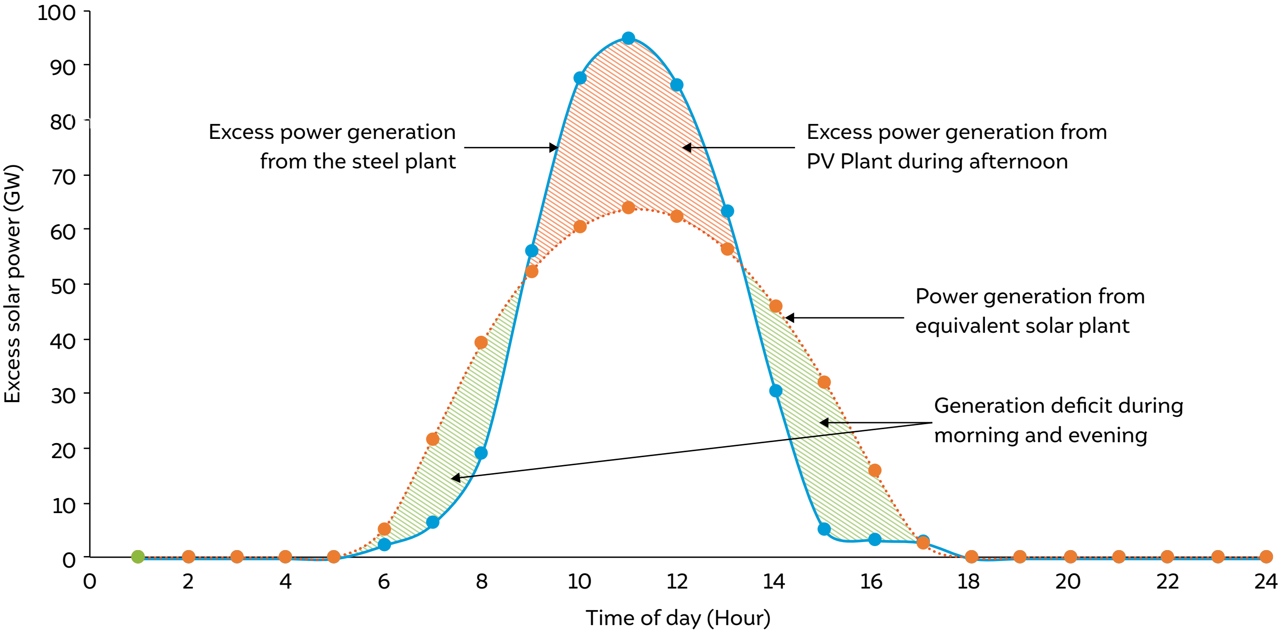
Our estimates indicate that with access to favourable renewable resources, the H-DRI process can become competitive with NG (at today's prices) in the medium to long term without imposing a carbon price. Further, it can also break even with the upper range of BF-BOF production costs by 2040. Adopting the hybrid H-DRI technology (using a combination of grey and green hydrogen) rollout in the medium term will ensure a low-cost transition to its green counterpart in the long run. The green-hydrogen process has a ~92–96 per cent lower carbon emissions footprint than conventional NG-based DRI and BF-BOF-based processes. However, the economic viability of the process is highly dependent on the availability of favourable RE profiles, lower tariffs, and aggressive price reductions in the electrolyser and storage technologies. It is imperative that the domestic policies address the right levers for commercialisation and large-scale deployment of green hydrogen-based steel production in the country.

BF-BOF process has a limited potential to blend hydrogen and any investments today will lock in future coal demand

5.1 A robust grid infrastructure to support large-scale deployment of green hydrogen-based steel production

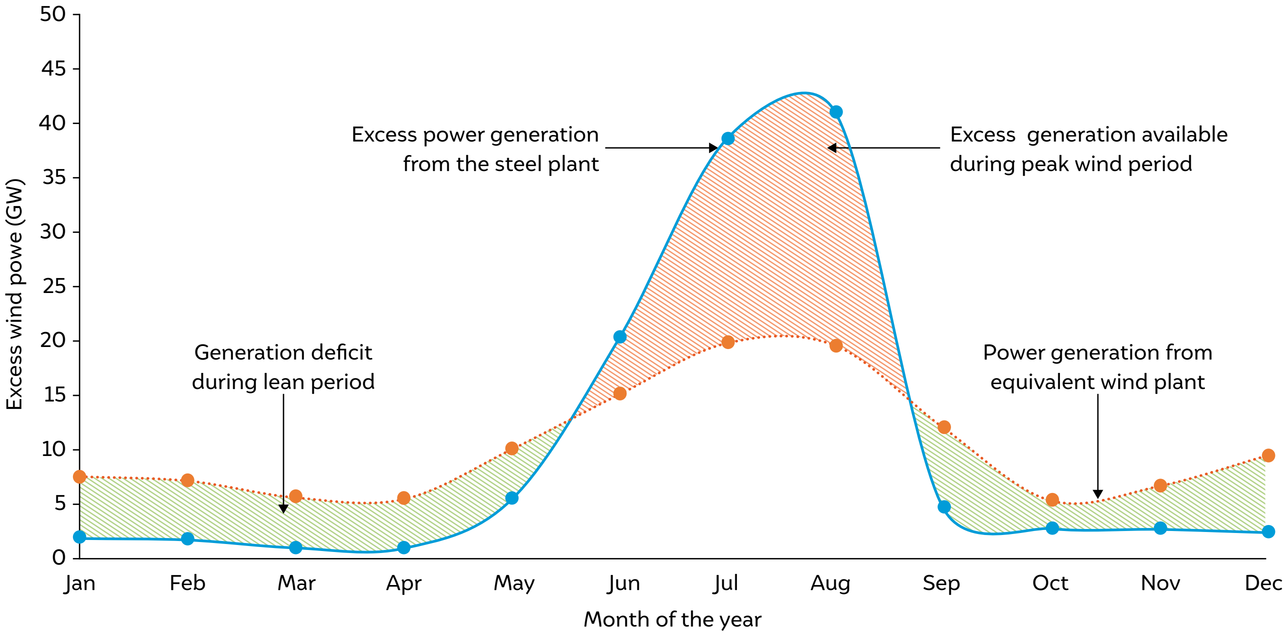
A 0.5 MTPA production capacity in Bellary will require 1157 MW of PV and 207 MW wind capacity. Further, the oversized system will also generate 580 GWh of excess electricity. Figures 10 and 11 indicate the time-of-day excess solar and seasonal excess wind power, respectively, for the 0.5 MTPA steel plant in Bellary. Excess solar and wind electricity are available only during peak periods of solar and wind availability. The magnitude of excess power produced in a year is equivalent to the annual power generation from 277 MW PV and 35 MW wind plants. However, as seen in Figures 10 and 11, solar and wind power generation from the equivalent renewable plant differs significantly from the excess renewable generation. For a solar plant, the equivalent solar plant generates more power during the morning and evening hours. The excess power from the steel plant is significantly higher during the daytime. Similarly, we see very high wind availability from the wind plant during the months of peak wind. During the lean months, the excess power from the steel plant decreases significantly. Therefore, it is essential to ensure that the power evacuation infrastructure is ready and flexible enough to support the large-scale deployment of hydrogen-based steelmaking.

Figure 10 Time-of-day excess solar electricity for Bellary, Karnataka



Source: Authors' analysis

Figure 11 Time-of-year excess wind electricity for Bellary, Karnataka



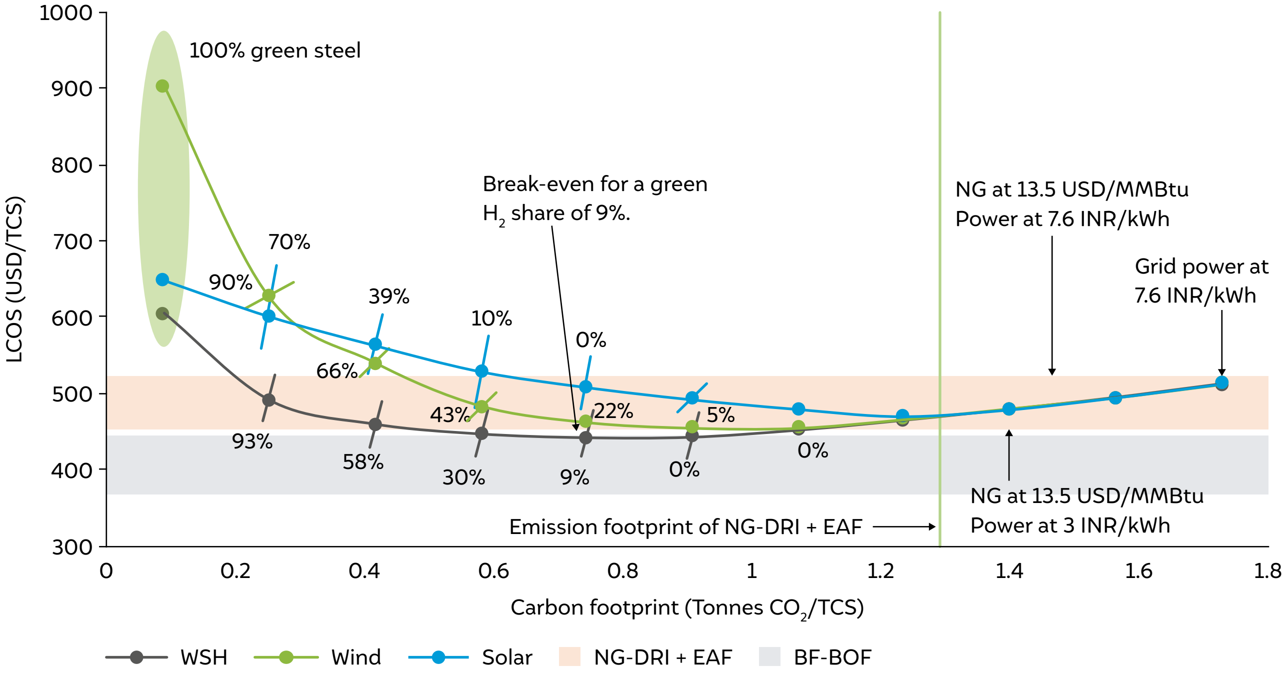
Source: Authors' analysis

5.2 Blending green hydrogen with grey hydrogen can simultaneously reduce production costs and emissions footprint, thereby incentivising a faster transition

The transition from fossil-based to green steelmaking will not be overnight. There will be a transition phase where renewable power is backed up with grid power, and green hydrogen is blended with grey hydrogen. Figure 12 shows the transition story for steelmaking in India. Here, we indicate the trend of variation in steel costs with the carbon footprint of steel for solar, wind, and WSHs for the year 2020. The curve is obtained for Bellary, Karnataka, which has access to both solar and wind energy. We consider that backup power from the grid is available at 102 USD/MWh (7.6 INR/kWh) with an increase of 13.33 USD/MWh (1 INR/kWh) between 6-10 pm and a decrease of 13.33 USD/MWH (1 INR/kWh) between 10 pm–6 am (KERC 2021a). In the model, we also allow flexibility to include a SMR unit. We consider capital, maintenance, and fuel costs as inputs to the model, and based on the emission constraint of steel, the model sizes for the SMR unit and its operating hours. For all cases, we consider an NG price of 13.5 USD/MMBtu as an input to the SMR unit.

As seen in Figure 12, the WSH offers significant advantages over solar- and wind-only profiles during the transition phase for fossil-free steel production. We notice that even in 2020, the hydrogen-based steelmaking breaks even with the lower end of the NG-based process for an emission footprint of 0.75 tonnes CO_2/TCS and a green hydrogen share of 9 per cent. An important observation is that during the transition phase, wind-only systems have lower costs than solar-only systems. However, for fossil-free steelmaking, the cost of a wind-based system increases significantly as the seasonal intermittency of wind energy increases the cost of energy storage. Therefore, a wind-only steelmaking plant needs to operate with a blend of grey hydrogen and grid electricity, and not aim for completely fossil-free steel production. Unlike wind-only systems, the cost increases proportionally for solar-only systems with a decrease in carbon footprint.

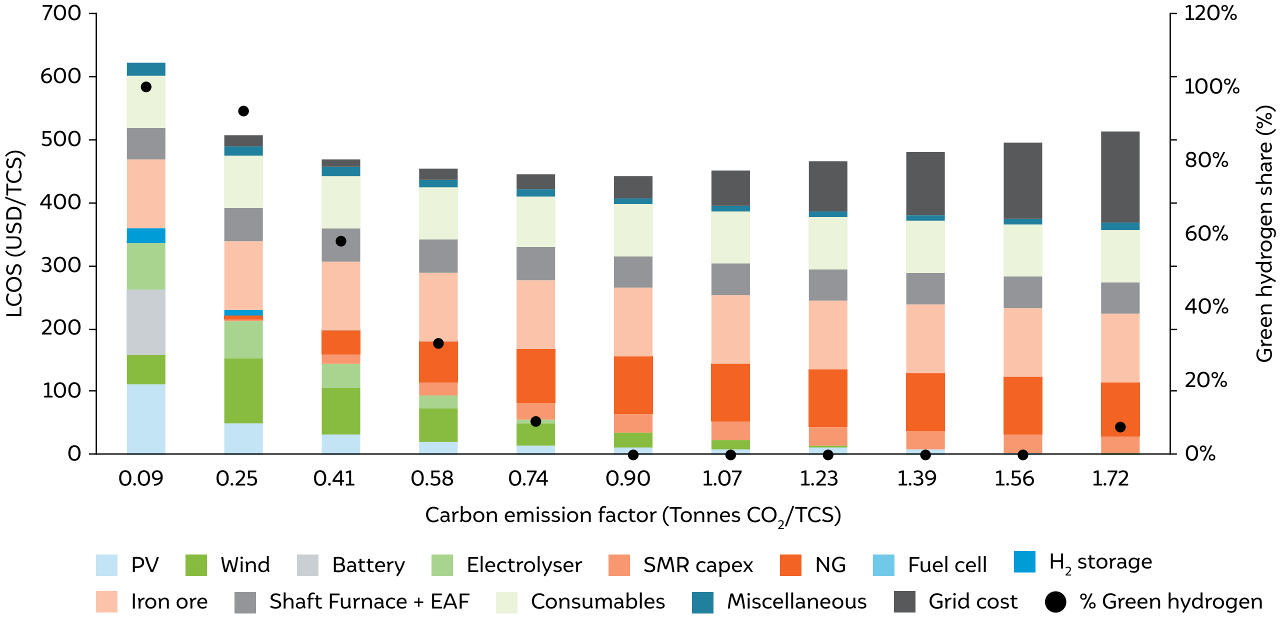
Figure 12 Wind-solar hybrid offers significant benefits in the transition phase (2020)



Source: Authors' analysis
Note: The values in percentage indicate the share of green hydrogen.

Figure 13 indicates the distribution of costs for various emission constraints on the primary Y-axis and the respective share of green hydrogen in the total hydrogen demand on the secondary Y-axis for a steelmaking plant in Bellary, Karnataka, which has access to both wind and solar energy. Emissions can be reduced from 1.73 Tonnes CO_2/TCS to 0.91 Tonnes CO_2/TCS by co-locating the H-DRI + EAF unit with captive wind and solar energy and using renewable power to manage the auxiliary loads in the plant. Even for an emission footprint of 0.91 Tonnes CO_2/TCS, the plant employs 100 per cent grey hydrogen. Green electricity alone significantly reduces the carbon footprint of the steel plant without the need for producing any green hydrogen. A further reduction of emissions intensity will require increasing the share of green hydrogen in the total hydrogen demand, thereby increasing the size of the electrolyser and RE systems. The WSH combines the advantages of solar and wind profiles. Therefore, for the transition phase, the share of wind energy in the mix is approximately 62-68 per cent and the remaining 38-32 per cent is obtained from solar energy. However, since wind has strong seasonality, the share of wind energy in the annual power consumption decreases to 29 per cent for fossil-free steelmaking. Furthermore, the share of battery and hydrogen storage costs increase significantly for fossil-free steelmaking, and thus, significantly increasing the cost of steel production.

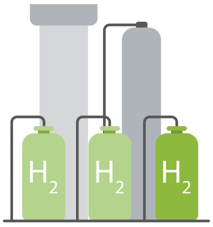
Figure 13 Emission footprint can be reduced by blending renewable power and green hydrogen in steelmaking



Source: Authors' analysis

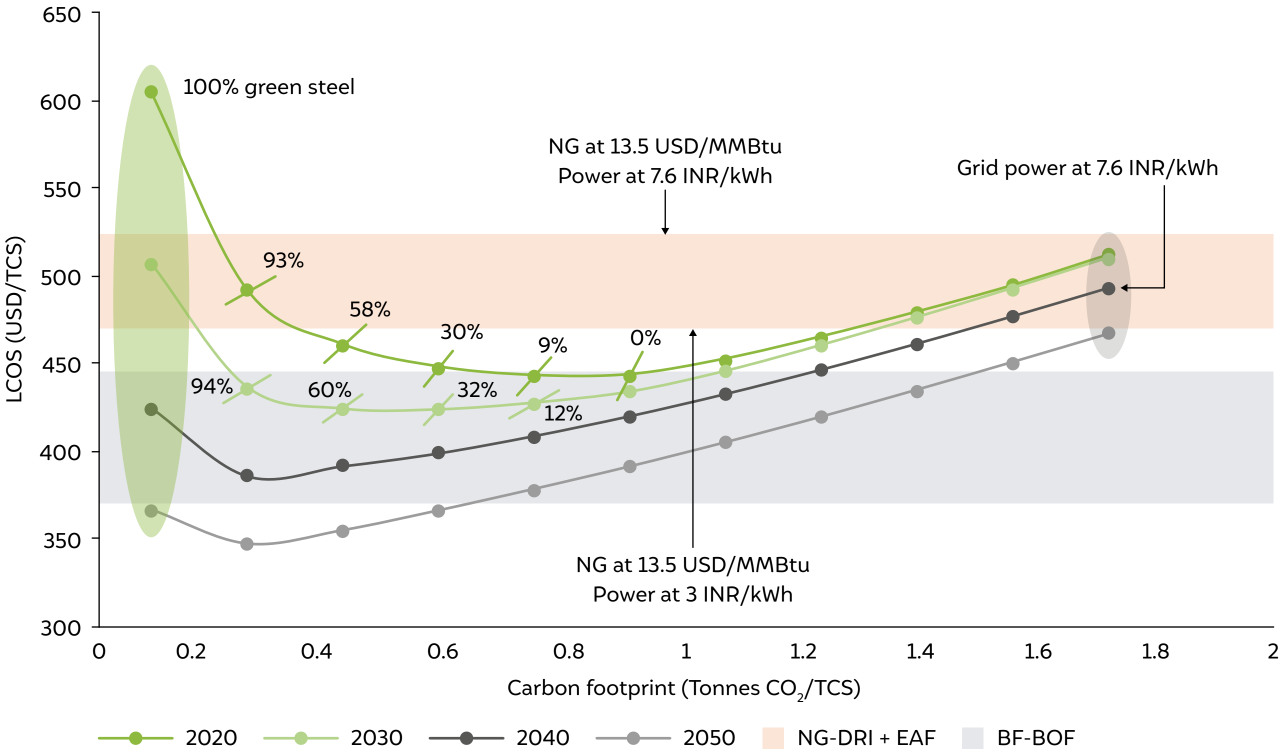
Figure 14 shows the transition curves for 2020, 2030, 2040, and 2050 in Bellary, Karnataka, with the hybrid wind-solar profile. The grey zone indicates the cost of producing steel from the BF-BOF process. The curves are shown for a system that initially uses grey hydrogen and grid power to transition towards RE and green hydrogen, respectively. In 2020, hydrogen-based steelmaking just about breaks even with the upper range (442 USD/TCS) of blast furnace cost for an emission footprint of 0.75 tonnes CO_2/TCS using 9 per cent green hydrogen in the plant. By 2030, it becomes competitive (with an LCOS of 424 USD/TCS) with the average blast furnace cost for an emission footprint of 0.57 tonnes CO_2/TCS by using 60 per cent green hydrogen. By 2040, it becomes competitive (with an LCOS of 386 USD/TCS) for an emission footprint of 0.4 tonnes CO_2/TCS . In this scenario, the emission constraint is met by using a mix of RE and grid power without the need of any SMR unit.

For the year 2020, steelmakers can install the shaft furnace and operate it with a mix of grey and green hydrogen. As the costs of renewable power, electrolysers, and storage systems decrease to the 2030 level, green hydrogen can be blended in the shaft furnace by up to 60 per cent. This simultaneously reduces both the carbon emissions and the overall production cost. Subsequently, when the costs across the hydrogen value chain decrease to the 2040 and 2050 levels, the steel units can reduce the emissions without requiring an SMR unit. In this scenario, the emission constraint at minimum cost value (0.25 tonnes CO_2/TCS) is met by using a blend of grid electricity and RE to power the electrolyser. However, for achieving fossil-free steelmaking, there is a very marginal gain in emissions at the expense of significantly increasing the costs. Therefore, for locations having access to wind and solar energy, it is ideal to operate at an emission footprint of 0.25 tonnes CO_2/TCS and not aim for fossil-free steelmaking. Moreover, as shown in Figure 13, a sudden transition to fossil-free



Today, steelmakers can blend up to 9% green H_2 and be competitive with the upper range of blast furnace costs steelmaking will need green field investments in additional solar installation and absorption of the excess wind capacity. Going ahead, this is expected to be a major barrier in moving to fossil-free steelmaking if the industry intends to follow a transition trajectory.

Figure 14 Incremental blending of green hydrogen and renewable power is the key during the transition phase (SMR + Grid power) for WSH profiles at Bellary

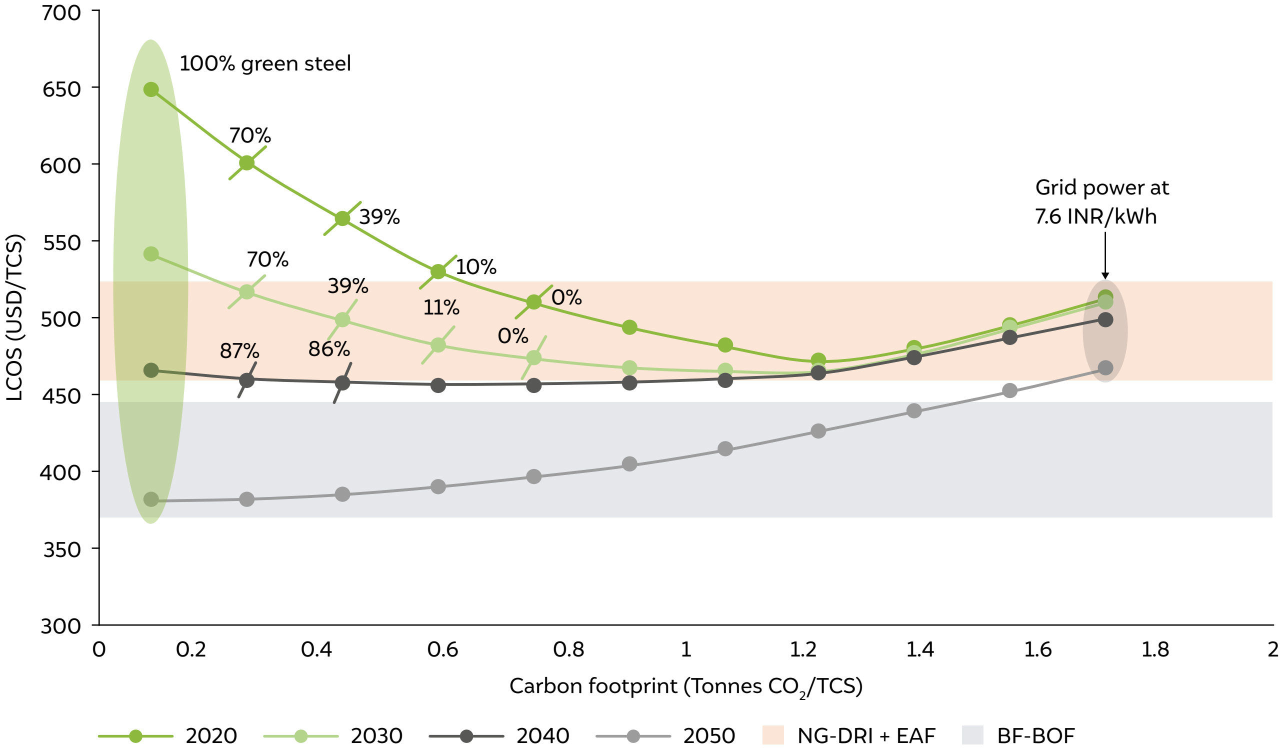


Source: Authors' analysis

Note: 1) The values in percentage indicate the share of green hydrogen. 2) The SMR unit is not needed in 2040 and 2050.

Figure 15 shows the transition story for Bellary, Karnataka, with a solar-only profile. Here, for the year 2020, the steel cost increases proportionally with the increasing blend of green hydrogen. Furthermore, unlike the WSH configuration, where the steel cost increases significantly for the last ten percentile of fossil-free steelmaking, there is only a proportional increase in steel cost. Therefore, locations with access to solar-only profiles can achieve fossil-free steelmaking without significantly compromising on costs. However, in the transition phase, the hybrid profile has a significant cost advantage over the solar-only profile. Unlike the WSH locations, production costs in solar-only locations break even with blast furnace production only in 2050. This showcases the significant advantages of co-locating wind and solar plants for green steelmaking.

Figure 15 Incremental blending of green hydrogen and renewable power is the key during the transition phase (SMR + Grid power) for Bellary with a solar-only profile

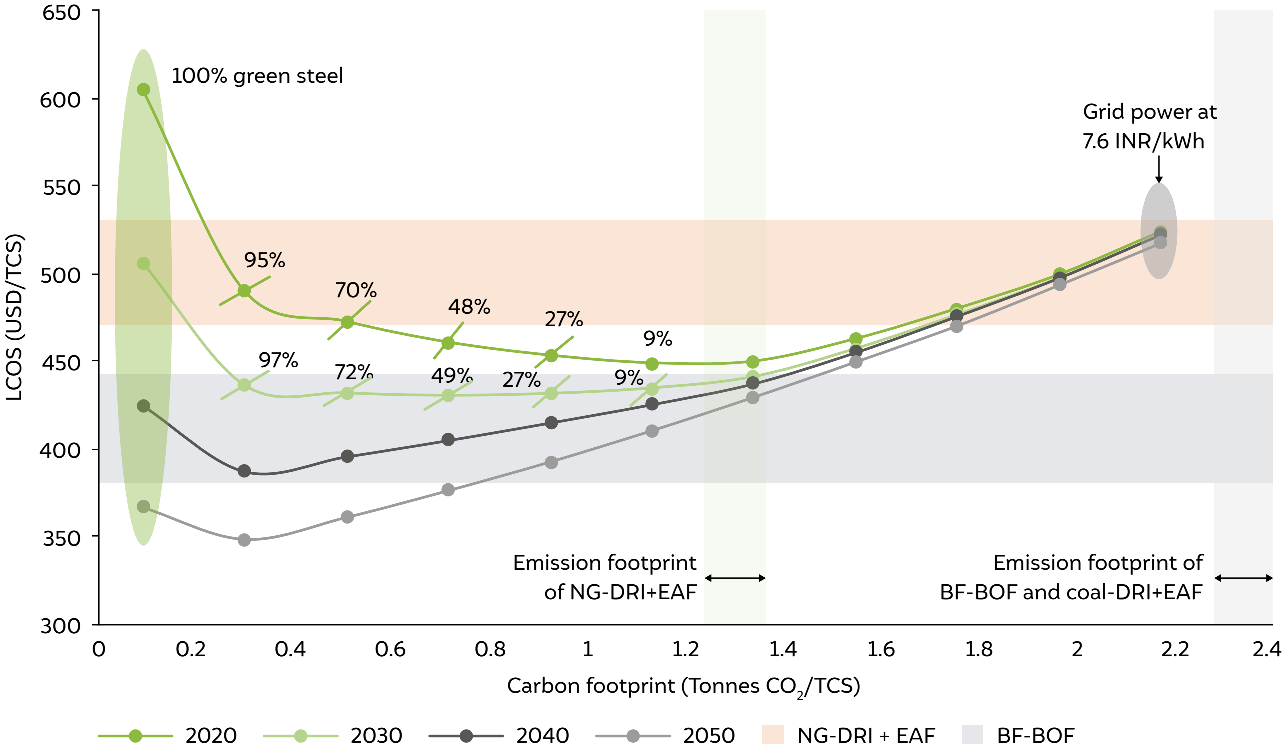


Source: Authors' analysis

Note: 1) The values in percentage indicate the share of green hydrogen. 2) The SMR unit is not needed in 2050.

Figure 16 shows the transition story for blending coal gasification derived hydrogen (black hydrogen) and grid power. For the coal-gasification process, the optimisation method is similar to the SMR unit, where we consider the capital, maintenance, and fuel costs as inputs to the model. The emission footprint of coal gasification-based hydrogen is higher than the NG process. Therefore, for grey steelmaking, the highest emission footprint of steel is 2.2 tonnes CO_2/TCS, unlike 1.75 tonnes CO_2/TCS for NG-based steelmaking. Further, the coal-gasification process has a higher transition cost than the NG-based process. The cost of hydrogen obtained from the coal gasification unit strongly depends on the capacity. For the 0.5 MTPA plant, the SMR and coal gasification plant are sized for a grey/black hydrogen production capacity of 0.15 TPH to 2.85 TPH. For such a small capacity plant, the cost of black hydrogen (obtained from coal gasification) is significantly higher than the grey hydrogen. The cost of steel with an emissions constraint of 1.12 tonnes CO_2/TCS is competitive with the upper range of blast furnace processes today. Further reduction in emissions and costs can be achieved in future scenarios. Interestingly, the coal gasification unit is not needed when costs reduce to 2040 and 2050, and the electrolyser produces hydrogen with a mix of RE and grid power.

Figure 16 Incremental blending of green hydrogen and renewable power is the key during the transition phase (Coal gasification + grid power) for WSH profile at Bellary



Source: Authors' analysis

Note: 1) The values in percentage indicate the share of green hydrogen. 2) The coal gasification unit is not needed in 2040 and 2050.

Box 3 Capital cost and component size for green steelmaking in India

Table 2 lists the capacities of various components for the 0.5 MTPA steel plant across emission factors of 0.1, 0.4, and 0.9 tonnes CO_2/TCS. It illustrates the component sizing for a WSH steel plant based in Bellary, Karnataka.

Table 2 Component size for the pilot, demonstration, and commercial-scale green steel plants

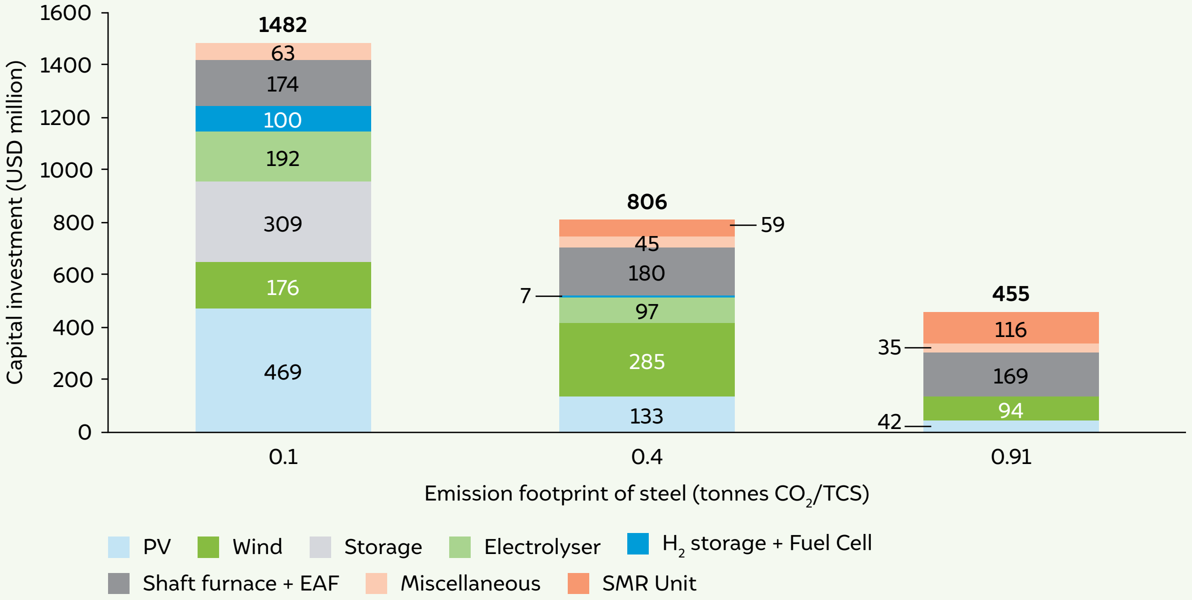
Sr. No.	Component	0.1 Tonnes CO_2/ TCS	0.4 Tonnes CO_2/ TCS	0.9 Tonnes CO_2/ TCS
1	PV (MW)	1157	328	103
2	Wind (MW)	207	336	111
3	Inverter (MW)	523	215	75
4	Battery Storage - Power (MW)	159	0	0
5	Battery Storage - Energy (MWh)	1218	0	0
6	Electrolyser (MW)	256	130	0
7	FC (MW)	0.3	0	0
8	Hydrogen Storage (Hours of demand)	67.4	4.4	0
9	Shaft furnace (TPH)	54	56	53
10	EAF (TPH)	59	61	57

Source: Authors' analysis

Figure 17 illustrates the investment needed across various components to set up a 0.5 MTPA hydrogen-based steelmaking plant operating with three emission footprint (0.1, 0.4, and 0.9 tonnes CO_2/TCS) constraints. The plot is illustrated for a WSH plant located in Bellary, Karnataka, for the year 2020. For fossil-free steelmaking, we expect renewable power, battery storage, and electrolyser to form approximately 80 per cent of the capital investments needed to set up the plant. Our analysis suggests a capital investment of ~USD 3 Billion (INR 22000 crore) per MTPA of fossil-free steel output.

For a hybrid configuration with an emission intensity of 0.4 tonnes CO_2/TCS, the capital cost reduces to ~USD 1.6 billion (INR 12000 crore) per MTPA. Further, with an emission intensity of 0.9 tonnes CO_2/TCS, we expect a capital investment of INR ~USD 0.9 Billion (7000 crore) per MTPA. This is marginally higher than the investment needed for setting up an integrated steel plant. Table 3 shows the land, water and energy requirement for green steelmaking.

Figure 17 Capital cost decreases significantly for a blended (green+grey) configuration (0.5 MTPA plant).



Source: Authors' analysis

Table 3 Land, water, and energy requirement for green steelmaking

	Land	Water	Electricity
Consumption intensity	30630 acres per MTPA	2.93 tonnes per TCS	5.3 MWh per TCS
To produce 111 MTPA of green steel (equivalent to India's steel output in 2019)	3.4 million acres	325.3 MTPA	264 GW of solar
	7 per cent of Gujarat's land area	16 per cent of Gujarat's annual supply	59 per cent of India's 450 GW target by 2030

Source: Authors' analysis

5.3 Creating a hydrogen-ready iron and steel industry in India

BF-BOF require investments of 676 million USD /MTPA locking in coal demand for 30-40 years

The primary iron-making industry in India is based on blast furnace technology. Over the years, the share of pig iron in India's iron production has decreased from 81 per cent in 2002 to 67 per cent in 2019 due to the increased production of sponge iron (WorldSteel 2020). However, India's sponge ironmaking technology is primarily based on RK technology that use coal as an energy source. Notably, the share of gas-based technologies in the whole ironmaking process was a modest 8 per cent in FY 2015-16 (IBM 2019).

A challenge with the existing coal-based routes (blast furnace and RK) for iron production is that these technologies do not allow a 100 per cent transition to hydrogen. Studies indicate that only 27.5 kg/THM of hydrogen can be injected in blast furnaces and can reduce carbon emissions by a maximum of 21.4 per cent (Yilmaz, Wendelstorf, and Turek 2017). The trial runs on hydrogen injection in blast furnaces target carbon reductions up to 20 per cent as compared to coke and PCI operation (Thyssenkrupp 2019). Further, there is limited literature on the amount of hydrogen that can be injected in the RK, although RK used in the cement industry can operate with a hydrogen feed of 20-50 per cent (Mineral Products Association, Cinar Ltd, and VDZ gGmbH 2019). Nevertheless, a key take-away is that coal-based technologies are not well-placed to transition to zero-carbon fuels like hydrogen.

Blast furnaces require investments to the tune of 676 million USD /MTPA (Environment Clearance 2015) and are recovered across a period of 40 to 50 years (IEA 2020a). Hence, any investments, if already made, will be challenging to decarbonise and will lock-in significant volumes of coal over the years. The majority of the Indian blast furnaces are also very young, with an average life of 13 years (IEA 2020a). Give that steel production in India is expected to double in the next decade, there is an opportunity to deploy hydrogen-ready technologies.

Shaft furnaces are hydrogen ready and can operate with a varying blend of green hydrogen. Further, they can be readily adapted to 100 per cent green hydrogen blends (Midrex 2018). Therefore, any investment decisions today should consider medium-to-long term transition plans for fuel switching. Given that shaft furnaces can operate with syngas derived from NG or coal gasification, industries must make a conscious decision to invest in hydrogen-ready technologies that can catalyse an eventual transition to green hydrogen.

5.4 Thorough evaluation and planning of raw-material and power infrastructure is critical to leverage the low-cost hydrogen produced in renewable rich states

The availability of solar and wind resources, low tariffs, and adequate land makes specific locations attractive to green hydrogen production. However, these locations are also located far away from the potential demand centres, requiring optimal supply and distribution infrastructure planning. Figure 18 shows the installed solar and wind plants in India (on the left), and the iron ore-rich areas along with steelmaking units (on the right). The size of the respective shapes is proportional to the installed capacity. In the figure, we cover 30 GW of solar and 38 GW of wind installed capacities representing 83 per cent and 100 per cent, respectively, of the total installed capacities till December 2020 (PIB 2020). The image on the right indicates iron ore mines, integrated steel plants, and coal and gas-based sponge iron units. Notably, the steel plants are concentrated in the Indian states of Odisha, Chhattisgarh, Jharkhand, and Karnataka. The three states in the east (Odisha, Chhattisgarh, and Jharkhand) do have wind installations and only have 1.8 per cent of India's total solar installed capacity but caters to 45% of national steel demand (PIB, 2019). These locations do not have any wind potential. Furthermore, only the steel plants located in and around Bellary (Karnataka) have access to utility-scale wind and solar plants.

Odisha, Chhattisgarh and Jharkhand only have 1.8% of India's solar capacity but cater to 45% of national steel demand

To assess the impact of not having access to co-located RE and iron ore resources for most of the country's steel plants, we evaluated several scenarios to estimate their supply chain costs. We consider a case of installing a RE plant in Kutch, Gujarat, and a steel plant in Angul, Odisha. Further, we consider the following three scenarios:

- Green hydrogen (from solar/wind power) is produced in Kutch, Gujarat, and transported to Angul, Odisha, by trucks and pipelines. The auxiliary electricity demand in the green steel plant located in Angul is met through open access to renewable power produced in Gujarat.
- RE (solar power) is produced in Kutch, Gujarat, at 2.2 INR/kWh and transported to Angul, Odisha, by the open-access mechanism (See Annexure-IV). The magnitude of renewable power is sufficiently high (4.1 MWh/TCS) to meet the auxiliary plant load and generate green hydrogen in the plant.
- Steel plants are set up in Kutch, Gujarat, and iron ore is transported from Angul, Odisha, by railways.

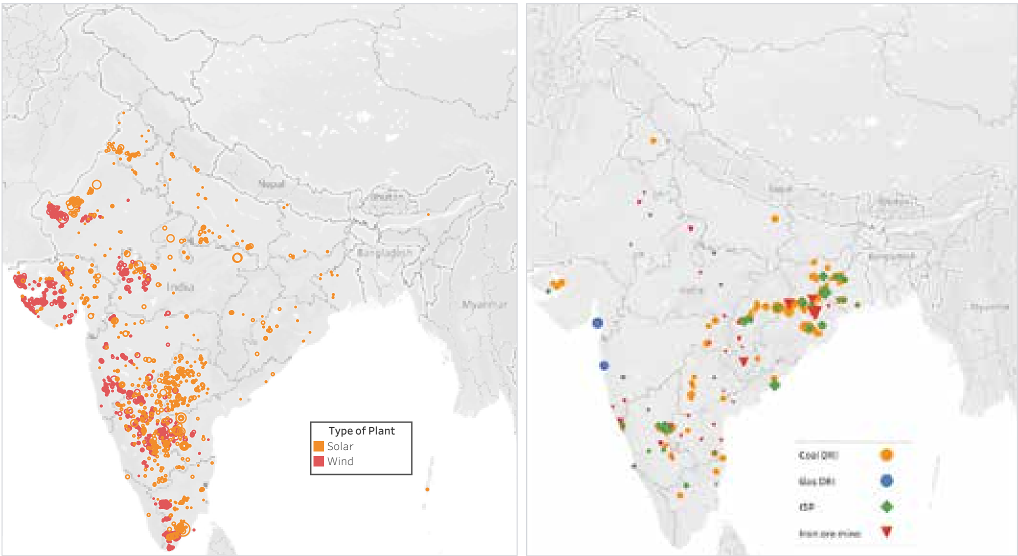


Figure 18
The iron ore-rich areas in India do not have access to large volumes of renewable energy

Source: Authors' analysis

Table 4 shows the transport scenarios considered for the analysis. Across scenarios, the increase in steel cost is the highest for liquid hydrogen transport. The increase in cost due to hydrogen transport in pipelines (having a capacity of ~500 TPD) and renewable power with open access is also significantly higher than transporting iron ore through railways. A key issue with transporting RE is uncertainty and fluctuations in open-access charges. Green hydrogen-based steelmaking is a capital-intensive process. Investors will need long-term stability in the open-access charges to minimise the investment risks. The transportation cost of hydrogen in a pipeline is inversely proportional to pipeline volumes. Reducing the pipeline capacity to 100 TPD will increase the transportation tariff to 3.5 $/kg of hydrogen. This will make it more expensive than transporting liquid hydrogen in trailers. However, setting up large-scale hydrogen pipelines is highly capital intensive and will require off-take guarantees well before the project's construction. India is already planning to add another 15,000kms of NG pipeline soon; careful infrastructure planning is needed to avoid the build-up of expensive stranded assets. One such alternative is to retrofit the existing pipeline or deploy hydrogen-ready pipelines. While transporting iron ore is the cheapest option, the rail infrastructure in the country will constrain the annual capacity that can be transported. Furthermore, similar to the open-access tariffs, the rail transportation charges also fluctuate, thus increasing the investment risks. Perhaps the RE-rich areas in India in the west can use imported iron ore for producing green steel. However, only locations with access to the port and renewable power can benefit in such a scenario. Nevertheless, we expect the price of green steel to roughly increase by 10-15 per cent due to the logistical challenges in moving iron ore and renewable power/hydrogen.

Transporting iron ore from Angul to Kutch is cheaper than moving renewable energy and hydrogen from Kutch to Angul

Table 4
Transport scenarios considered for the analysis (Kutch, Gujarat, to Angul, Odisha and vice-versa)

Sr. No.	Transport medium	Sourced from	Delivered to	Transport tariff	Consumption	Total transport costs (USD/ TCS)*
1.a	H_2 (Liquid) + RE power (Open access)	Kutch	Angul	2.57 USD/kg H_2 +1.65 INR/ kWh	50 kg H_2/TCS + 1.6 MWh/ TCS	163
1.b	H_2 (Pipeline) + RE power (Open access)	Kutch	Angul	1.20 USD/kg H_2 +1.65 INR/ kWh	50 kg H_2/TCS + 1.6 MWh/ TCS	95
2	RE power (Open access)	Kutch	Angul	1.65 INR/kWh	4.1 MWh/TCS	90
3	Iron ore (Railways)	Angul	Kutch	41.2 USD/t-Ore	1.4 t-Ore/TCS	58

** Assuming USD to INR conversion rate of 75*

Source: Authors' analysis

5.5 R&D and technology demonstration partnerships to establish commercial feasibility

Horizon technologies like green-hydrogen-based iron making can significantly mitigate emissions from the iron and steel sector. However, these technologies also have equally high risks due to the possibilities of technology failures, and other unanticipated factors like ecological effect or geopolitical events (Biswas, Ganesan, and Ghosh 2019). Therefore, rapid scaling of horizon technologies will need collaborative research from industry, government, and academia that will often extend beyond the national boundaries. However, the current research and development (R&D) ecosystem in India is frail. R&D investments in the country represented a meagre 0.65 per cent of the gross domestic product compared with the global average of 2.3 per cent in 2018 (The World Bank 2020).

R&D investments within the steel industry also remained sparse. According to a report by the Ministry of Steel, the average R&D expenditure by the Indian steel plants remained at less than 1 per cent of their annual turnover (MoS 2020). In 2017-18, the total R&D investment by major public sector undertakings like the Steel Authority of India and the Rashtriya Ispat Nigam Limited were USD 46 million and USD 3 million, respectively. In the same year, Tata Steel, a leading private sector player, had spent USD 25 million (MoS 2020). In comparison, the total investment planned or earmarked by major global steelmakers on innovative steelmaking technologies amounts to USD 14.7 billion (Figure 19).

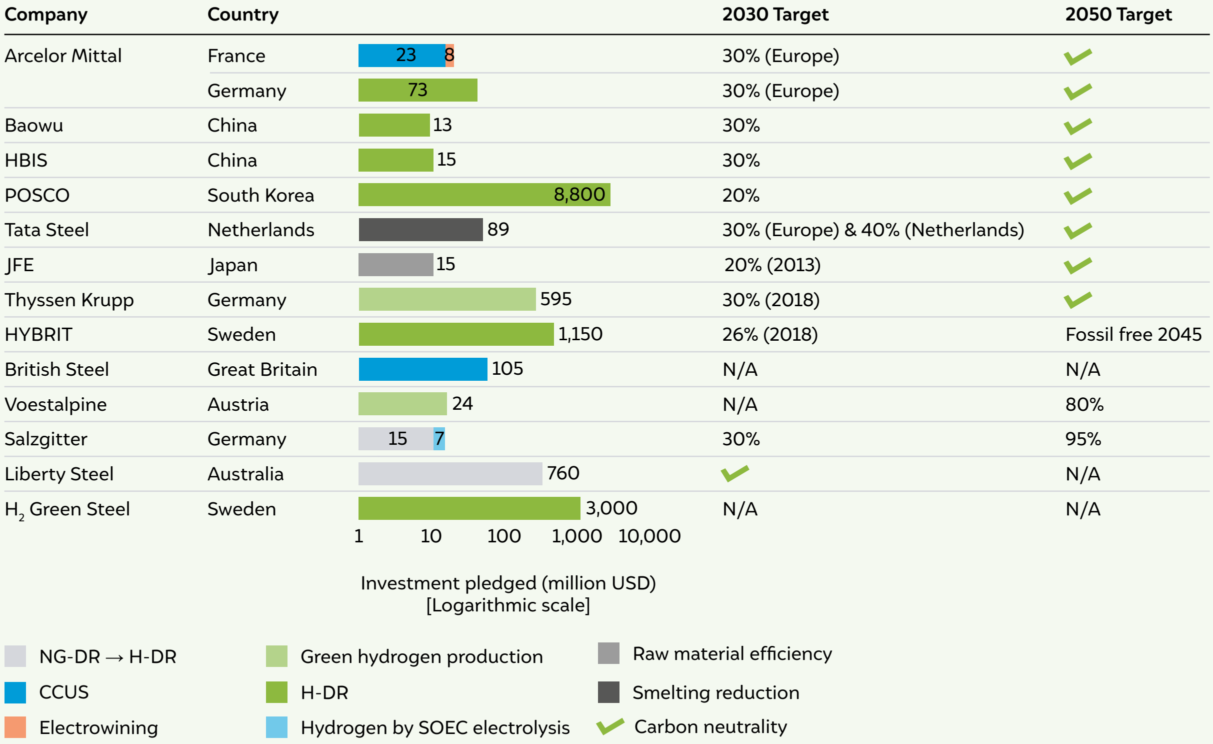
In 2017-18, the average R&D expenditure by Indian steel plants was less than 1 per cent of their annual turnover

Globally, several industry-government research collaborations on green hydrogen-based applications are already underway. For example, a joint venture founded by Swedish companies SSAB, Luossavaara-Kiirunavaara Aktiebolag, and Vattenfall aims to achieve 100 per cent fossil-free steelmaking by 2035. Their pre-feasibility study indicates that the green hydrogen-based steelmaking cost is 20-30 per cent higher than the conventional process (BF-BOF) (HYBRIT 2017). Further, Voestalpine, an Austrian steel company in partnership with Siemens and VERBUND, has installed a 6 MW electrolyser in their steelmaking plant in Linz (H2Future 2019a). Domestic policies should nudge domestic steelmakers to institutionalise increased R&D spending and participate in technology collaboration and pilots. Further, earmarking a certain percentage of the funds towards low-carbon technology pilots will support a faster transition.

Box 4 Global developments in low-carbon steel production

Figure 19 shows the investments needed to realise the low-carbon technologies planned by various industries. Notably, a majority of the investments in clean technologies are in favour of hydrogen-based steelmaking and green hydrogen production. A few industries are also planning investments in CCUS and blending green hydrogen with NG. We also indicate 2030 and 2050 (along with the base year wherever available) emission reduction targets set by the companies globally. Most of these investments in low-carbon technologies are concentrated within developed countries. India remains the only country within the top-three steelmakers that is yet to invest in these low-carbon steelmaking technologies.

Figure 19 Investment needs for realising low-carbon technologies

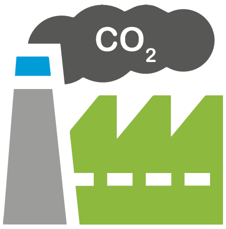


Company	Country		2030 Target	2050 Target
Arcelor Mittal	France	23 8	30% (Europe)	✓
	Germany	73	30% (Europe)	✓
Baowu	China	13	30%	✓
HBIS	China	15	30%	✓
POSCO	South Korea	8,800	20%	✓
Tata Steel	Netherlands	89	30% (Europe) & 40% (Netherlands)	✓
JFE	Japan	15	20% (2013)	✓
Thyssen Krupp	Germany	595	30% (2018)	✓
HYBRIT	Sweden	1,150	26% (2018)	Fossil free 2045
British Steel	Great Britain	105	N/A	N/A
Voestalpine	Austria	24	N/A	80%
Salzgitter	Germany	15 7	30%	95%
Liberty Steel	Australia	760	✓	N/A
H_2 Green Steel	Sweden	3,000	N/A	N/A

Source: (Vogl et al. 2021)

5.6 Regulatory drivers for a faster transition to the hydrogen economy

The domestic steel industry has large-scale integrated steel plants and medium to small-scale secondary producers. However, unlike the ISPs, most of these smaller coal-based DRI-EAF units operate using substandard and inefficient production processes. The typical energy intensity of the coal-based DRI units is estimated to be ~21 GJ/tonne DRI compared with the globally BAT of ~18.8 GJ/tonne DRI (Gupta 2014). The absence of a regulatory mechanism penalising such production inefficiencies and associated environmental effects allows such producers to compete in the market. Let alone CO_2 emissions, the existing emissions standards for these DRI units only cover particulate matter emissions, whereas SO_x and NO_x emissions are left unchecked (MoEFCC 2012). As a first step, the Central/State Pollution Control Boards need to conduct a detailed assessment of the existing processes and technologies to revise the emissions standards for the steel industry and simultaneously establish a robust monitoring infrastructure. Further, a gradual tightening of the emissions norms will automatically preclude the use of polluting fuels. Enforcing strict emissions norms now will ensure that the additional ~200 million TCS to be built are compliant and with a lower transition cost.



The existing emissions standards for these DRI units only cover particulate matter emissions, whereas SOx and NOx emissions are left unchecked

Besides non-economic drivers, the transition to the hydrogen economy will necessitate implementing a pricing mechanism that penalises the polluting fuels and incentivises their cleaner alternatives. While the future price projections of hydrogen-based steel are encouraging, they are contingent on the commercialised volumes in the near term. Hence, there is a need for an emissions mitigation mechanism that can spur investments at least in locations with favourable renewable profiles.

5.7 Create a domestic market for green steel

The domestic steel industry is struggling to remain competitive and is constantly threatened due to cheaper imports. A transition to cleaner manufacturing processes will adversely affect its competitiveness unless markets absorb the incremental cost of low-carbon steel. Governments across many countries have leveraged the market forces to create demand for environment-friendly products and services. The South Korean government is supporting a transition to a low-carbon lifestyle by offering credit card reward points on the purchase of green products (ClimateAction 2011). Similarly, in India, the Bureau of Energy Efficiency (BEE) is supporting a market transition towards energy-efficient appliances by promoting consumer awareness through its *Star Labelling Programme* (BEE 2019).

Across the various end-users of steel, the construction sector is the single largest consumer, representing ~62 per cent of the steel consumed in 2019 (PWC 2019). Demand for low-carbon steel in the sector will unlock investments in cleaner manufacturing technologies. The public procurement mechanism can create demand for low-carbon steel in the ongoing large-scale infrastructure projects such *AMRUT*, *Bharatmala*, and *Sagarmala*. Further, the inclusion of low-carbon steel as an alternative and sustainable building material within the green building rating systems such as *Leadership in Energy and Environment Design*, and *Green Rating for Integrated Habitat Assessment* will promote consumer awareness.

6. Conclusion

Expanding production capacity with the existing set of technology options in the iron and steel industry will significantly affect the country's future greenhouse gas emissions. The findings from our report will help strengthen both the *National Hydrogen Energy Mission* and *National Steel Policy 2017* in supporting the transition to green hydrogen-based steel production. We find that a 100 per cent green hydrogen operation only becomes viable in the next two decades. Our results comparing the production costs across various locations indicate that access to wind and solar resources is critical towards an early break-even with the conventional production processes. Producing green steel using only solar resources (which is true for most locations in the country) will push back the break-even period to 2050.

A faster way to incentivise the transition is by blending green hydrogen with conventional grey hydrogen (produced from SMR). The high renewables intermittency costs of 100 per cent fossil-free operation can be significantly reduced by blending 7 per cent grey hydrogen while marginally increasing the emissions footprint of the process. At today's prices, blending ~9 per cent of green hydrogen (with grey hydrogen) is competitive with the upper range of BF-BOF costs. Nevertheless, our findings indicate that green hydrogen is a promising technology to decarbonise the sector.

At today's prices, blending ~9% of green hydrogen (with grey hydrogen) is competitive with the upper range of BF-BOF costs

We also highlight the major challenges in transitioning to green hydrogen-based steel production. A green steel plant needs an investment of USD 3 Billion per MTPA, more than three times the conventional BF-BOF route. Considering the current situation of thin R&D and innovations investments by steelmakers (less than 1 per cent of their annual turnover), the transition will be extremely challenging. Further, converting the current steelmaking capacity to green hydrogen-based production will require 264 GW of solar capacity and annual water consumption representing approximately 16 per cent of Gujarat's annual water supply.

We recommend that the current policy framework should incentivise increased R&D investments to evaluate the performance and production costs across the various transition pathways. Further, a detailed evaluation of raw-material and energy (including hydrogen) delivery infrastructure will help identify the optimal locations of future investments and evaluate the potential impact on jobs and revenues due to a potential shift in existing supply chains. Our recommendations are aimed at strengthening the existing policy framework to support a green hydrogen transition in the steel industry.

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Annexures

Annexure I

Table A1 shows the material-energy balance of the hydrogen-direct reduced iron (H-DRI) + electric arc furnace (EAF) plant for producing green steel. The stream numbers are identified in Figure 3. The material-energy balance is indicated for a typical operating hour of the plant with a wind-solar hybrid (WSH) plant in Bellary for the year 2020.

Table A1 Material-energy balance for the hydrogen-based direct reduced ore + electric arc furnace plant

Stream	Flow			Mass (kg/h)	Temperature (K)
	Stream	From	To		
1	Water	Tank	Electrolyser	23277	298
2	Hydrogen	Electrolyser	Mixer	5100	298
3	Hydrogen	Mixer	Hydrogen storage	2164	298
4	Hydrogen	Hydrogen storage	Mixer	0	298
5	Hydrogen	Mixer	Hydrogen splitter	3982	298
6	Hydrogen	Splitter	Heat exchanger	3982	298
7	Hydrogen	Splitter	Fuel cell (FC)	0	298
8	Hydrogen	Heat exchanger	Hydrogen heater	3982	997
9	Hydrogen	Hydrogen heater	Shaft furnace	3982	1073
10	Iron ore	Storage	Induction heater	74525	298
11	Iron ore	Induction heater	Shaft furnace	74525	1073
12	Hydrogen/Steam	Shaft furnace	Heat exchanger	1046/22620	1073
13	Hydrogen/Steam	Heat exchanger	Cooler	1046/22620	428
14	Hydrogen/Water	Cooler	Separator	1046/22620	298
15	Hydrogen	Separator	Mixer	1046	298
16	Water	Separator	Tank	22620	298
17	Oxygen	Electrolyser	Storage	40798	298
18	DRI	Shaft furnace	EAF	54418	1073
19	Scrap	Storage	EAF	9603	298
20	Lime	Storage	EAF	5993	298
21	Coke	Storage	EAF	704	298
22	Ferroalloys	Storage	EAF	939	298
23	Electrode	Storage	EAF	117	298
24	Slag	EAF	Storage	8695	1073
25	Steel	EAF	Storage	58682	1073

Source: Authors' analysis

Annexure II

Table A2 lists the break-up of power consumption for the H-DRI + EAF plant. The power balance is indicated for a typical operating hour of the plant with a WSH plant in Bellary for the year 2020.

We see that more than the bulk of the renewable electricity is consumed in the electrolyser followed by the EAF and heaters. The streams are identified in Figure 3.

Point	From	To	Power (MW)	Energy per tonne Steel (MWh/ tonne)
a-1	Solar	Power converter	479.86	8.18
a-2	Wind	Power converter	43.14	0.74
a-3	Grid power	Power converter	0	0
b-1	Power converter	Iron ore heater	16.48	0.28
b-2	Battery/FC	Iron ore heater	0	0
c-1	Power converter	Shaft	11.25	0.19
c-2	Battery/FC	Shaft	0	0
d-1	Power converter	EAF	44.65	0.76
d-2	Battery/FC	EAF	0	0
e-1	Power converter	Electrolyser	255.65	4.36
e-2	Battery/FC	Electrolyser	0	0
f-1	Power converter	Hydrogen heater	1.47	0.03
f-2	Battery/FC	Hydrogen heater	0	0
i	Power converter	Battery	172.57	2.94
g	Battery	Power converter	0	0
h	FC	Power converter	0	0

Table A2
Power consumption for the hydrogen-based direct reduced ore + electric arc furnace plant

Source: Authors' analysis

Annexure III

Typical chemical reactions modelled in the hydrogen-based direct reduced ore + electric arc furnace process:

A. Chemical reactions in electrolyser:

$$H_2O(gas) \rightarrow H_2 + \frac{1}{2}O_2\ \Delta H = +242\frac{kJ}{mol} \quad \text{(A1)}$$

B. Chemical reactions in DRI furnace:

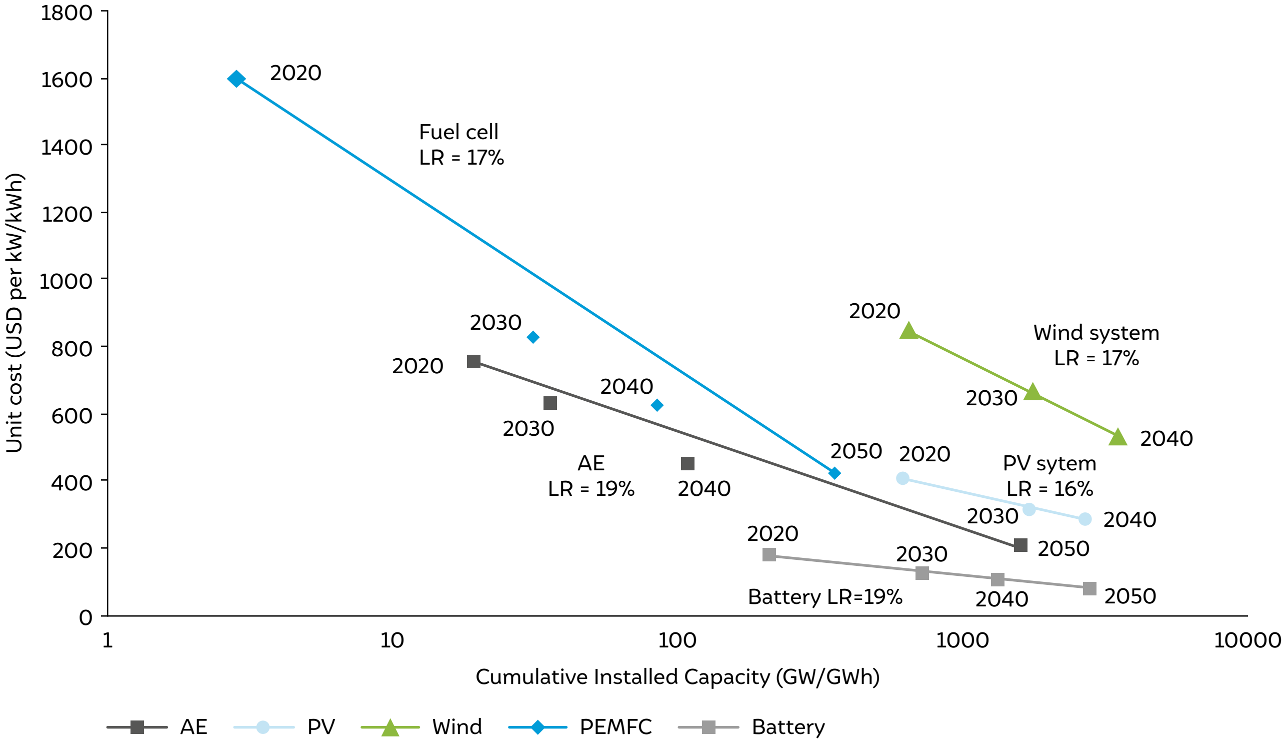
$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O(gas)\ \Delta HR = +99.5\frac{kJ}{mol} \quad \text{(A2)}$$

$$Fe_2O_3 + 3H_2 \rightarrow 2FeO + H_2O(gas) \quad \text{(A3)}$$

Annexure IV

Figure A1 shows the likely decrease in costs of various components across the green hydrogen value chain in the future. The projected cost of a component depends on the historical learning rates and the expected cumulative production capacity in the future. The learning rate primarily refers to the percentage reduction in unit costs for doubling of cumulative production or capacity (Chawla, Aggarwal, and Dutt 2020). The price of solar photovoltaic modules has historically decreased at a rate of 18-22 per cent (IRENA 2016; Schmidt et al. 2017). In India, the cost of balance of plant components has decreased at a rate of 17 per cent (Elshurafa et al. 2018), which is consistent with the global trend (Schmidt et al. 2017). Unlike the module and inverter costs, factors like land and facility charges are not expected to change over the years. Therefore, considering all aspects, we expect the costs of utility-scale solar photovoltaic systems to decrease at a rate of 15.5 per cent, in line with the earlier estimates for India (Chawla, Aggarwal, and Dutt 2020). For wind systems, there is a wide range of learning rates that vary from 7-23 per cent (Rubin et al. 2015). The levelised cost of electricity (LCOE) for onshore wind systems reduced by 12 per cent between 1983 and 2014 (IRENA 2017b). In the previous decade (2010-2020), the learning rate of wind systems was 19 per cent (Hydrogen Council 2020). In this study, we consider a learning rate of 17.4 per cent for wind systems, which is within the range of studies mentioned above. This value is also consistent with the learning rate obtained from the expected average cost reductions and cumulative installed capacities of wind systems in the future (IRENA 2019).

Figure A1 Learning rates of various components in the green hydrogen plant



Source: Authors' analysis

The global installed capacity of electrolysers used in power-to-X (PtX) systems today is 0.2 GW (IRENA 2020) with an expected learning rate of 9-13 per cent in the future (Hydrogen Council 2020). However, fundamentally, water electrolysis is very similar to hydrogen production in the Chlor-alkali industry (IRENA 2020). Today, the total installed capacity of electrolysers (inclusive of Chlor-alkali industry) is approximately 20 GW with a historical learning rate of 18.7 per cent (Schmidt et al. 2017).Therefore, in this study, we consider that the costs of AEs will reduce with a learning rate of 18.7 per cent in the future. Based on the average projected costs in the future for various years (IEA 2019), we estimate the cumulative production capacities needed to meet the cost targets. The learning rates and cumulative production capacities of lithium-ion batteries are widely discussed in the literature. We estimate the future costs of battery systems from the literature (Frazier and Will 2019) and indicate the future capacity targets needed to meet the cost targets based on learning rates (Schmidt et al. 2017). The historical learning rate of residential combined heat and power systems has been 16 per cent (Schmidt et al. 2017) with a 20 per cent contribution to the overall costs from the FC (Staffell and Green 2013). With these assumptions, the 2015 cost of an FC is 3500 USD/kW. This is in line with other estimates (IEA 2015). However, in the literature, there are no estimates on the cumulative installed capacity in 2020. Studies indicate an FC cost of 1600 USD/kW (IEA 2019), which corresponds to an installed capacity of 2.8 GW assuming a learning rate of 16 per cent from 2015-2020. Here, we consider a learning rate of 16 per cent and an installed capacity of 2.8 GW to project the cost reductions in the future. Our FC prices for the future years are consistent with other studies (IEA 2015; IEA 2019; CSIRO 2018).

Table A3 lists the cost, life, and efficiency-related assumptions for the green steelmaking plant. The maintenance costs as a percentage of the total cost are indicated in Table A4.

Table A3
Cost and life assumptions for the hydrogen-based steelmaking unit

Source: Authors' compilation

Sr. No.	Parameter	Unit	2020	2030	2040	2050	Source
1	Compressor cost	USD/kW	1200	1200	1200	1200	Fu et al. (2010)
2	Proton-exchange membrane fuel cell (PEMFC) - Stack Cost as % of Total Cost	USD/kW	50%	50%	50%	50%	IEA (2015)
3	AE - Stack Cost as % of Total Cost	USD/kW	45%	45%	45%	45%	IRENA (2020)
4	PEMFC - BoP Cost as % of Total Cost	%	50%	50%	50%	50%	IEA (2015)
5	AE - BoP Cost as % of Total Cost	%	55%	55%	55%	55%	IRENA (2020)
6	Power Converter	Years	12.5	12.5	12.5	12.5	Hinkley et al. (2016)
7	Electric heater efficiency	%	87%	87%	87%	87%	COINDIA (2015)
8	Demand charges for grid power	USD/kVA	2.9	2.9	2.9	2.9	KERC (2021b)

Sr. No.	Maintenance	Unit	2020	2030	2040	2050	Source
1	Solar	%	1.0	1.0	1.0	1.0	Mallapragada et al. (2020)
2	Wind	%	2.0	2.0	2.0	2.0	Hiendro et al. (2013)
3	AE	%	5	5	3	2	Buttler and Spliethoff (2018)
4	Power converter	%	2	2	2	2	Fu et al. (2010)
5	Storage	%	1	1	1	1	Mallapragada et al. (2020)
6	Battery	%	2.5	2.5	2.5	2.5	NREL (2019)
7	PEMFC	%	5.0	5.0	5.0	5.0	IEA (2015)
8	Shaft furnace	%	3.0	3.0	3.0	3.0	Vogl, Åhman, and Nilsson (2018)
9	EAF	%	3.0	3.0	3.0	3.0	Vogl, Åhman, and Nilsson (2018)
Operation							
10	DM Water Cost	USD/tonnes	1.25	1.25	1.25	1.25	Fu et al. (2010)

Table A4
Maintenance cost assumption for the hydrogen-based steelmaking unit

Source: Authors' compilation

Table A5 shows the material consumption in the shaft furnace and EAF unit. The costs of various raw materials are indicated in Table A6. Based on the relative costing of iron ore fines and lump ore (PTI 2021) and cost of converting fines to pellets (Ferrexpo 2017), we consider a premium of 9 USD/tonne for iron ore pellets compared to lump ore used in blast furnaces and rotary kiln.

Sr. No.	Component	Unit	Value	Reference
1	Scrap blend ratio	%	15	Authors' assumption
2	DRI metallisation	%	92	Authors' assumption
3	Ferro alloy consumption	kg/TCS	16	Authors' assumption
4	EAF coke consumption	kg/TCS	12	Steelonthenet (2020a)
5	Electrode consumption	kg/TCS	2	Steelonthenet (2020a)

Table A5
Material consumption in the shaft furnace and electric arc furnace units

Source: Authors' compilation

Sr. No.	Component	Unit	Value	Reference
1	Grid electricity cost	$/MWh	102	KERC (2021b)
2	Iron ore cost	$/Tonne	86.5	Steelonthenet (2020b)
3	Scrap steel price	$/Tonne	274	Steelonthenet (2020b)
4	Flux price	$/Tonne	48.5	Steelonthenet (2020b)
5	Oxygen price	$/Tonne	40	Chandler C. Dorris (2016)
6	Electrode price	$/Tonne	9500	Steelonthenet (2020a)
7	Ferro alloy price	$/Tonne	1100	Steelonthenet (2020b)
8	Coke price	$/Tonne	250	Department of Commerce (2020)

Table A6
Cost of raw material consumed in the shaft furnace and electric arc furnace unit

Source: Authors' compilation

Annexure V

Table A7 shows the parameters considered for the techno-economic analysis of coal- and gas-based DRI production processes. For fossil-based processes, we use capital costs of the rotary kiln (RK) and shaft furnace from the literature (Atibir Industries 2018; IEA 2010) and adjust it for inflation. The cost of the EAF route for making steel from DRI is obtained from the literature (IEA 2010; Steelonthenet 2020a). Based on data from the literature (CPCB 2007) and annual survey of industries (Gupta et al. 2019), we consider a coal cost of 2.2-5.87 USD/MMBtu and a specific coal consumption of 0.86-1.2 Tonnes/Tonne of DRI. Similarly, for natural gas (NG)-based sponge iron making, we consider a gas price of 6.7-13.5 USD/MMBtu and energy intensity of 10.7-13.7 GJ/T-DRI (HHV basis). We consider iron ore consumption of 1.58 tonne/tonne of DRI for coal and gas based processes.

Table A7
Parameters for techno-economic analysis of coal- and gas-based DRI processes

Sr. No.	Component	Unit	Value	Reference
1	RK cost	USD/ t-DRI	61	Atibir Industries (2018)
2	Specific coal consumption in RK process	Tonne/t-DRI	0.86-1.2	CPCB (2007); Gupta et al. (2019)
3	Coal cost	USD/MMBtu	2.2-5.87	Gupta et al. (2019)
4	Heating value of coal	MJ/kg	21.7	Industry sources
5	NG Shaft furnace cost	USD/t-DRI	228	Duarte (2004); IEA (2010)
6	NG process energy intensity	GJ/t-DRI	10.7-13.7	Chatterjee (2012); IETD (2020)
7	NG price	USD/MMBtu	6.7-13.5	Gupta et al. (2019)
8	Electricity output from the DRI plant	kWh/t-DRI	300	Agrawal, Sahoo, and Mohanty (2015); Chatterjee (2012); Worrell et al. (2008)
9	Electricity consumption in the shaft furnace	kWh/t-DRI	120	Chatterjee (2012); Sarangi and Sarangi (2011)
10	Grid power price	INR/kWh	3-7.6	KERC (2021b)

Source: Authors' compilation

Annexure VI

Table A8 and Table *A9* show the open-access tariff in India for solar and wind power transport with an injection tariff for 3 INR/kWh (40 USD/MWh), respectively.

Table A8
Open-access tariffs in India for solar power

Injection Tariff (INR/kWh)			Injection States					
			Solar (INR/kWh)					
			Gujarat	**Rajasthan**	**Karnataka**	**MP**	**Telangana**	**Maharashtra**
			3	**3**	**3**	**3**	**3**	**3**
Withdrawal Tariff (INR/ kWh)	Odisha	C*	4.85	5.45	5.46	4.41	4.04	5.36
		TP*	4.85	5.45	5.46	4.85	4.04	5.36
	Chhattisgarh	C	6.71	7.36	7.32	6.22	5.81	7.23
		TP	6.71	7.36	7.32	6.68	5.82	7.23
	Jharkhand	C	5.21	5.82	5.82	4.76	4.38	5.73
		TP	5.21	5.82	5.82	5.21	4.38	5.73
	Karnataka	C	5.94	6.59	4.25	5.44	5.03	6.43
		TP	6.24	6.89	4.91	5.82	5.34	6.73

C and TP* are Captive and Third-Party cost, respectively.*

Source: CEEW-CEF

Table A9
Open-access tariffs in India for wind power

Source: CEEW-CEF

Injection Tariff (INR/kWh)			**Injection States**					
			Wind (INR/kWh)					
			Gujarat	**Rajasthan**	**Karnataka**	**MP**	**Telangana**	**Maharashtra**
			3	**3**	**3**	**3**	**3**	**3**
Withdrawal Tariff (INR/ kWh)	Odisha	C*	4.94	5.45	5.46	4.41	4.04	5.36
		TP*	4.94	5.45	5.46	4.85	4.04	5.36
	Chhattisgarh	C	6.8	7.36	7.32	6.22	5.81	7.23
		TP	6.8	7.36	7.32	6.68	5.81	7.23
	Jharkhand	C	7.01	7.54	7.5	6.44	6.05	7.42
		TP	6.94	7.48	7.44	6.83	5.99	7.36
	Karnataka	C	6.05	6.6	4.27	5.45	5.05	6.44
		TP	6.35	6.9	4.57	6.21	5.35	6.74

C and TP* are Captive and Third-Party cost, respectively.*

Annexure VII

The water footprint of solar electricity is 400 Litres/MWh (Jin et al. 2019). Table A10 lists the land requirement for various components of the green steel plant.

Table A10
Land requirement for green steel plants in India

Source: Authors' compilation

Sr. No.	**Component**	**Land Area**	**Unit**	**Reference**
1	Wind	9	MW per sq. km	Deshmukh et al. (2018)
2	Solar photovoltaic (PV)	30	MW per sq. km	Deshmukh et al. (2018)
3	Battery Storage	12900	MWh per sq. km	Aurecon (2020); Hornsdale (2020)
4	AE	5882.3	MW per sq. km	IRENA (2020)
5	Stationary FC	2471	MW per sq. km	FCHEA (2020)

Annexure VIII

Table A11 and Table A12 list the assumptions considered for the techno-economic analysis of hydrogen production from NG and coal gasification routes, respectively.

Table A11
Assumptions for analysis of the steam methane reforming (SMR) process

Source: Authors' compilation

Sr. No.	**Component**	**Unit**	**Cost**	**Reference**
1	Plant capacity	Tonnes per hour (TPH)	1	Authors' assumption
2	SMR Unit capital cost	Million USD/TPH	40.5	IEAGHG (2017)
3	Operation and Maintenance cost (O&M)	per cent of capital cost	1.5	IEAGHG (2017)
4	Life of SMR unit	Years	25	IEAGHG (2017)
5	Heating value of NG used in the reformer	MJ/kg (LHV)	49.5	PPAC (2020)

Sr. No.	Component	Unit	Cost	Reference
6	Specific NG consumption	kg NG/kg of H_2	3.2	IEAGHG (2017)
7	Electricity export from the SMR unit	kWh/kg of H_2	1.1	IEAGHG (2017)
8	NG price	USD/MMBtu	13.5	Authors' assumption
9	Chemical and catalyst cost	USD/kg of H_2	0.01	IEAGHG (2017)
10	Scaling factor for the SMR unit	-	0.8	ECN (2020)
11	Plant availability	Hours in a year	8322	IEAGHG (2017)
12	Emission footprint of grey hydrogen	kg CO_2/kg of H_2	10.7	Parkinson et al. (2019)
13	Emission footprint of Indian grid	kg CO_2/kWh	0.78	CEA (2020)

Table A12 Assumptions for analysis of the coal gasification process

Sr. No.	Component	Unit	Cost	Reference
1	Plant capacity	Tonnes per hour (TPH)	1	Authors' assumption
2	Capital cost of the coal gasification plant	Million USD/TPH	96.3	Mueller-Langer et al. (2007)
3	O&M	per cent of capital cost	4.6	Mueller-Langer et al. (2007)
4	Life of coal gasification plant	Years	20	Mueller-Langer et al. (2007)
5	Heating value of coal used in the gasifier	MJ/kg (LHV)	29	Mueller-Langer et al. (2007)
6	Specific coal consumption	kg coal/kg of H_2	8.9	Mueller-Langer et al. (2007)
7	Electricity export from the SMR unit	kWh/kg of H_2	3.19	Mueller-Langer et al. (2007)
8	Coal cost	Paise/Mcal (USD/MMBtu)	108 (3.45)	Authors' assumption
9	Scaling factor for the plant	-	0.7	Lau et al. (2002)
10	Plant availability	Hours in a year	8322	Authors' assumption
11	Emission footprint of black hydrogen	kg CO_2/kg H_2	19.7	Parkinson et al. (2019)
12	Emission footprint of Indian grid	kg CO_2/kWh	0.78	CEA (2020)

Source: Authors' compilation

For a 0.5 MTPA hydrogen-based steelmaking unit, the size of the SMR and coal gasification plant ranges from 0.15 TPH to 2.8 TPH. For our analysis, we consider the cost of producing fossil hydrogen for a plant size of 1 TPH. Figure A2 shows the cost distribution for hydrogen obtained from SMR and coal gasification routes for a 1 TPH system. The costs are indicated without considering any benefits derived from the electricity generated in the plant as a by-product. We see that the cost of SMR derived hydrogen significantly depends on the fuel cost (price of NG), whereas for the coal gasification process, the plant's capital cost is the primary driver for hydrogen production cost.

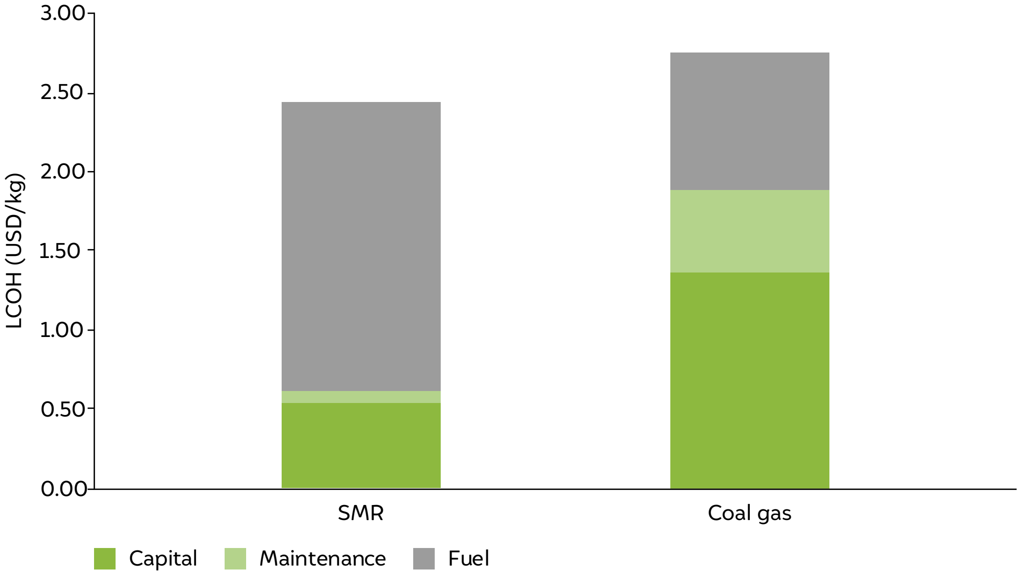
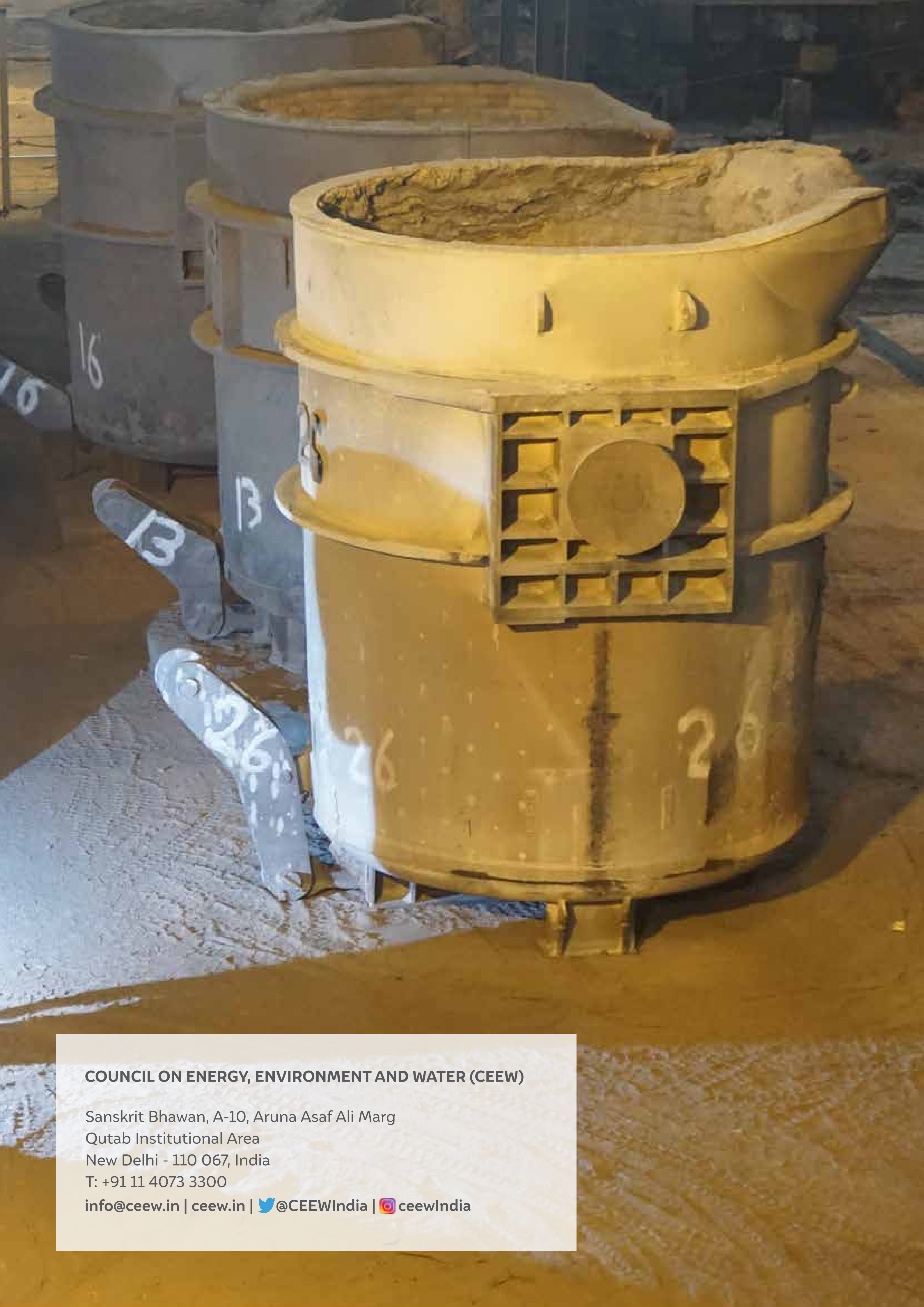


Figure A2
Hydrogen production cost from coal gasification and SMR process for a 1 TPH system

Source: Authors' analysis

Blending grey hydrogen with green hydrogen and grid power with renewable electricity can significantly reduce costs with only a marginal increase in carbon emissions.

Image: iStock



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