Green steel through hydrogen direct reduction

A study on the role of Hydrogen in the Indian iron and steel sector

About

This paper is the result of a joint effort between The Energy and Resources Institute (TERI), India, PrimetalsTechnologies Austria GmbH, Austria and Siemens India.

The Energy and Resources Institute (TERI) is an independent, not-for-profit research organization working in the fields of energy, environment, and sustainable development. TERI has pioneered conversations and activities in these areas for over four decades, having a transformative impact on industries and communities. TERI's headquarters are located in Delhi, with most of their work focused in India.

Primetals Technologies, is a leading metallurgical plant builder for the iron and steel industry and a full-line supplier across the entire value chain, from raw materials to the finished steel product.

Acknowledgements

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Key messages

- There is a growing need to reduce CO_2 emissions from iron & steel production to prevent the worst effects of climate change.

- One of the leading technology options is using low-carbon or carbon free hydrogen as a reducing agent in a direct reduction (DR) plant and subsequently such low-carbon/carbon free power for the electric arc furnace (EAF), to allow the production of green steel.

- Currently steel production via the DR/EAF route based on hydrogen is more expensive compared to the conventional steelmaking routes (BF/BOF and natural gas-based direct reduction/EAF). However, there is a path to cost-competitiveness for "hydrogen steelmaking", accelerated by broader action around the hydrogen production, as well as a supportive climate policy.

- With proactive collaboration between companies and government, hydrogen steelmaking has the potential to drastically reduce CO_2 emissions from primary steelmaking in India, making it one of the first major economies to industrialise without the need to 'carbonise'.

- For this to happen, complementary actions are required to ensure that demand for low carbon products is established, as support is given to green steel production.

Supply Push	***Demand Pull***
Access to natural gas / syngas *Demonstration plants* *Large-scale green finance* *Emissions penalty on production* *Transition support for small-scale plants*	*Green product standards* *Corporate buyers' clubs* *Public procurement*

Background

Steel is the foundation of a developed economy. It supports the infrastructure that facilitates growth, the housing that drives urbanization, and the machinery and tools that power industrialization. No country has achieved high levels of income per capita without substantially raising steel consumption per capita. India's steel consumption per capita is still at a low level of only 75 kg per year, consistent with India's low GDP per capita compared to other countries. This is only 27% of the world average, a clear indication of the large growth in steel consumption required to raise Indian GDP per capita and improve the welfare of its citizens.

Although critical for economic growth, the iron and steel sector is energy- and resource-intensive. As such, rapid growth of steel demand, using conventional production methods will have significant environmental consequences. Today, the iron and steel sector is already the largest industrial sector in terms of energy consumption and contributes around 7% of global direct CO_2 emissions (IEA, 2017) (IEA, 2019).

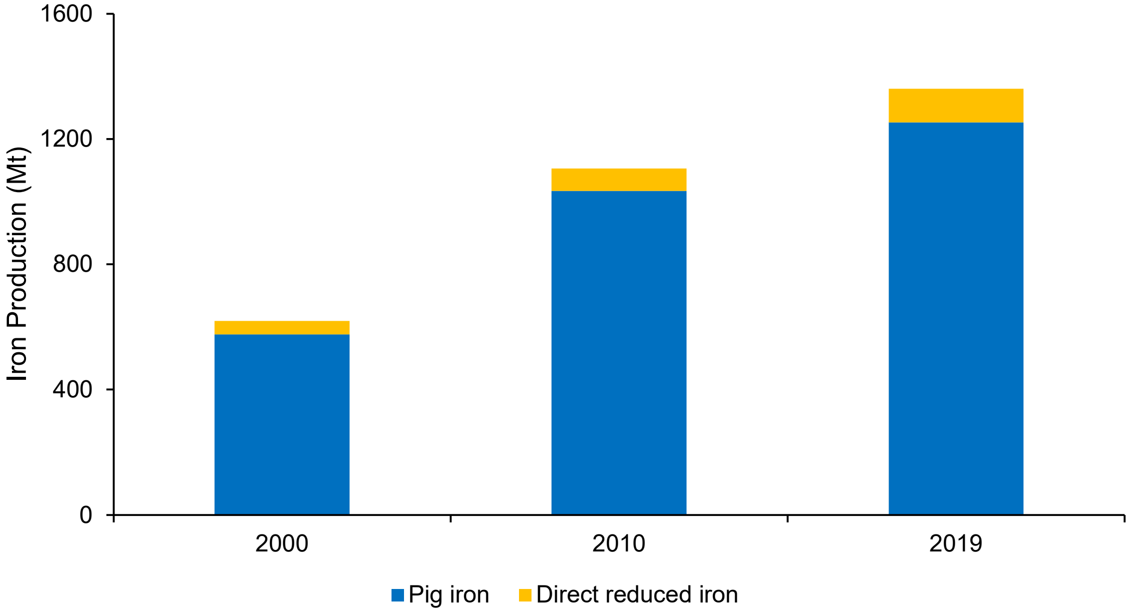
Even with expected energy efficiency improvements in the iron and steel sector, direct emissions are set to more than treble out to 2050, from around 252 Mt CO_2 in 2019 to 837 $MtCO_2$ (Placeholder1). Clearly, this level of CO_2 emissions is a concern. Incremental measures to improve energy and carbon efficiency in the iron and steel sector will not not be enough to place it on a trajectory consistent with limiting warming target of less than 2 C. As a result, we need to look at more radical changes to the iron and steelmaking technologies compared to the technologies used today. One of the leading technologies, which is well-suited to the Indian context is using low carbon hydrogen for direct reduction, paired with EAFs powered by renewable electricity.

This paper introduces the direct reduction technology in Section 1. Section 2 provides a techno-economic analysis of the direct reduction process based on hydrogen and Section 3 outlines the potential of green hydrogen technologies. Section 4 discusses the suitability of this technology for the Indian context, setting out the scale of emission reductions possible from pursuing this technology. Section 5 concludes, setting out recommendations for the next steps to advance this technology.

1. Direct reduction of iron ore

Currently, over 90% of iron production is through the blast furnace route, with direct reduction making up a growing share since its commercialisation in the 1970s. Since the year 2000 direct reduced iron (DRI) production has increased by 250%, illustrating the rapid growth of the sector. Global DRI production rose by 7.3% to 108 Million tonnes (Mt) in 2019, representing the fourth consecutive record year for annual growth in DRI production (see Figure 1).

Figure 1: Iron production, 2000, 2010, 2019

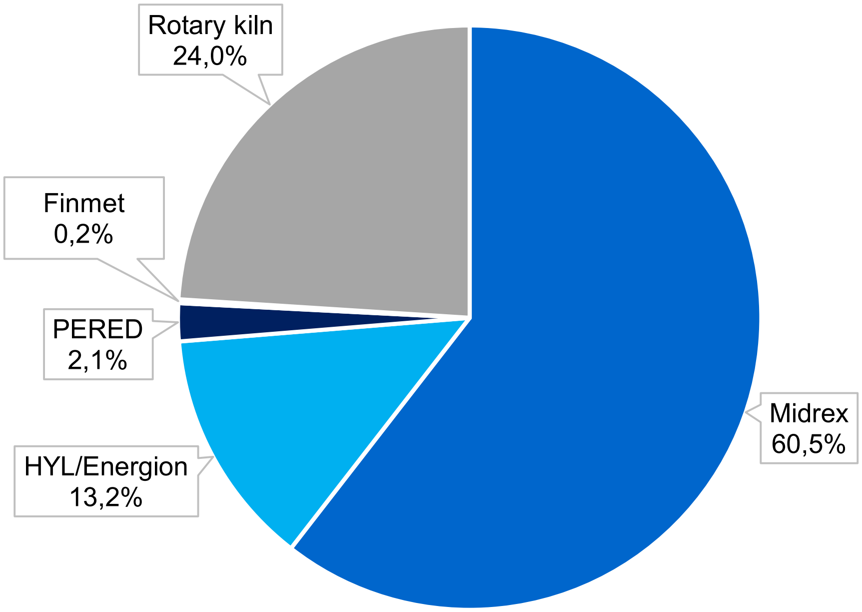


Source: (WSA, 2019)

India is the country with the largest DRI production, reaching 34 Mt in 2019, accounting for around a third of global DRI (WSA, 2019). The majority of Indian DRI is produced via the coal-based route, using rotary kilns, making partly use of domestic coal. Elsewhere in the world, direct reduction based on natural gas dominates, driven by availability of low-cost natural gas and reduced emissions. Due to limited availability of natural gas at competitive prices, gas-based direct reduction has seen limited growth in India. There are currently numerous gas-based direct reduction units in India, using natural gas, syngas, and off-gases (Essar, JSPL, JSW Toranagallu, JSW Dolvi, etc.).

Natural gas based direct reduction is a well-established technology, operating for many decades with a production rate of nearly 82 Mt in the year 2019. There are two dominant shaft based direct reduction processes, with MIDREX® leading the market with an 80% market share in 2019, followed by Tenova HYL™ being the next largest (see Figure 2).

Figure 2: Global DRI production by process, 2019



Source: (MIDREX, 2020)

The MIDREX® process is highly flexible regarding the source of energy for direct reduction. It has been demonstrated on an industrial scale with natural gas, syngas (from coal gasification), coke oven gas, COREX® off-gas, and other combinations. The reducing gas ratio (H_2:CO) in a standard natural gas based plant is typically in a range of 1.5 to 1.7 (equal to H_2 content of 55% in the reducing gas) while there are industrial MIDREX® plants also operating up to a H_2/CO ratio of 3.2 to 3.9 (close to 70% H_2 content in the reducing gas). The natural gas based direct reduction and EAF route can already reduce CO_2 emissions by 30-60% compared to the conventional blast furnace (BF) and basic oxygen furnace (BOF) route.

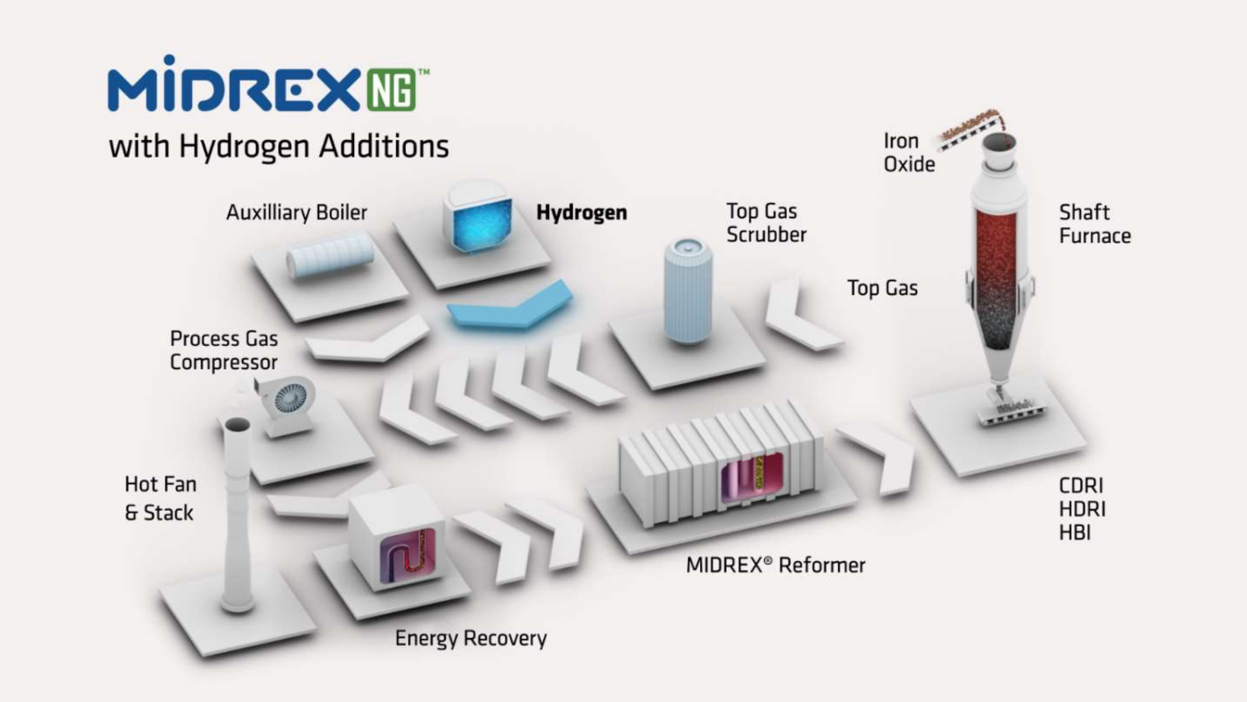
A MIDREX® direct reduction plant consists of a reduction furnace, a top gas scrubber, a reformer, process gas compressors and heat recovery. The reduction gas is generated and heated in the reformer and used for reduction of iron oxide material in the reduction furnace in a counter-current flow to the solid material. Thereby the oxygen of the oxide material is removed by the hot reducing gas consisting mainly of hydrogen (H_2) and carbon monoxide (CO) and the material is metallized. The direct reduced iron is discharged in either hot (HDRI) or cold (CDRI) condition or is hot briquetted into iron briquettes (HBI).

Whilst natural gas is the most used feedstock for the direct reduction process, MIDREX® also offers its MXCOL™ technology which can use coal-based syngas as the reducing agent. This has potential in India, where natural gas supplies are limited/high in cost, and the government has recently announced an expansion in activity around coal gasification [REF].

2. Hydrogen based Direct Reduction

As a highly flexible technology, a MIDREX® plant can be operated using hydrogen in a range between 0 to 100%, resulting in further CO_2 reduction. The MIDREX® H_2 process flow sheet for use of H_2 is shown in Figure 3. The hydrogen can be supplied via an external pipeline 'over-the-fence' or can be produced on-site. The process does not require high purity hydrogen, making it suitable for fossil-fuel derived hydrogen (grey), fossil-fuel derived hydrogen with CCUS (blue), or hydrogen produced from renewables via an electrolyser (green). A more detailed discussion of green hydrogen can be found in Section 3.

Figure 3: MIDREX™ process based on hydrogen



Source: (MIDREX, 2020)

The natural gas MIDREX NG™ plant can be converted in stages to a MIDREX H_2™ plant as low carbon hydrogen becomes available at a suitable cost, allowing steelmakers to reduce CO_2 emissions immediately and further reduce them in the future without major additional capital expenditure (see Figure 4). Such an approach provides steelmakers with a large degree of flexibility that can ensure plants built today are 'transition-ready', minimizing stranded asset risk as policies on emission reductions become increasingly strict.

Figure 4: A stepwise approach to reducing CO2 emissions via the direct reduction route

Step 1

Build a MIDREX NG™ or MX COL™ plant using the most readily available gas. The product of this plant (CDRI, HDRI, or HBI) can be used in existing melting shops, including BF, BOF and EAF.

Step 2

Replace up to 30% of the gas used in the existing process with hydrogen as it becomes available, without the need for equipment modifications. Up to 100% hydrogen can be used with minor equipment additions to protect the reformer. The MIDREX™ process can accommodate fluctuating rates of hydrogen addition and or reduce production to take advantage of periods of excess renewable electricity generation.

Step 3

Complete transition to MIDREX H_2™ as low carbon hydrogen becomes available and cost-effective. Some adaptions are required to accommodate plant operation for 100% hydrogen.).

Source: (MIDREX, 2020)

3. Techno-economic analysis of the hydrogen direct reduction process

This section covers the energy and raw material requirements for the hydrogen direct reduction process, establishing costs of production based on average cost figures. Exact costs of production will vary on project basis.

To produce virgin metallics (DRI or HBI) from lump iron ore or pellets require approximately 650 Nm³ of hydrogen (or 58 kg) per ton of DRI (see Table 1). Hydrogen with a purity of 99.8% is required for this process, which can be produced from a range of technologies, including gas reformation and electrolysis. For reference, hydrogen for use in fuel cell electric vehicles requires a purity of 99.999999% to avoid degradation of the fuel cell. Hydrogen for use in this process does not need to be of high purity, allowing for more flexibility of the production processes.

Table 1: Specific hydrogen consumption and requirements for direct reduction

Parameter	Unit	Value
H_2 amount:	Nm³/t DRI kg/ t DRI	650 58
H_2 purity:	vol%	99.8
H_2 pressure (at TOP):	bar_g	min. 4.5

Source: (Primetals, 2020)

In addition, energy is required for reducing gas heating, due to the endothermic nature of the direct reaction between H_2 and Fe. In the conventional direct reduction process, available CO in the reducing gas results in an exothermic reaction and so an additional heat source is not required. Such a heat source could be provided by top gas fuel and/or natural gas. In future, as steel producers seek to further reduce their emissions, this heat source can be provided by biomass or electric heaters, although this needs to be better understood.

For a comparison of direct reduction based on hydrogen with the conventional route, the below main unit costs (Table 2) are used for the natural gas based MIDREX® plant, which provides a 'base case' (CASE 1).

Table 2: Capacity and typical consumption figures for CASE 1

	DR Plant based on NG (Base Case)	**Unit Rates (India)**
Rough Investment budget (Core Area Turn-key India)	$250m	
DRI Capacity	1 Mtpa	
Hourly DRI production:	125 t_{DRI}/h	
Consumption figures:		
- DR grade pellets	1.42 tons/t DRI	$100 / t Oxide
- Natural gas	2.5 net Gcal	$10 / mmBTU
- Electric power	120 kWh	$0.036 / kWh
- Water (assuming cooling towers)	1.5 m³	$1 / m³
- Labor (including administration)	0.12 man-hours	$20 / manhour
- Maintenance and supplies	$4.00	

Source: (Primetals, 2020)

CASE 2 and CASE 3 consider the installation of a 50 MW and 350 MW Polymer Electrolyte Membrane (PEM) electrolyser plant, respectively, and use the hydrogen from these plants for the production of DRI. The amount of hydrogen, the energy inputs as well as the operation costs (OPEX) are listed in Table 3. The CASE 2 and CASE 3 reflect the 'Step 2' and 'Step 3' as set out in Figure 4, whereby a share of green hydrogen is blended into the gas feedstock initially, before switching to 100% hydrogen.

Table 3: Cases for direct reduction plant operation

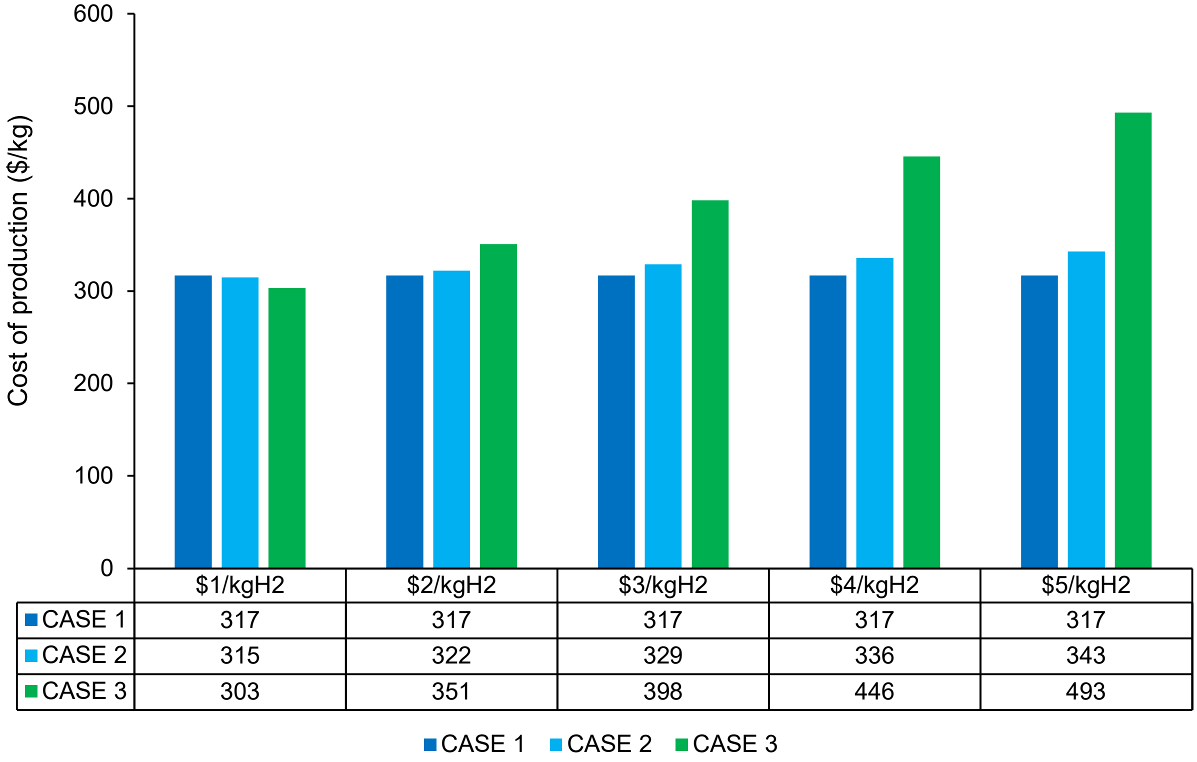
	CASE 1	**CASE 2**	**CASE 3**
	DR Plant based on NG (BASE CASE)	DR Plant with H2 addition (50 MW electrolyser)	DR Plant with H2 addition (350 MW electrolyser)
Electrolyser capacity (MW)	n.a.	50	350
H_2 used (Nm³/h)	0	11,000	75,000
(kg/h)	0	1,000	7,000
Energy input:			
- Hydrogen (H_2) (mmBTU)	0.0	0.9	6.1
- Natural gas (mmBTU)	9.9	8.9	3.0
- Total (mmBTU)	9.9	9.8	9.1
- H_2 energy/total energy	0% H_2	9.2 % H_2	67.2 % H_2
Carbon content in DRI	2.5 wt%	~2 wt%	~0 wt%
Operation cost (OPEX) per ton of DRI	$ 252.97		
- H_2 price 1.0 $/kg		$ 250.73 (-1.2%)	$ 237.69 (-6.0%)
- H_2 price 2.0 $/kg		$ 258.64 (+2.2%)	$ 291.63 (+15.3%)
- H_2 price 3.0 $/kg		$ 266.55 (+5.4%)	$ 345.57 (+36.6%)
- H_2 price 4.0 $/kg		$ 274.46 (+8.5%)	$ 399.51 (+57.9%)
- H_2 price 5.0 $/kg		$ 282.37 (+11.6%)	$ 453.45 (+79.2%)

Source: (Primetals, 2021)

The calculation of the OPEX has been carried out for hydrogen prices ranging between $1/kg and $5/kg. This price range reflects the range of potential cost of green hydrogen, which is discussed in more detail in Section 4., as well as elsewhere for the Indian context (TERI, 2020). If the hydrogen is produced via electrolysis using renewable electricity, emissions from the direct reduction process can be reduced by around 20% in CASE 2 and up to 100% in CASE 3, versus CASE 1.

As can be seen from this analysis (see Figure 5), at an assumed natural gas price of $10/mmBtu, using hydrogen is competitive at a hydrogen price between $1/kg and $2/kg only. Natural gas prices in India have fluctuated considerably in recent years, currently showing lower prices due to reduced demand. In the longer term, it is expected that prices will align to LNG price at around $10/mmBtu.

Figure 5: OPEX comparison for the DRI + EAF route



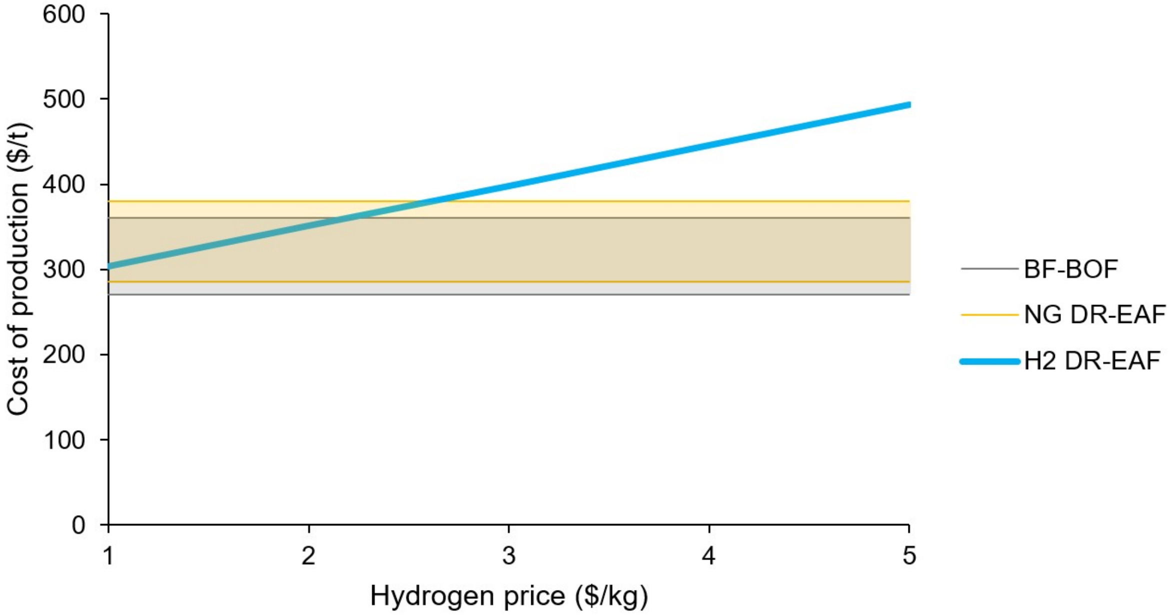
	$1/kgH2	$2/kgH2	$3/kgH2	$4/kgH2	$5/kgH2
CASE 1	317	317	317	317	317
CASE 2	315	322	329	336	343
CASE 3	303	351	398	446	493

Source: (Primetals, 2021)

The installation of a PEM electrolyser can also be used to increase the MIDREX® plant capacity. It is possible to use the by-product oxygen from the PEM electrolyser in the direct reduction shaft, particularly for DRI production. The oxygen could be added to the bustle gas to increase the reducing gas temperature and enhance the plant productivity for HDRI plants by up to 5%. Alternatively, the such oxygen can also be used in the EAF or for oxygen enrichment in a blast furnace, if nearby. This can provide an additional revenue for the electrolyser, improving the competitiveness of operation.

Beside comparing steel production cost for the DR/EAF route based on natural gas versus hydrogen, it is also necessary to compare the steel production costs for the BF-BOF route, which is the major route for primary steel production in India. As can be seen in Figure 6, the production costs of a BF-BOF route tend to be slightly lower than natural based DR/EAF, mainly due to the relative price differences of coking coal and natural gas. The range for these production costs reflect the 5-yearly range of natural gas and coking coal prices for India.

Figure 6: Costs of steel production for various routes



Source: (Primetals, 2021; TERI, 2020). BF-BOF = blast furnace – basic oxygen furnace, NG DR-EAF = natural gas based direct reduction with electric arc furnace, H2 DR-EAF = hydrogen based direct reduction with electric arc furnace. Range for BF-BOF and NG DR-EAF based on range of coking coal and natural gas prices.

Even with low hydrogen costs, the BF-BOF route could still be competitive without further policy measures. To accelerate the speed of transition from fossil fuels towards low carbon hydrogen policies a carbon price could be introduced. By 2030, costs of hydrogen in India could be around $2/kg, at which point a carbon price of around $40/tCO$_2$ would be needed to support the transition from BF-BOF to the DR-EAF route.

Emission reduction potential

When comparing the specific CO$_2$ emissions from the three cases above with emissions from the BF-BOF route, large savings across all emission scopes[1] are possible. Emissions reductions are heavily dependent on the CO$_2$ intensity of the electricity being used in the production of hydrogen and for the EAF. Table 4 sets out an emissions pathway for grid electricity CO$_2$ intensity in India, reflecting the high dominating share of coal-fired power generation, but also indicating the potential of renewables to start to replace coal out to 2060.

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[1] Scope 1 covers direct emissions from owned or controlled sources. Scope 2 covers indirect emissions from the generation of purchased electricity, steam, oxygen, heating and cooling consumed by the reporting process. Scope 3 includes all other indirect emissions that occur in a process's value chain e.g. mining, transport, etc.

Table 4: Projection of CO_2 intensity of grid electricity in India

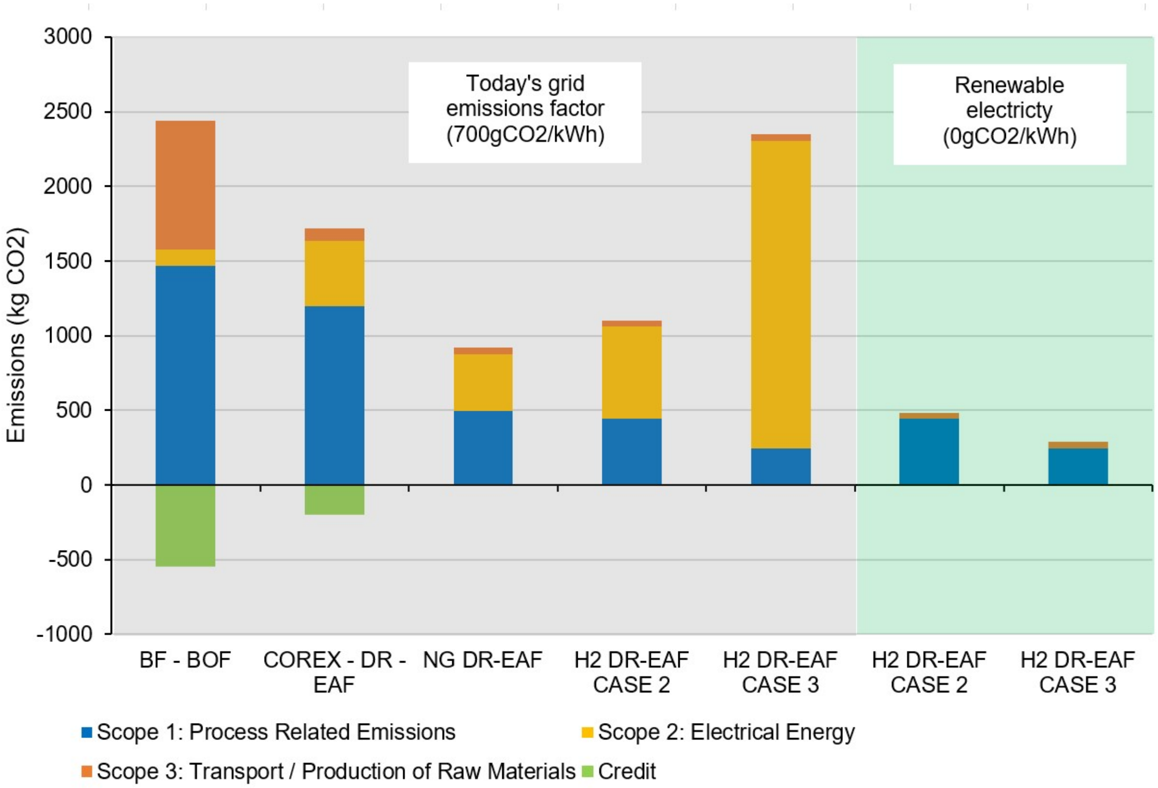
Year	**2020**	**2030**	**2040**	**2050**	**2060**
CO_2 intensity of grid electricity (g CO_2/kWh)	698	567	300	100	0

Source: (TERI, 2020)

An alternative model would be for electricity for both the hydrogen and the EAF to be sourced directly from renewable electricity sources, via stand-alone renewable projects that are off-grid. For such projects the CO2 emission factor can be assumed as zero. This is already a model being used by Indian industry to avoid expensive grid charges, which are higher on industry versus other electricity customers. We discuss the impact of this on the cost of hydrogen in the subsequent section.

Figure 7 shows the CO_2 emissions per ton of crude steel for the different production routes using electricity based on the current grid emission intensity factor (around 700 g CO_2/kWh) or the emissions based on electricity from renewables (0 g CO_2/kWh).

Figure 7: CO_2 emissions for different steel production routes



Source: (Primetals, 2021)

This Figure shows the potential for emission reduction of more than 60% for the natural gas DR route (CASE 1) versus the conventional BF-BOF, when considering Scope 1, 2 and 3 emissions without credits. In 2020, establishing a hydrogen DR plant in India using grid electricity would increase emissions, making it important that steel producers look to increasingly to build renewable electricity assets allowing to generate the required hydrogen. Many are already doing this via ‘open access’ or off-grid projects, to help to reduce the cost of energy, as well as local pollution.

Table 5: Emissions reduction potential for the different routes

Route	BF-BOF	COREX/DR-EAF	NG DR-EAF CASE 1	H_2 DR-EAF CASE 2	H_2 DR-EAF CASE 3	H_2 DR-EAF CASE 2	H_2 DR-EAF CASE 3
CO_2 of grid electricity (g CO_2/kWh)	698	698	698	698	698	**0**	**0**
Emissions without credits (t CO_2/t_{LS})	2440	1721	920	1099	2349	485	289
Emissions reduction versus BF-BOF		-29%	-62%	-55%	-4%	-80%	-88%

Source: Author’s analysis

We can see here that the emission reduction potential for CASE 3 is close to 90% versus the conventional BF-BOF route, assuming all required electricity is sourced from renewable energie. If the hydrogen is produced from grid electricity based on the current specific CO_2 intensity of the grid electricity, the emissions savings will be minimal.

4. Producing green hydrogen

Background

Hydrogen is the most basic and plentiful element in the universe. However, it is not naturally occurring on earth and requires extraction from other compounds, such as methane (CH_4) or water (H_2O). The main routes include natural gas reformation, biomass, waste or coal gasification, and electrolysis, of which alkaline and Proton Exchange Membrane (PEM) technologies are the main commercially available options.

To generate low carbon hydrogen at the scale needed to decarbonize global energy systems, Siemens has invested in generating hydrogen from water, using PEM electrolysis technology. Simply put, the PEM process uses low-cost renewable energy sources to split water - H_2O - into its constituent elements without generating carbon emissions, which is known as ‘green hydrogen’.

Traditional methods of producing hydrogen, such as natural gas reforming (the leading technology being steam-methane reforming) or coal gasification, use fossil fuels and therefore generate carbon emissions. In fact, steam methane reforming (SMR) methods using natural gas as feedstock generate 8-10 kg of CO_2 for each kilogram of hydrogen produced (TERI, 2020). ~~Carbon capture and storage infrastructure would be required to mitigate emissions from these processes, which is an uncertain prospect in India. In contrast, the PEM process produces green hydrogen, which can be used as an important industrial feedstock.~~

PEM electrolysis

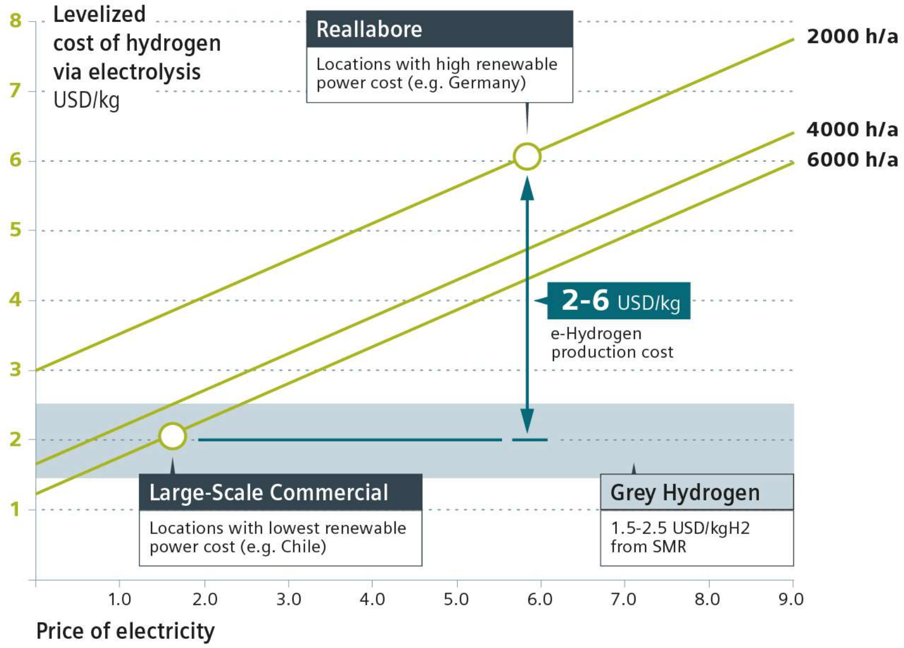
PEM electrolysis is a proven high-efficiency hydrogen production technology that has been commercially deployed since the early 2000s. PEM electrolysis uses a cathode-anode cell that features a solid polymer electrolyte that conducts protons, separates water into hydrogen and oxygen, and protects the cell's electrodes. Developed as a more efficient alternative to traditional alkaline water electrolysis, PEM electrolysis has three main advantages:

- **Responsive and flexible:** PEM electrolysis can be coupled directly to renewable energy sources. It has black-start capabilities, which means it does not need an external power source to restart from a partial or total shutdown. With an extended operating range, PEM technology can ramp up to 10 percent or more in its operating capacity in less than one second. It can operate from 5 – 100 percent of capacity, providing exceptional operating flexibility. This can be used to support grid operations, particularly as countries seek to integrate higher and higher shares of variable renewables.

- **Inherently clean operation**: With only water, green hydrogen, and oxygen in a PEM electrolysis system, the technology requires no aggressive chemical electrolytes, such as the potassium hydroxide (KOH) electrolyte required by alkaline electrolysis systems. As with alkaline electrolysis, it produces hydrogen that is more than 99.9 per cent pure and without any CO_2 emissions.

- **Economically competitive**. Compared to alkaline electrolyser systems, PEM electrolysers have a smaller footprint, and require less maintenance, often resulting in lower operating expenses and total cost of ownership (exact cost differences will vary project by project). While 95% of today's global production of hydrogen is via SMR and coal gasification methods with both generating significant CO_2 emissions, PEM electrolysis can produce emission-free hydrogen at competitive prices when electricity from renewable sources costs less than $40/MWh. Costs of power generation from renewables, such as solar and wind, are already around $30/MWh in India, with further cost reductions expected (TERI, 2020).

Figure 8: Typical cost of hydrogen versus price of electricity



Source: (Siemens, 2020)

Achieving scale

It's clear that there is a path to competitiveness for electrolyser technologies to produce green hydrogen but most projects today are relatively small, at a low megawatt (MW) scale. A commercial-scale steel plant of 1 MTPA production capacity would require a 350 MW electrolyser facility (see Table 3). A step-change in electrolyser manufacturing capacity would therefore be required to allow steel sector decarbonisation using green hydrogen.

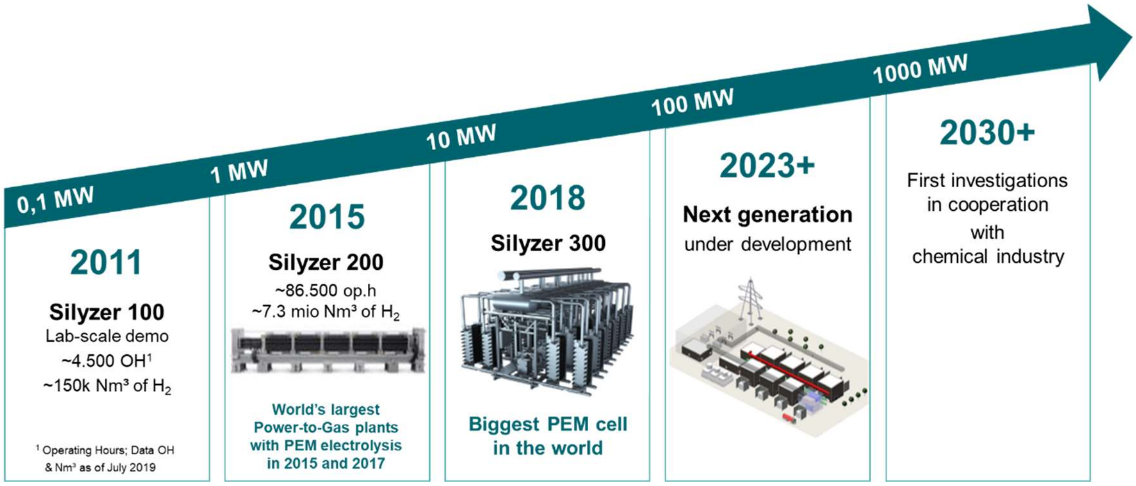
As a result, Siemens is scaling up its manufacturing capability to meet the demands of future industrial users. In 2015 Siemens deployed the SILYZER 200 electrolyser, a MW-scale, commercial PEM electrolyser, which currently represents one of the world's largest Power to Gas (PtG) plants in Germany (Siemens, 2020).

Cognisant of the need for further expansion, Siemens has taken that technology into its 3rd generation with the deployment of the SILYZER 300 at the H2FUTURE project, in partnership with VERBUND Solutions GmbH, voestalpine Stahl GmbH, K1-MET GmbH and the Austrian Power Grid AG.

The SILYZER 300 consists typically of 24 PEM electrolytic modules that together draw 17.5 MW of power to produce up to 340 kg/h of high purity hydrogen with no CO_2 emissions. This is one of the highest output rates of any electrolyser currently on the market. The system operates at 75 to 88% efficiency depending on the load, which contributes towards achieving cost effective green hydrogen production.

SILYZER 300 is the latest, most powerful product line in the double-digit megawatt range of Siemens' PEM electrolyser portfolio. Its modular design makes unique use of scaling effects to minimize investment costs for large-scale industrial electrolysis plants resulting in very low hydrogen production costs thanks to high plant efficiency and availability. Such a system would pair well with DRI production, as the high output rate of hydrogen is well-suited to the requirements of the direct reduction shaft.

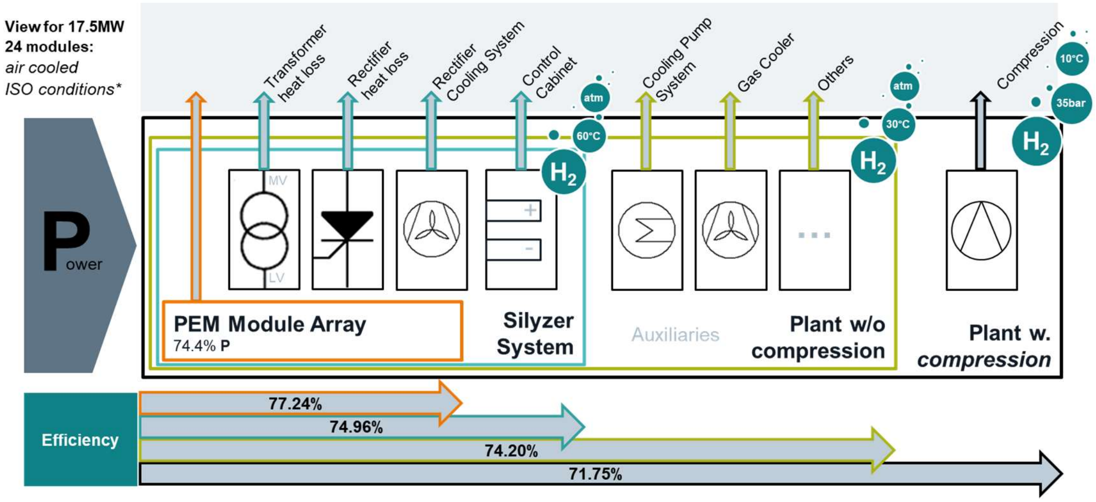
Figure 9: Siemens SILYZER Development Roadmap



Source: (Siemens, 2020)

The Siemens SILYZER development roadmap targets fourth generation hydrogen plants that by 2023 can draw more than 100 MW of power for hydrogen production at even greater efficiencies. By 2030 and beyond, Siemens envisions building 1,000 MW, fifth-generation plants, making it an ideal technology for use in large-scale direct reduction plants based on hydrogen.

Figure 10: Siemens SILYZER 300 System Efficiencies



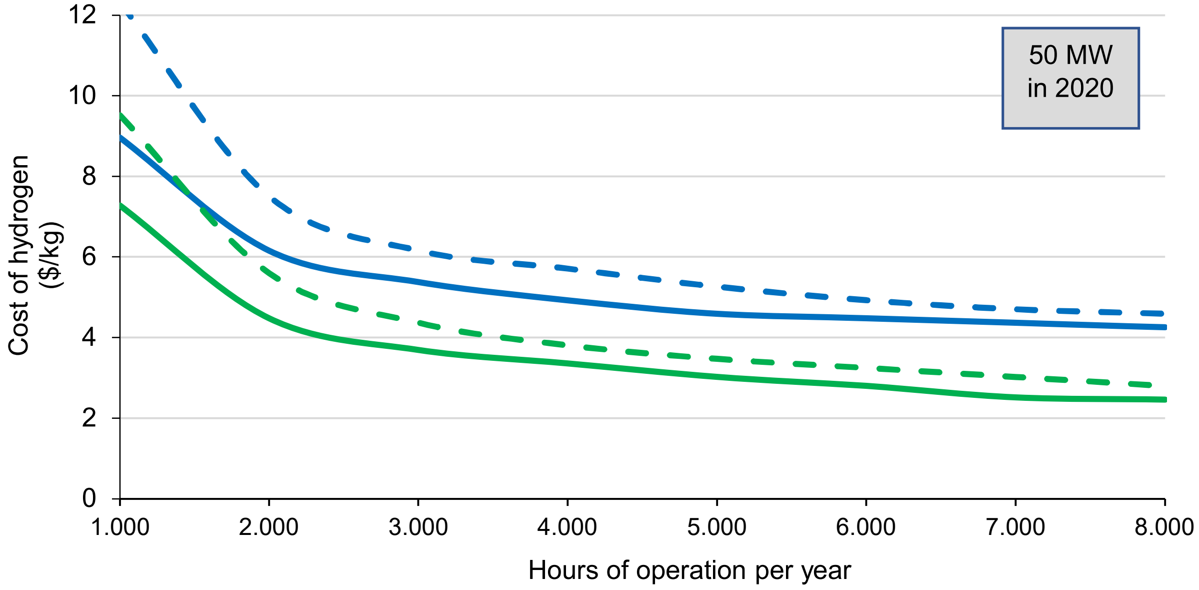
Source: (Siemens, 2020)

Costs of producing green hydrogen

The cost of electricity, operating costs, annual operating time (or utilisation rate), efficiency, and capital investment costs have the greatest influence on hydrogen production costs. With a reduced specific investment cost over time, with increased scale of manufacture, higher annual operating times hydrogen production becomes more cost-effective.

Estimating total hydrogen production cost is useful for comparing PEM electrolysis to other technologies, as it incorporates CAPEX, OPEX, efficiency, power price and yearly operating time. Figures 8 and 9 below show hydrogen production costs for a 50 MW PEM plant (in 2020 and 2050), taking into consideration electricity cost, cost for compression and oxygen removal (DeOxo), and operation hours.

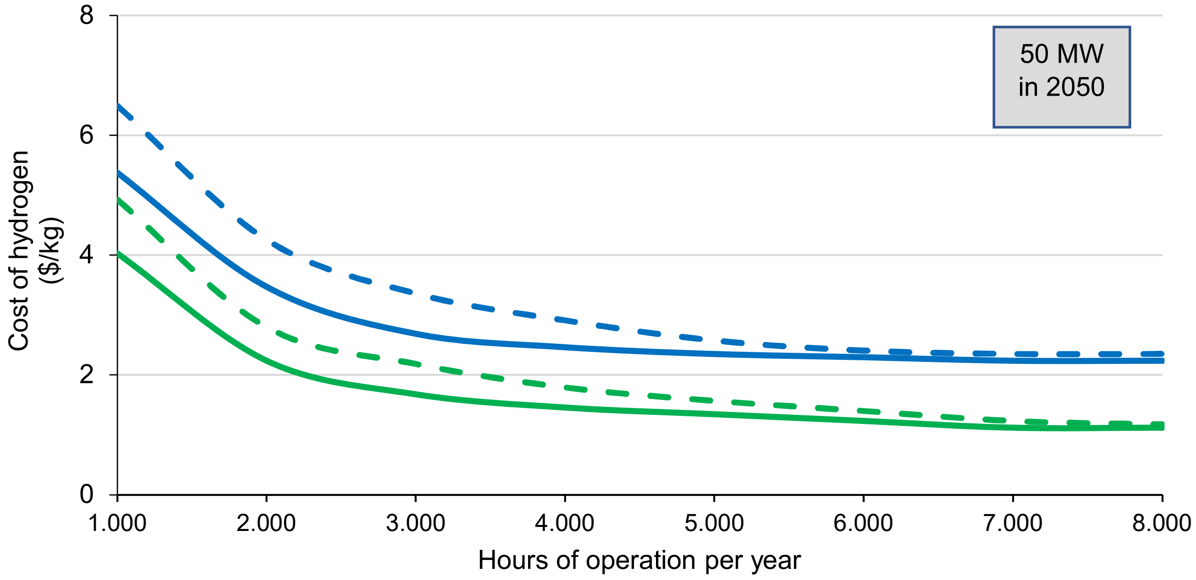
Figure 11: Costs of electrolytic hydrogen production in 2020



Source: (Siemens, 2020). Blue lines for less favourable renewable regions (Europe), green lines for more favourable renewable regions (Western India). Dashed lines refer to cost with compression and DeOxo, straight line is without.

Hydrogen cost from electrolysis can range from around \$3/kg to \$10/kg in the less favourable conditions. Costs of grey hydrogen in India are around \$1.5-2/kg hydrogen, meaning hydrogen from electrolysis would find it difficult to compete, without additional policy support.

Figure 12: Costs of electrolytic hydrogen in 2050

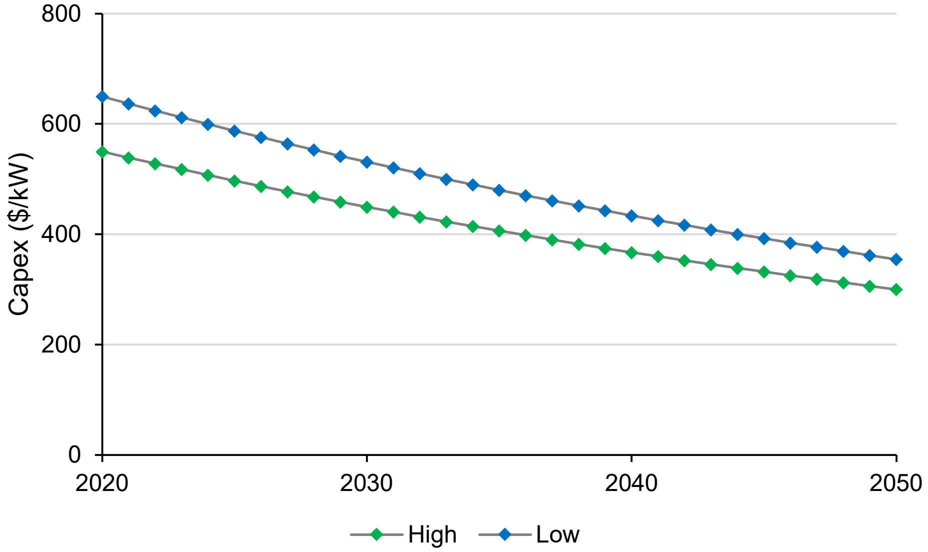


Source: (Siemens, 2020). Blue lines for less favourable renewable regions (Europe), green lines for more favourable renewable regions (Western India). Dashed line refers to costs with compression and DeOxo, straight line is without.

Over the longer-term, as cost of electrolysers along with the cost of renewables will fall, the hydrogen cost from electrolysis will reduce significantly. Under favourable conditions, costs of hydrogen would be around $1/kg, rising to $2-3/kg in the less favourable conditions. At these cost electrolytic hydrogen will start to compete with grey hydrogen, helping to reduce fossil fuel consumption.

It is worth noting that the investment cost for electrolysers depends on the scope of supply and the plant size (MW). The larger the plant, the lower the specific cost. For example, for a 50 MW plant, including rectifier, feedwater treatment, cooling, installation, and commissioning, $550-650/kW can be assumed in the near-term. Over time this could fall to $300/kW, due to economy of scale (see Figure 13). Gas treatment (DeOxo, compression to 30-100 bar) would add approximately $175-350/kW, which is not required for use in DR plants.

Figure 13: Capex reductions for PEM electrolysers, 2020 to 2050



Source: (Siemens, 2020). Costs are without compression and DeOxo. Estimates are based on 50 MW electrolysers, with ~2% price decrease per annum.

To conclude, electrolyser technology, such as PEM, provide a viable option for producing green hydrogen for direct reduction at the scales required. A clear pipeline of projects will be required to allow scale-up manufacturing capacity, which can deliver on these cost targets and achieve deep decarbonisation of iron and steel production.

5. Hydrogen direct reduction for India

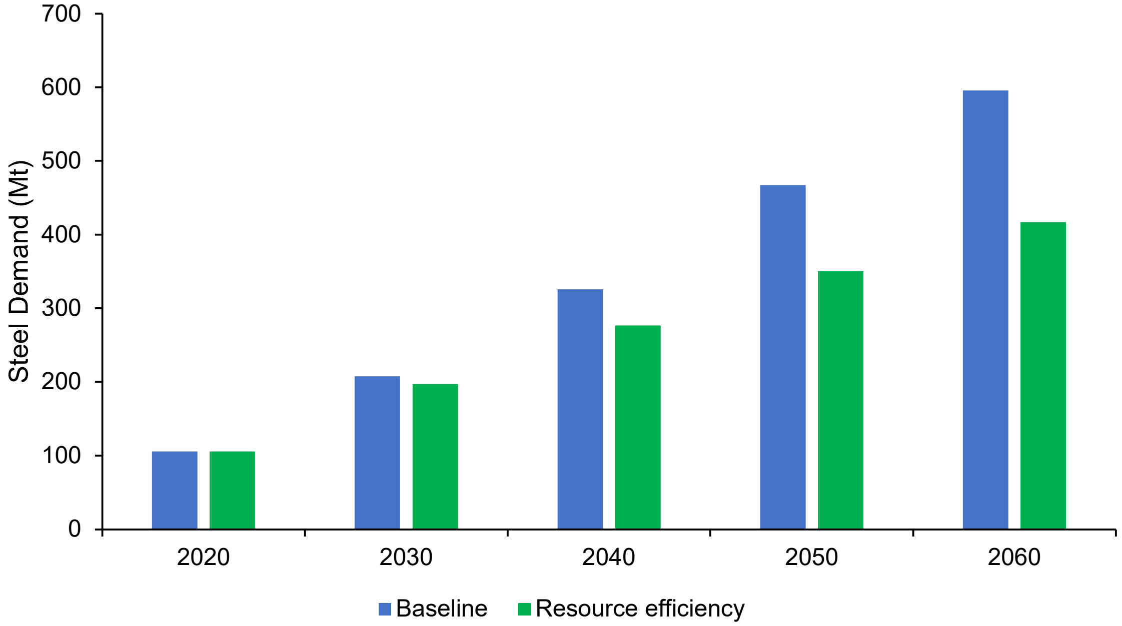
Based on the preceding analysis, this section lays out an illustrative deep decarbonisation scenario for the Indian iron and steel sector. This scenario assumes a large-scale adoption of the hydrogen direct reduction technology with a 100% adoption by 2060, resulting in a significant reduction in carbon emissions, equivalent to net-zero.

Steel demand

Steel demand in India today sits at around 100 Mt of crude steel, equating to approximately 74 kg of steel per capita. Production is slightly higher, at 111 Mt of crude steel per annum, being met by an installed capacity of 142 Mt (MoS, 2020). Domestic demand is largely met through domestic production, with low imports or exports.

Whilst the near-term outlook is highly uncertain, as a result of the COVID-19 pandemic and subsequent economic impacts, there will likely be a return to strong growth in steel demand in India in the medium- to long-term. The fundamentals underpinning demand for steel, namely economic growth and urbanisation, which require new infrastructure and the supply of modern goods, will remain.

Figure 14: Steel demand under a baseline and resource efficiency scenario, 2020-2060



Source: (Hall, Spencer, & Kumar, 2020)

Through the development of an econometric forecasting model, we can develop an understanding of the scale of potential demand growth (Hall, Spencer, & Kumar, 2020). In the scenario outlined in Figure 14, we assume some level of resource efficiency measures have been put in place, lowering the steel demand from its baseline. This includes increasing the lifetime of goods, maximizing recycling, and structural shifts, such as ridesharing, which reduces steel consumption for vehicles.

These demand projections imply significant new capacity in the coming years. Whether this capacity is primary, currently mainly through the BF-BOF route or the direct reduction and EAF route (or some combination of the two), or secondary – the use of scrap steel in EAFs, will be largely down to the availability of scrap.

Scrap availability

It is estimated that India currently uses around 30 Mt of scrap, 5 Mt of which is imported. Domestic scrap availability has been rising but given the low stock of steel relative to the growth in demand, this only accounts for around 20% of new demand growth (MoS, 2019).

Imported scrap largely comes from developed countries, with the top 5 export countries including the UAE, the USA, the UK, Singapore, and the Netherlands (Department of Commerce and Industry, 2019). The import of scrap has been important in helping to maintain the quality of steel produced via the electric route, which is often a combination of scrap steel and direct reduced iron (DRI). It is also used to reduce energy consumption in the BF-BOF route, by using up to 20% scrap steel in the basic oxygen furnace. Limited scrap availability results in that that typically less than 10% is used in the BOF today.

It is expected that the availability of scrap for import will steadily reduce as developed countries begin to implement tougher emissions reduction policies, including net-zero targets. To achieve such targets, it will require greater scrap recycling rates at these countries, to reduce domestic production of steel via the primary route.

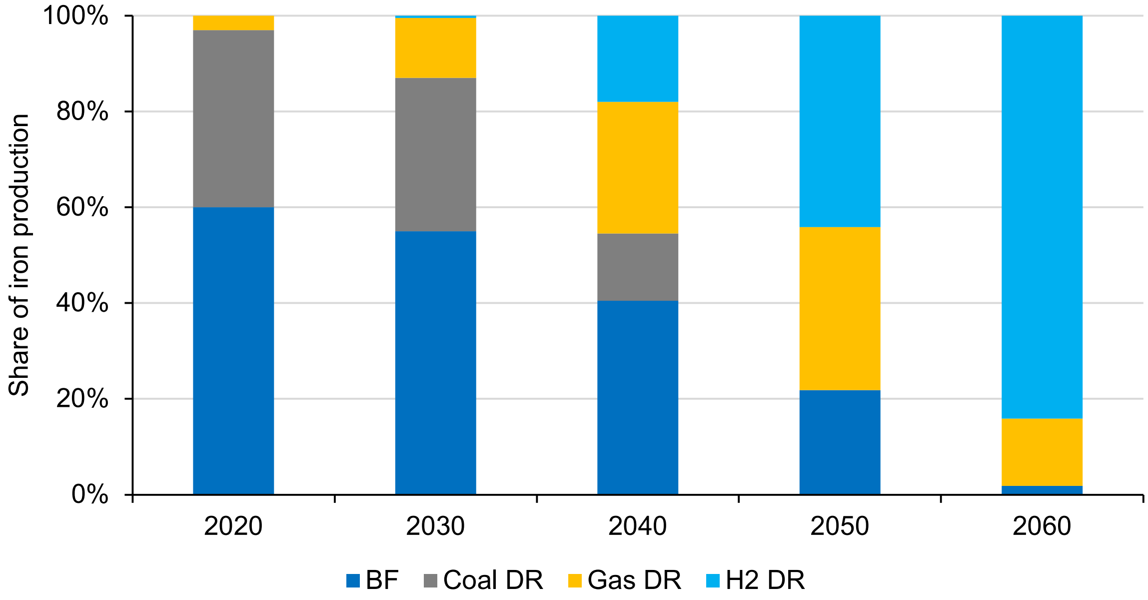
In line with an internationally reducing scrap availability, the Steel Scrap Recycling Policy assumes that no scrap steel will be imported by 2030, setting out a strategy to increase the domestic availability of steel scrap through improved recycling. As a result, the Ministry of Steel expects domestic steel scrap availability to increase to approximately 50 Mt by 2030 (MoS, 2019). As a share of the total steel demand, this equates to around 20%, illustrating that even with an ambitious policy on steel scrap, new primary steelmaking capacity will be needed to meet growing demand.

Scenario for hydrogen direct reduction

For this scenario, it is assumed that gas based direct reduction plants are installed during the 2020s, primarily using natural gas. When low-cost hydrogen is available, these plants can switch over to hydrogen. From 2030 onwards, it is assumed that further direct reduction plants using high shares of green hydrogen from the beginning will be constructed.

The existing blast furnaces are steadily decommissioned as they reach the end of their economic life. By 2060, very few blast furnaces remain. Coal-based direct reduction units have a shorter lifetime versus blast furnaces and so we see these units being phased out before 2050, with natural gas and hydrogen based direct reduction units being deployed in their place.

Figure 15: Scenario for hydrogen direct reduction in India



Source: Author’s analysis

In such a scenario, demand for key fuels in the iron & steel sector change significantly. At present, the iron & steel sector consumes around 60 Mt of coking coal, over 80% of which is imported. Demand for coking coal starts to fall over the 2020s, as gas-based capacity is introduced, paving the way for higher shares for hydrogen direct reduction out to 2060. By 2060, the sector could consume approximately 20 Mt of low carbon hydrogen (which in turn would require approximately 1,000 TWh of electricity), alongside 250 TWh of electricity for EAFs using DRI and scrap steel. Whilst there would be a significant benefit to reducing energy imports of coal and, eventually, natural gas, the pace and scale of renewable electricity expansion would prove to be a challenge.

To achieve this, we estimate that a carbon price in the steel sector would need to be approximately $40/tCO$_2$ in 2030. This would make hydrogen direct reduction competitive with BF-BOF plants, assuming a cost of hydrogen at $2/kg. An increasing carbon price from this point onwards would ensure a steady phase-out of natural gas in the direct reduction process, aided also by the falling cost for green hydrogen.

6. Conclusion and recommendations

This paper has illustrated that deep decarbonisation of the Indian iron and steel sector is technically possible and companies, such as Primetals Technologies and Siemens, have the technologies available to deliver this vision. However, it is clear that in the near-term, the cost of producing green steel using these methods would exceed the cost of steel production from conventional routes. It is therefore important that the public and private sector can work together to implement policies that can accelerate this transition, to help to realise the benefits of steel sector decarbonisation, which include tackling climate change, reducing air pollution, and delivering sustainable economic growth.

To deliver an accelerated transition of the steel sector from the wide-scale use of fossil fuels to the use of low carbon energy sources, such as hydrogen, would require a holistic policy framework that provides a 'supply push' along with a 'demand pull'. This would give companies clear direction for future investments, reducing their risk of investing in low carbon production processes.

SUPPLY PUSH	DEMAND PULL
Access to natural gas or syngas To facilitate immediate term expansion of natural gas-based capacity, which provides an easier switch to green hydrogen in the medium term, access to natural gas or syngas at suitable prices is required. Prices between $6-8/mmBtu are necessary to be competitive with blast furnaces (Hall, Spencer, & Kumar, 2020). **Demonstration plants** Medium to large-scale demonstration plants should be established to familiarize the sector with the technology, start scale-up of technology	**Green product standards** There will be a need to distinguish between 'dirty' steel and 'green' steel, to help consumers decide between more or less sustainable products, as they seek to decarbonize their supply chains. GreenPro being developed by the Confederation of Indian Industry (CII), as well the ResponsibleSteel standard, are both examples of private sector initiatives in this area. **Corporate buyers' clubs**

manufacture, and signal a serious intention for deep decarbonisation. Several demonstration projects are under construction or under consideration. **Large-scale green finance** To enable large demonstration projects and ultimately commercial-scale plants, significant financial capital will be required. This will require working with consortia of finance providers, including multi-lateral development banks, institutional investors, public sector banks, export finance, and large climate funds (e.g. the Green Climate Fund). **Emissions penalty on production** To provide a clear, sector-wide direction for deep decarbonisation will require ambitious policy to limit CO_2 emissions. The most common method for doing so would be the implementation of a carbon tax, so that high-polluting steel plants would pay more. This could be paired with a carbon border tax, so that cheaper, dirty steel would not be imported, thus protecting the domestic industry. **Transition support for small-scale plants** The Indian DRI sector today mostly consists of small coal-based direct reduction plants, serving local markets. As these are the highest polluting, they would pay the most carbon tax. They would also be better suited to switching from coal-based technologies, to hydrogen direct reduction, given the output product would be the same – DRI. Public support will be required to help transition these smaller plants, helping to retain local employment and supply chains.	To send clear demand signals to steel producers to start producing green steel, groups of corporates who use steel can band together to create clubs which achieve a critical mass of demand. Over time, such clubs could provide guaranteed markets for green steel, helping to derisk investments for producers. SteelZero is an example of such an initiative. Although discussions are at an early stage in India, companies such as Mahindra Lifespaces have expressed an interest in such initiatives (TERI, 2020). **Public procurement** To drive initial large-scale demand for green products, governments and public bodies should commit to procuring environmentally sustainable products, such as green steel. Infrastructure accounts for around 27% of steel demand in India, most of which is used in public projects such as roads, bridges, railways, metros, etc. (Placeholder1). Public Works Departments could help drive this initial demand, providing a guaranteed market for domestic green steel producers.

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