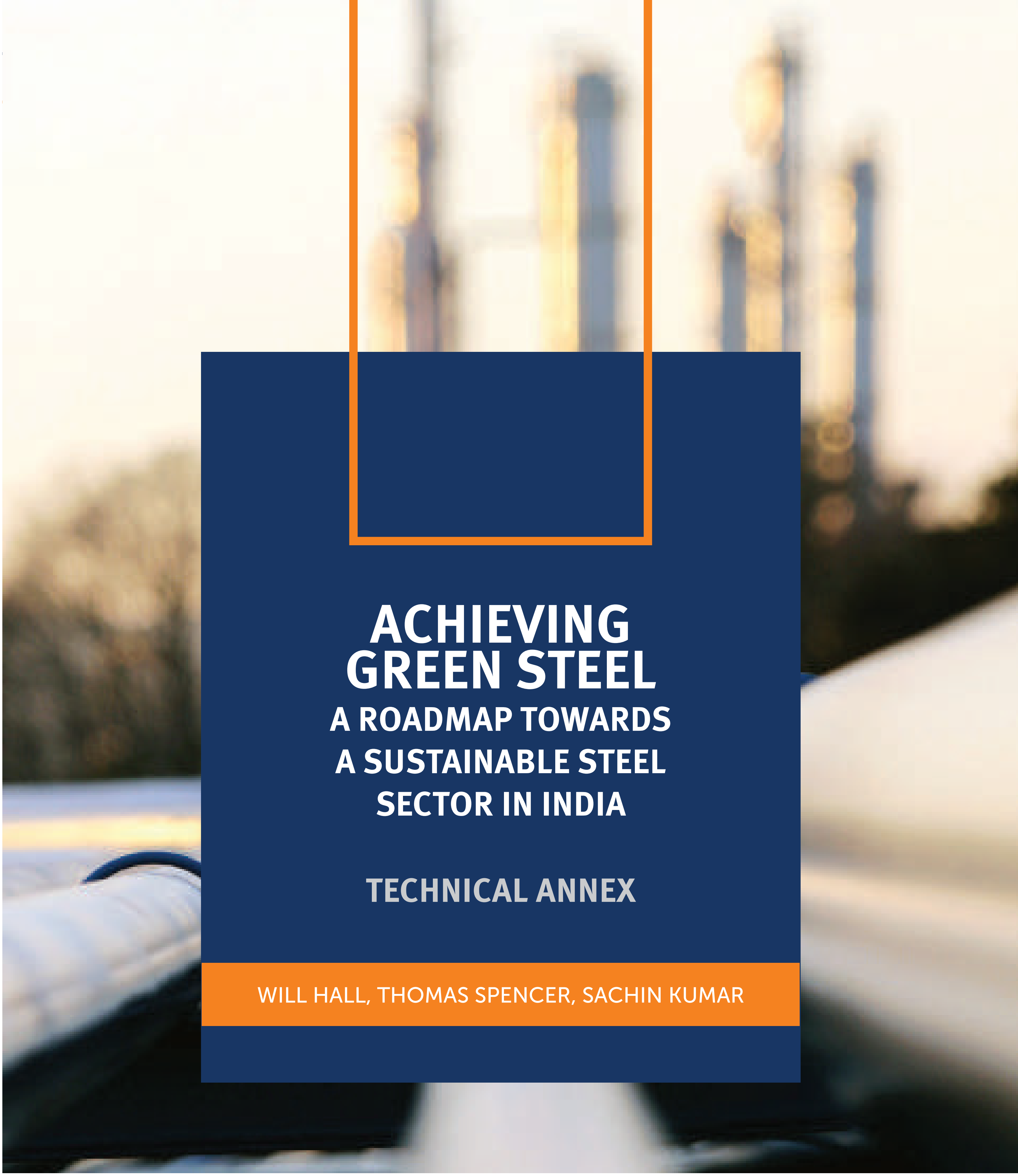

ACHIEVING GREEN STEEL

A ROADMAP TOWARDS A SUSTAINABLE STEEL SECTOR IN INDIA

TECHNICAL ANNEX

WILL HALL, THOMAS SPENCER, SACHIN KUMAR

SHAKTI SUSTAINABLE ENERGY FOUNDATION

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Creating Innovative Solutions for a Sustainable Future

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ENERGY TRANSITIONS COMMISSION INDIA

Energy Transitions Commission (ETC) India is a research platform based in The Energy and Resources Institute (TERI) in Delhi. ETC India is the Indian chapter of the global Energy Transitions Commission, which is chaired by Lord Adair Turner.

In 2018, ETC launched its 'Mission Possible' report, which detailed decarbonization pathways for the 'hard-to-abate' sectors. This included a sectoral focus on steel, which provided the impetus to start work on the same in India.

ETC India initiated activities in 2017-18 with a focus on the decarbonization of India's power sector. Whilst that work is still continuing, ETC India has also started to work on industry transformation, particularly in the 'harder-to-abate' sectors including iron & steel, cement, and other industry sub-sectors.

Learn more at: https://www.teriin.org/energy-transitions

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ABOUT TECHNICAL ANNEX

While India builds the infrastructure and supplies the goods that are required to improve living standard, the demand for energy-intensive materials is set to explode in the decades to come. Steel is one of those vital commodities and it plays an essential role in strengthening the economy. Steel sector is also a resource, energy, and emission intensive industry. The consumption of steel is likely to grow four times from now until 2050, because of greater demand in the building, automobile, infrastructure, metal goods, and industrial equipment end-use sectors. This comes in hand with alarming concern of negative environmental impact due to production processes and this could not be brushed aside.

TERI is working under the flagship of Energy Transitions Commission (ETC) India for decarbonization of hard to abate sectors to help recognize pathways for shifting heavy industry from fossil fuels to cleaner energy sources, chiefly iron and steel sector. As a primary step in this work, we came out with a detailed report 'Towards a Low Carbon Steel Sector: Overview of the Changing Market, Technology, and Policy Context for Indian Steel'. The report suggests a comprehensive package of measures that would keep the sector competitive while reducing its environmental impacts. We consulted an array of stakeholders and carried out broad modelling exercise to project the steel demand in the country until 2050. Hon'ble Union Minister of Steel, Petroleum and Natural Gas, Government of India launched the consultation document during the World Sustainable Development Summit (WSDS) - an annual event by TERI on January 30, 2020.

This technical annex 'Achieving Green Steel: A roadmap towards a sustainable steel sector in India' is the updated version of the consultation document. The annex comprises an overview of the Indian steel sector and the options to mitigate its impact on the environment, through reducing emissions along with the impact of resource efficiency. We are publishing this annex as a know-how document along with our steel roadmap 'Achieving Green Steel: Roadmap to a net zero steel sector in India'. The roadmap is the next step in our work providing concrete near and long-term strategies for emission reduction in steel sector such as maximizing energy efficiency, increasing utilization of scrap, introducing green product standards, supporting policies and regulatory measures, establishing demonstration and commercial-scale plants while retiring old emission intensive plants to project the sector on a net-zero pathway.

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GLOSSARY

BF-BOF – Blast Furnace-Basic Oxygen Furnace

CCUS – Carbon Capture, Use and Storage

CDQ – Coke Dry Quenching

CGD – City Gas Distribution

CO_2 – Carbon Dioxide

COG – Coke Oven Gas

DR – Direct Reduction

EAF – Electric Arc Furnace

EIF – Electric Induction Furnace

H_2 – Hydrogen

KTPY – Kilotonnes Per Year

MOE – Molten Oxide Electrolysis

Mt – Millions of tonnes

Mtpa – Millions of tonnes per annum

NG – Natural Gas

PCI – Pulverized Coal Injection

R,D&D – Research, Development and Deployment

TBP – To Be Published

TRT – Top Pressure Recovery Turbine

1
EXECUTIVE SUMMARY

Steel Is Essential to the Development of the Indian Economy and the Welfare of Its Citizens

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 very low at only about 74 kg per year, consistent with India's low GDP per capita. This is only 33% 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 (WSA 2020).[1]

As India's Economy Grows, Its Steel Demand Will Grow Substantially

India's GDP per capita, even when measured at Purchasing Power Parity (PPP), is only around 6900 USD, just 43% of the world average. A significant portion of the population still lives below the poverty line: as of 2011, the year of the last Census, 20% of the population lived below the minimum international poverty benchmark of 1.90 USD per day of consumption expenditure. Clearly, India must grow its economy to provide for higher incomes per capita and improved welfare for its citizens. This raises the question of the impact of India's economic growth on its steel demand. In this report, we have made projections for the Indian economy out to 2050, and from these economic scenarios derived projections for India's steel demand. In our Baseline Scenario, India's GDP per capita grows from the current level to about 25,000 USD by 2050, measured in constant 2011 PPP. This is an ambitious but feasible long-term growth scenario, which would bring India into the ranks of the high-income countries. In this *Baseline* scenario, India's steel demand grows by more than a factor of 5 between now and 2050 – from about 94 million tonnes (Mt) to 489 Mt. Indeed, we do not project that India's steel demand would saturate by 2050, but would instead continue to grow beyond this point.

There Is Substantial Uncertainty in These Projections, Even Before We Consider More Disruptive Factors

There is clearly a lot of uncertainty in projecting both the Indian economy and steel demand out to 2050. Both the rate of economic growth, as well as its key drivers, are uncertain. Will India follow a more service-based economy? Or will its rate of infrastructure investment and industrialization pick up, following a path more similar to that charted by China and other East Asian industrial powerhouses like Taiwan and South Korea? Indeed, in our analysis of the historical experiences of a large number of countries, we find that the most significant determinants of steel demand are the rate of investment and industrialization in the economy, not the absolute level of GDP per capita.

In order to analyse the full range of possible pathways for Indian steel demand, we constructed sensitivities on our Baseline Economic Scenario out to 2050. In the High Scenario, the rate of investment, industrialization, and overall growth is higher than in our Baseline Scenario, consistent with a 'Make in India' style development scenario. In the Low Scenario, investment, industrialization, and aggregate growth are lower than in the Baseline, consistent with a more services-led and potentially more unequal development trajectory.

1 The above figures are based on the data from the World Steel Association and take true steel consumption per capita as the metric. The figure quoted for the world is the value for a panel of 74 countries for which the World Steel Association provides data on true steel consumption per capita.

These different economic scenarios have a huge impact on our projection of Indian steel demand out to 2050. The High Scenario sees steel demand become almost 40% higher than in the Baseline Scenario (at 755 Mt by 2050), which is close to but still below China's level of steel demand in 2017. On the other hand, in the Low Scenario, steel consumption is almost 40% lower than the Baseline Scenario (at 289 Mt by 2050). In this report, we use the Baseline Scenario as our central scenario. However, the large spread between the High and Low Scenarios indicates a wide band of possible outcomes, dependent on the development trajectory of the Indian economy. Figure E1 shows the results of these scenarios.

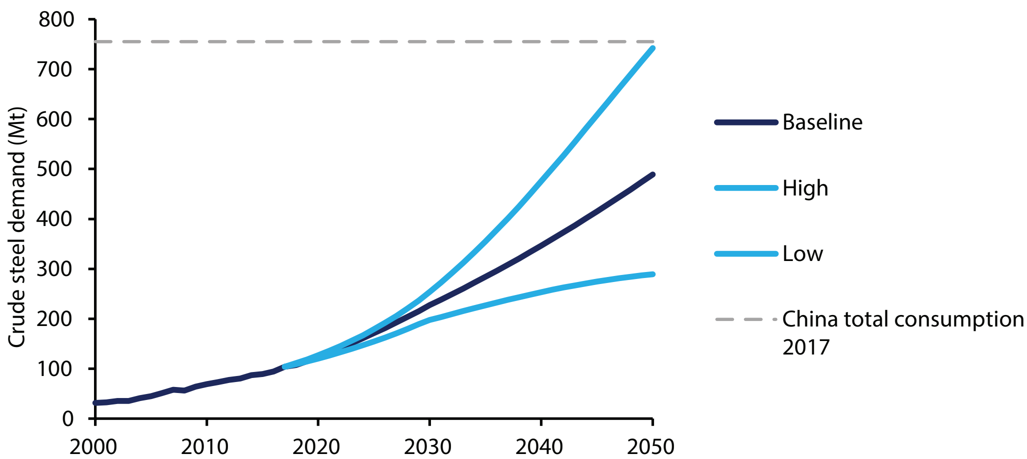


Figure E1: Range of projections for Indian steel demand out to 2050

Source: TERI modelling and analysis

The Level of Steel Demand Growth Projected in the Baseline Would Have Significant Economic and Environmental Externalities

Although critical for economic growth, the iron and steel sector is energy and resource intensive. Rapid growth of Indian steel demand cannot but have significant environmental and economic consequences. Today, the iron and steel sector is already the largest industrial sector in terms of energy consumption. In addition, it accounts for a significant share of India's manufacturing goods trade deficit – at about 7.4% if we include both the net import of coking coal and iron and steel products.

In our Baseline Scenario, by 2050, energy demand from the iron and steel sector would grow by a factor 4, from about 59 million tonnes of oil equivalent (Mtoe) in 2016 to about 235 Mtoe. This is substantially slower than the growth in total steel demand (a factor 5 increase), indicating that we expect substantial improvements in energy efficiency to occur even in our Baseline Scenario. Coking coal requirements could grow from 60 Mt to 218 Mt, implying an increase in the import bill from 10 billion USD today to 33–40 billion USD by 2050. Emissions of CO_2 would grow from today's level of 251 Mt to about 798 Mt by 2050 in our Baseline Scenario. The growth in emissions by a factor of 3.45 is lower than our projected growth of energy demand (factor 4), indicating that we consider some decarbonization of iron and steel production even in our Baseline Scenario.

Clearly, this level of resource consumption, energy consumption, and GHG emissions is a concern. Incremental measures to improve energy and carbon efficiency in the iron and steel sector are not enough to place it on a trajectory consistent with limiting warming to less than 2°C.

The Iron and Steel Sector Can No Longer Be Excluded from International or Indian Climate Policy Focus

In 2015, the iron and steel sector accounted for about 6.2% of global emissions from fossil fuel combustion. If the sector were a country, it would be the fifth largest emitter, after China, the United States, the European Union, and India. Despite its large emissions footprint, the iron and steel sector has largely been exempt from stringent climate policy measures. It is economically significant and exposed to international competition, and countries have long been concerned about the impact of unilateral measures on the domestic industry's international competitiveness. At the same time, coordinated international approaches have not been developed. In addition, the level of technical and commercial readiness of mitigation technologies has been lower in the iron and steel sector compared to other sectors like electricity production. Thus, policy-makers and corporations have implemented strategies to incrementally improve energy efficiency, but shied away from more profound decarbonization of the iron and steel sector.

However, this cannot continue. By 2050, in scenarios consistent with limiting warming to less than 2°C, the carbon intensity of steel production needs to be reduced by at least 70% globally. In 2050, India will be one of the few world regions (alongside Africa) still expecting further growth in iron and steel demand; China's steel demand will have peaked (indeed may already have peaked), and will following the trajectory of plateau and decline charted by developed countries before it.

Thus, in order for India's long-term development to be consistent with a global scenario limiting warming to 2°C, it is essential that the world innovates a pathway towards zero carbon steel and that India transitions towards this pathway too.

Strategies Toward Iron and Steel Sector Transition Need Not Be 'All or Nothing'

Because of the large facilities, huge investments and long plant lifetimes, it may seem that a pathway towards zero carbon steel is 'all or nothing'. If this were so, it is understandable that policy-makers and business strategists would shy away from such a proposition, particularly while decarbonization technology in the iron and steel sector is still far from commercially available. However, we argue that this is an incorrect framing. It is possible to envisage a feasible, cost-effective, step-wise pathway for Indian iron and steel that would allow the sector to contribute to a global effort to limit warming to less than 2°C. We argue that this pathway is firmly in India's interest; it would innovate a much less resource-, import-, and energy-intensive pattern of industrialization for India. In the following sections, we outline the three key pillars of this pathway.

Pillar 1: Improve Energy Efficiency, Resource Efficiency, and Material Circularity

Due to the heavy reliance on coal-based Direct Reduction (DR), and the presence of many older, relatively inefficient blast furnace units, the Indian iron and steel sector is relatively energy intensive compared to international benchmarks. However, on reviewing a large number of possible energy efficiency measures, we have shown that the average plant could lower energy consumption per unit output by between 24–38%, depending on the production route. This would have important benefits in lowering aggregate energy consumption and CO_2 emissions, where adoption of best available energy efficiency technologies could reduce overall emissions by up to 15% by 2050, versus the Baseline (where some energy efficiency measures are adopted).

Reducing steel consumption through resource efficiency can have a substantial benefit in terms of more efficient aggregate resource use across the Indian economy. Indeed, certain structural trends like the emergence of ride-sharing (Uber/Ola), the emergence of the gig economy, teleworking, and co-working suggest that the future Indian economy, even in the absence of further policy measures, may in fact be less steel intensive than the Baseline Scenario presented above. If we also consider policies to actively promote resource efficiency, steel demand could be 25% lower by 2050, compared to our Baseline Scenario. Production of energy-intensive primary steel can be avoided by increasing the collection and use of domestic scrap steel, which is 85% less emissions intensive than primary steel today. In addition, India already imports substantial quantities of scrap and there may not be much scope for increasing scrap imports. In a low carbon future, demand for scrap in developed countries is likely to increase, given the reduced emissions through the secondary production route. A scenario combining resource efficiency and increased circularity could further reduce emissions by 20% by 2050.

Pillar 2: Implement Transition Strategies by the 2030s and Deep Decarbonization Options by the 2040s

Even with the above-described energy and resource efficiency measures, the iron and steel sector would still emit around 500 Mt of CO_2 by 2050. Theoretically, substituting natural gas for coal could further lower emissions, but this option must be discounted given the lack of domestic gas and the expense of imported gas in India. A more promising transition option would be the HIsarna process, which can reduce emissions by 20%, compared to the traditional Blast Furnace–Basic Oxygen Furnace route (BF-BOF). If the resulting pure stream of CO_2 from the blast furnace route is captured using the Carbon Capture Use and Storage (CCUS) route, then emissions could be reduced by up to 80%. This technology is already being trialled in Europe by Tata Steel, the owner of the technology.

By the 2040s, it is expected that more radical decarbonization technologies, which are currently being demonstrated, would be commercially available. Of particular interest is the hydrogen route, which involves the substitution of coal or natural gas as a reducing agent with hydrogen. If hydrogen is produced from emissions free electricity, total iron and steel emissions can be reduced by 94%. According to the analysis developed in this report, if hydrogen can be delivered at a cost of 2.5–3.5 USD/kg, the hydrogen route can be cost competitive with the BF-BOF route. This would require electrolyser costs to fall to around 400 USD/kW and renewable electricity to be priced in the range of 20–30 USD/MWh. Both of these assumptions are perfectly feasible by 2050 (renewable electricity is already in the range of 35 USD/MWh in India).

Assuming that new facilities after 2040 are based on the hydrogen route and hydrogen is increasingly blended in existing facilities to substitute coal, emissions can be reduced by further 8% by 2050. More importantly, the sector would be on a pathway to fully decarbonize thereafter. India would be the first ever country to industrialize while decarbonizing its steel production. The cumulative effects of these measures are shown in Figure E2.

Pillar 3: Promote International Collaboration, Innovation, and Technology Diffusion and Develop a Domestic Low Carbon Steel Strategy

India is faced with a paradox. Between now and 2050, it will be one of the major sources of growth of global steel demand. By 2050, India will be one of the few world regions whose steel demand will still be growing, even while the pressure to reduce global CO_2 emissions will only increase. It is thus in India's interest that global efforts to

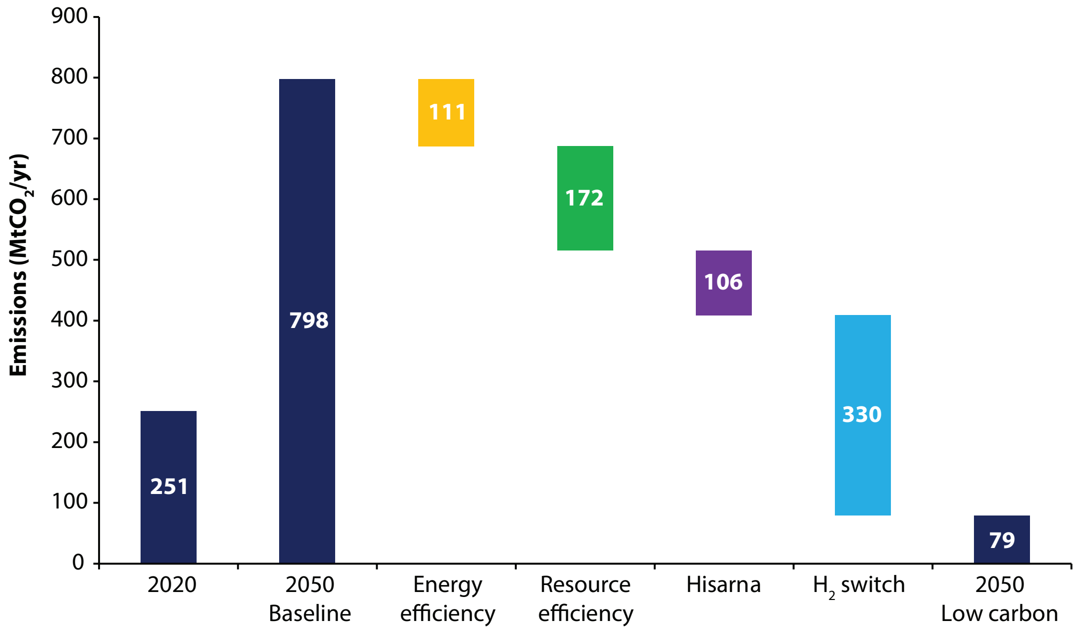


Figure E2: Cumulative impacts of the proposed measures

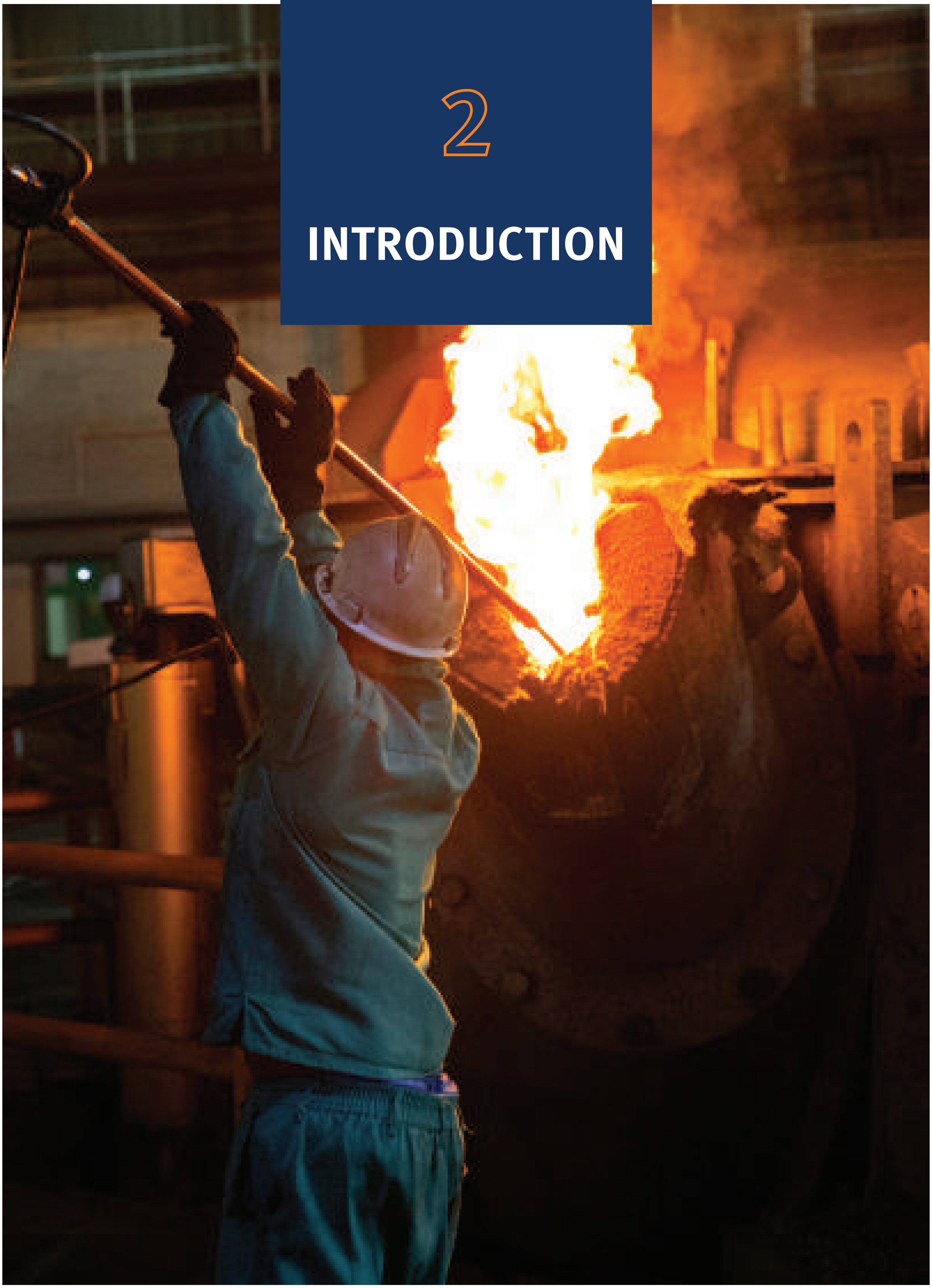
Source: TERI modelling and analysis

innovate a zero-carbon pathway for iron and steel succeed. In addition, Indian firms, notably Tata Steel, are active in the global market and own a number of key low carbon technologies. India doesn't have cost-effective reserves of natural gas or coking coal and so the development of a renewables plus hydrogen economy is in its interest. India should therefore actively promote international innovation, technology learning and diffusion, and become a major driver of the push to zero-carbon steel; it stands to be the major beneficiary.

Secondly, India should develop a domestic pathway towards a low-emissions iron and steel sector by 2050, and zero emissions shortly thereafter, ideally by 2060. The long-term low emissions development strategy that India will submit to the UNFCCC provides an opportunity to do so, as does the India 2047 vision being developed by NITI Aayog. Domestic policy frameworks to promote energy and resource efficiency already exist in the form of the Perform Achieve and Trade Scheme, the Steel Scrap Recycling Policy, and the Draft National Resource Efficiency Policy. These can be implemented and strengthened over time. They should also be complemented with policies to promote innovation and technology demonstration for crucial technologies such as HIsarna, CCUS, and hydrogen-based steel production. This could include proactively pushing for international collaborative research, development and demonstration (RD&D) programmes, engaging in international consortia, and seeking funding and technology from international donors. In this regard, developed countries also need to realize that the climate policy agenda has to shift towards promoting industry decarbonization and supporting India in its endeavours to deploy low carbon technologies out to 2050.

Moreover, in combination with various supply-side policies, it will be important to complement these with measures to stimulate demand for low carbon steel. This can be in the form of buyers' clubs, whereby groups of businesses who use steel in their products (e.g., automotive manufacturers) agree to buy low carbon steel at a premium, so that they can then market their products as environment-friendly alternatives. This can be supported by standard setting systems, such as the ResponsibleSteel™ standard. In pathway to promote Eco-labelling initiatives, Tata Steel in collaboration with CII Green Business Centre and relevant stakeholders in the Indian steel sector has developed GreenPro framework for steel rebars. The government can also play an important role here, buying up large quantities of low carbon steel to help scale up production, as has been done so effectively with LEDs under the UJALA scheme.

Finally, India should engage in the sensitive topic of international trade and potential measures to protect domestic industry in a world of uneven carbon prices and climate policy efforts. Carbon border adjustments are already being actively considered by the European Union, and appear inevitable in a world of ever growing, but unevenly shared, concern about climate change. The iron and steel sector is likely to be the first to be targeted by such measures; Europe is one of India's major destinations for its steel exports. By engaging in global efforts to transition in the iron and steel sector, India can hedge against the risk of the imposition of climate-related trade measures.



2

INTRODUCTION

Heavy industry provides the building blocks for a modern economy, supplying materials such as iron, steel, cement, and petrochemicals for key infrastructure, goods and services. Industrialization, infrastructure development, and urbanization require large quantities of energy and emissions-intensive materials such as steel, cement, glass, and other metals. Industrialization in India has been a slow but continuing process, which increased more rapidly with the liberalization of the Indian economy in the 1990s (Siddiqui 2015). However, India is still a relatively low income country, and its process of economic development, industrialization, and urbanization still has a long way to go.

Thus, demand for energy-intensive materials is expected to explode in the decades to come, as India builds the infrastructure and supplies the goods that are required to improve standards of living. Steel consumption is set to quadruple between 2020 and 2050, as a result of greater demand in the building, automobile, infrastructure, metal goods, and industrial equipment end-use sectors.

Whilst development should be prioritized, the significant negative environmental impacts from iron and steel production cannot be ignored. The iron and steel sector currently consumes the most energy of all industrial sectors within India, including around 13% of India's total coal consumption, resulting in large quantities of greenhouse gas emissions (IEA 2018). India is also one of the most at-risk countries when it comes to the impacts of climate change, with higher average temperatures impacting water scarcity, desertification, the propagation of disease and heat-related illnesses (IPCC 2018). Action needs to be taken to mitigate future emission increases; the earlier the better.

As a high-emitting sector, the iron and steel industry is not exempted from the need to reduce emissions. If warming is to be kept below 2°C, global greenhouse gas emissions (CO_2 and non-CO_2) must reach zero by the middle of the second half of this century, implying that CO_2 emissions from the energy system should be at or near zero by 2050. This means that the iron and steel sector must also rapidly transition to a pathway towards net zero emissions. However, while climate policy has made strides in driving emissions reductions in some sectors (notably electricity), the iron and steel sector has not seen comparable change. There are a series of barriers, which are relatively unique to the steel industry, that make rapid emissions reduction challenging. These include:

- **Replacement cycles** for capital equipment in the heavy industry sectors are long and this is especially true for the Indian iron and steel sector. One of the Tata Steel's facilities, located in Jamshedpur, first started production in 1912 and is still in operation today. Whilst it has been significantly upgraded and expanded over the years, such that it is now one of the most efficient plants in the country, it provides an illustration of the potentially long lifetimes of plants built today. On the cusp of **rapid expansion**, India needs to ensure that steel plants built in the near future are built in a way that anticipates and enables a switch to zero-carbon energy to avoid lock-in into high emitting technologies.
- The incumbent steelmaking technologies are highly **resource-, energy- and emissions- intensive**. In India, steelmaking facilities are mainly divided between the basic oxygen furnace and electric furnace routes, the latter being fed by direct reduced iron, largely from coal-based facilities. Even with the most ambitious policies for energy and resource efficiency, the carbon dioxide emissions resulting from steel production from these routes will be significant. A large-scale shift away from current fossil fuel based production routes is required to reach low emissions levels.
- Whilst the **capital costs** of energy efficiency measures are recoverable over short payback periods (BEE 2018), capital requirements for a more profound transition towards low carbon production technologies are large. **Access to capital** is already challenging for incumbent technologies in India. Banks and financial institutions will need to be provided with the security of a robust policy framework that can support the steel sector in a low carbon transition.

- Moreover, **adoption of new low carbon technologies** is likely to increase the costs of production in the near term. Steel is a globally traded commodity, in a highly competitive and oversupplied market. Excess global steel producing capacities, currently 20% greater than demand, has impacted profit margins, making long-term planning and investment more difficult (OECD 2019a). Any strategy for the steel sector needs to be cognizant of **international trade and competitiveness** dynamics and how government policy and business planning can ensure robust and sustainable growth of the domestic sector.

As we will discuss in this report, overcoming these barriers to reduce emissions from the iron and steel sector does not require an all-or-nothing approach. There are a range of areas to focus on in the near term which can deliver emissions savings such as ensuring the highest levels of energy and resource efficiency. To some extent, the government and industry are already moving in this direction, with the adoption of the Perform, Achieve and Trade (PAT) scheme (to encourage energy efficiency), the Steel Scrap Recycling Policy, and the Resource Efficiency Policy (TBP) driving progress in these areas. Nevertheless, if India is to achieve a long-term transition consistent with a global pathway to 2°C, the iron and steel sector must look beyond incremental improvements in energy efficiency.

India is presented with an almost unique opportunity to place itself on a path of green industrialization, a world-first for a developing economy. Such an approach would greatly reduce the environmental impact of the sector, both on India and the world. It would also prepare the sector for the future, where low carbon steel production will likely become the norm in many parts of the world. Getting ahead of the curve can help the industry guarantee long-term markets and avoid stranded asset risks. To seize this opportunity will require robust, forward-looking policies and business strategies.

This report will set out the current status of the sector (Section 3), before detailing the future challenges it faces, including rapid demand growth (Section 4), resources and environmental footprint (Section 5), the impact of trade and competitiveness (Section 6), and the transition options for new technologies (Section 7).

3

CURRENT STATUS

Current Status

India is currently the world's second-largest steel producer, and second-largest steel consumer (WSA 2020).The steel industry in India is far more heterogeneous than in many other countries, with a wide range of different sized facilities in the primary and secondary steelmaking sectors. There are also a number of different technologies currently being used, including the Blast Furnace - Basic Oxygen Furnace (BF-BOF), coal-based Direct Reduction (DR), gas-based DR, Electric Induction Furnace (EIF), and Electric Arc Furnace (EAF). Coal-based DR in particular is unique to the Indian steel sector to satisfy highly localized steel demands. Reliance on this technology is driven by India's cheap domestic coal reserves, and the lack of sufficient domestic natural gas supplies and coking coal of sufficient quality.

As with any industrializing economy, the steel sector is of vital importance to India's economy, contributing around 2% to the country's GDP and employing around 2.5 million people in the steel and related sectors (MoS 2019).

This section provides an overview of current production statistics, energy and raw materials use, the current market structure, and steel demand.

3.1 Production

India remained the world's second-largest producer of crude steel during 2019-20 (provisional) and produced 99.57 Mt of crude steel. However, the crude steel production showed a decline of 11% over the Corresponding Period Last Year (CPLY) (MoS 2021). The decrease in production is mainly due to impact of COVID-19 pandemic. Table 1 outlines the current production status within the sector.

Table 1: Production status 2020-21*

Type of industry	No. of units	Total capacity ('000 tonnes)	No of working units	Production ('000 tonnes)	Capacity utilization (%)
Blast Furnace – hot metal	65	79,569	57	67,737	85.1
Basic Oxygen Furnace	17	57,295	17	44,807	78.2
Electric Arc Furnace	55	40,508	39	27,880	68.8
Induction Furnace	1104	44,496	858	26,884	60.4
Sponge Iron	333	47,849	285	33,128	69.2

** Upto December, 2020*

Source: TERI based on data from JPC (2020), MoS (2021)

The main production routes in India are BF-BOF (45%), EAF (28%) and IF (27%) (MoS 2021). India is unique in its extensive use of coal-based DR, as opposed to natural gas-based DR, which is more commonly used around the world. The use of Induction Furnaces along with coal-based DR often results in lower quality steel, as a result of the residual phosphorous which is not removed, unlike with EAFs. To improve the quality of the steel from the coal-based Direct Reduction with Induction Furnace route would require either an additional refining step or the use of higher shares of good quality scrap. Otherwise, this steel is restricted to use in non-critical or non-load bearing applications. There is discussion of increasing natural gas use (or other gases) in the reduction process.

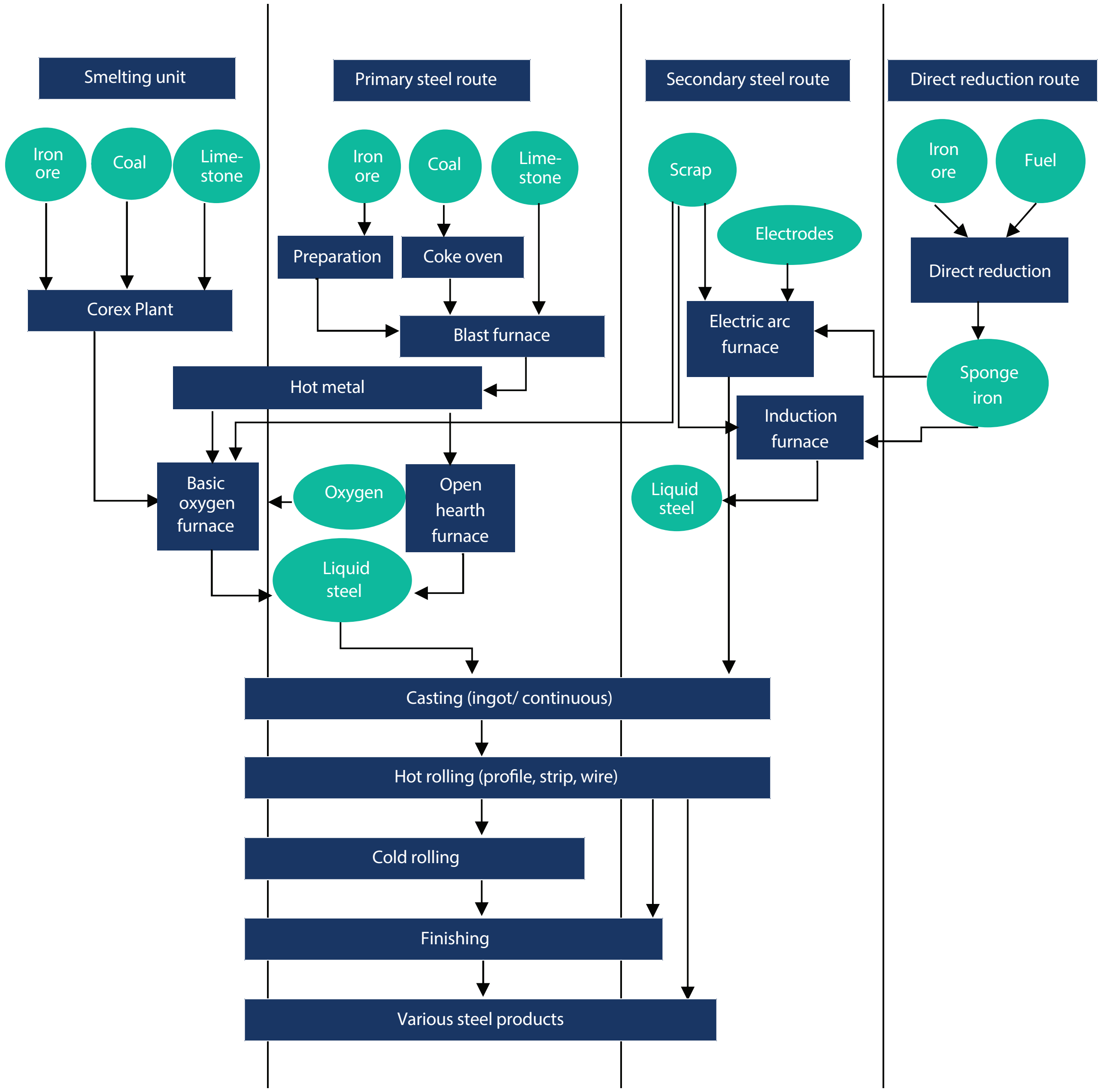


Figure 1: Steel production routes

However, the limited availability of domestic supplies and the high cost of imported gas make this difficult.

We have collected data on the large steel plants, commonly referred to as Integrated Steel Plants (ISPs). These are facilities above a production capacity of 1 Mt per annum, and which have the entire production line integrated at a single facility. This is commonplace in steel industries, as it helps improve operational efficiencies and allows producers to achieve significant economies of scale. A full list of large steel plants can be found in Annex A (Section 8.1).

Of the large steel plants in India, 70% are BF-BOF. Mini steel mills tend to use the electric route, and are often established to serve local demand, as opposed to the Indian market as a whole.

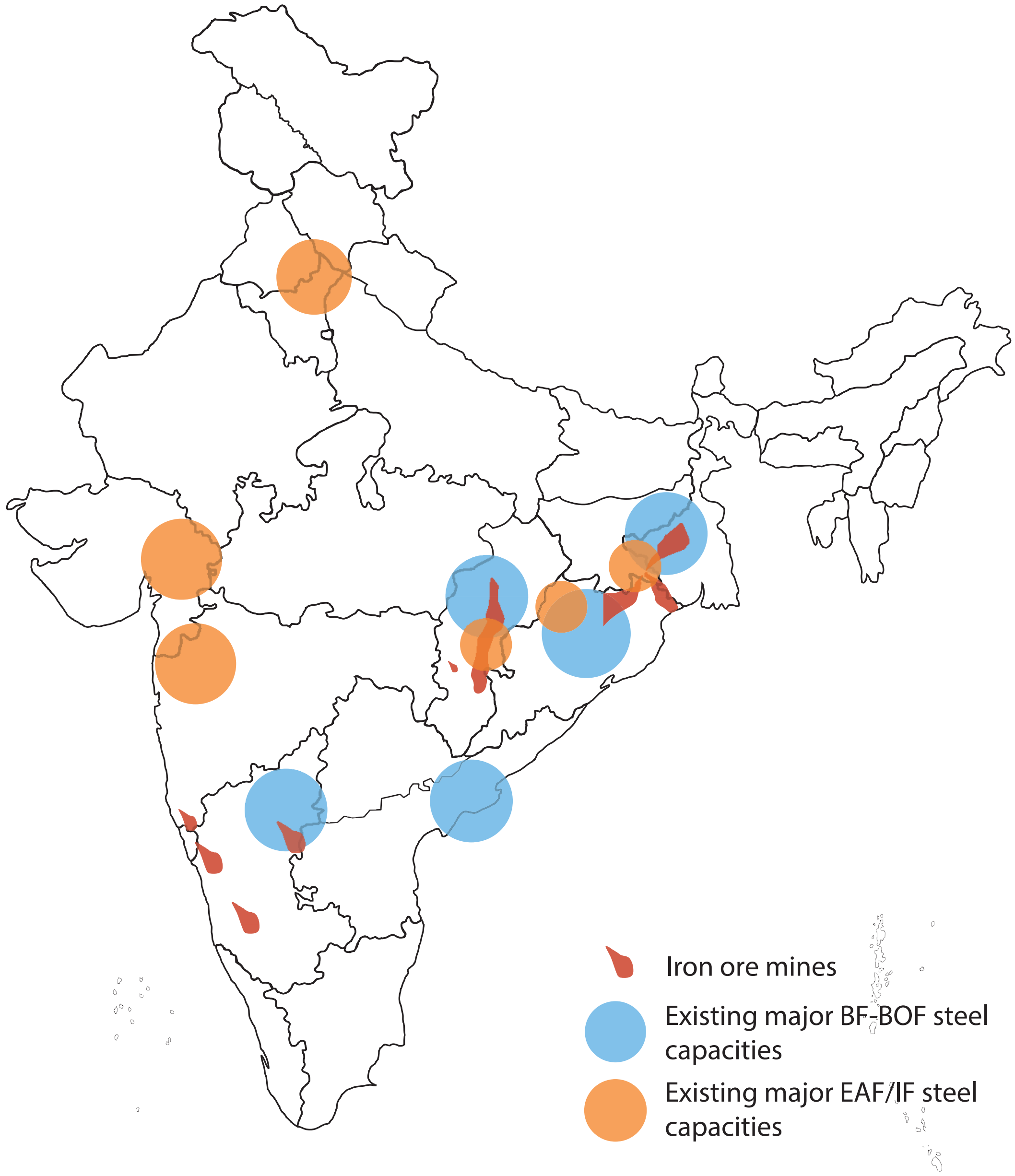


Figure 2: Plant locations and iron ore mines
Source: MoS (2017)

The main centres of production are located in Jharkhand, Orissa, West Bengal, Karnataka, Chhattisgarh, and Gujarat (Figure 2). These are close to the main iron and coal deposits, in order to reduce costs of material transportation. The geographic concentration of the steel sector and its related industries, means that it is of strategic importance within certain states and districts, in terms of employment and economic activity.

The import and export of steel in India fluctuates significantly year to year, based on domestic and global macroeconomic conditions, and the demand and supply scenario in the global steel market. In 2018, exports of finished steel stood at 6.4 Mt, representing a decline of 34% over the previous year. Imports of finished steel were at a similar level, around 7.8 Mt, an increase of 4.7%. India currently requires imports, despite also exporting, due to insufficient production of high quality steel, in particular for niche (specialist) steel products. Exports are primarily in semi-finished products of iron or non-alloy steel and small amounts of various stainless alloy steel products. International trade and competitiveness is covered in detail in Section 6.

3.2 Energy and Raw Materials

Within industry, the iron and steel sector is the largest energy consuming sub-sector, accounting for over 20% of industrial energy use (see Figure 3). Other sub-sectors which consume large amounts of energy in India are the brick, cement, petrochemical and fertilizer sectors.

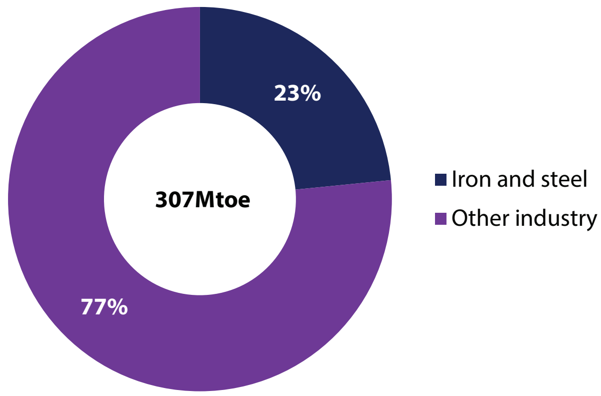


Figure 3: Iron and steel's share of industrial energy use, 2018-19

Source: TERI analysis using MoSPI (2019a)

The main fuel supply for the steel sector is coal, followed by electricity and then natural gas (IEA 2018). Coal is plentiful and cheap, although the large variations in quality can make the steelmaking process more challenging to control. India has a limited supply of coking coal and therefore imports much of its coking coal from abroad, mainly from Australia. There are, however, plans to increase domestic coking coal supplies to satisfy growing demand, which will be discussed further in Section 5.4.

In terms of electricity supply, this is still largely coal-based, and will continue to be so for the near future. The Government of India has set ambitious targets to increase renewables penetration, with announcements of 175 GW by 2022, increasing to 450 GW. However, due to the higher cost and unreliability of the electricity grid, many industries have set-up large captive power plants, i.e. electricity produced on-site. The iron and steel sector is no exception here, with captive plants providing 44% of electricity consumed in the industry in 2015–16. Of this captive generation, 91% is derived from coal, 7% from natural gas and 1% from diesel (CEA 2017). Compared to the electricity grid, captive power makes greater economic sense, but is still a rather expensive option for power generation. This in turn raises challenges with the viability of electro-intensive steel production routes.

Natural gas supplies in India are limited, and imports are expensive. Use of domestic natural gas is restricted to only a few sectors, specified by the government. These include the fertilizer, power, transport and cooking (CGD) sectors. The few iron and steel plants that are designed for the use of natural gas have suffered issues with limited supplies, and so have been running well below their optimal utilization factors. The future role of natural gas in the Indian steel sector is uncertain (see Section 7.1.1).

The Indian iron and steel sector is relatively inefficient in terms of energy consumption per unit output, when compared with international benchmarks (see Figure 4). Whilst there a few plants which have recently been upgraded to best available technologies to improve their efficiency, there is significant potential for energy savings across the sector as a whole.

In Section 5, we cover the range of different energy efficiency technologies available for different production routes, and the resulting impact on energy and emissions. The PAT scheme has already started to drive forward progress in this area, and is raising awareness in the industry, although further efforts are required to incentivize investments and provide finance for the requisite technologies.

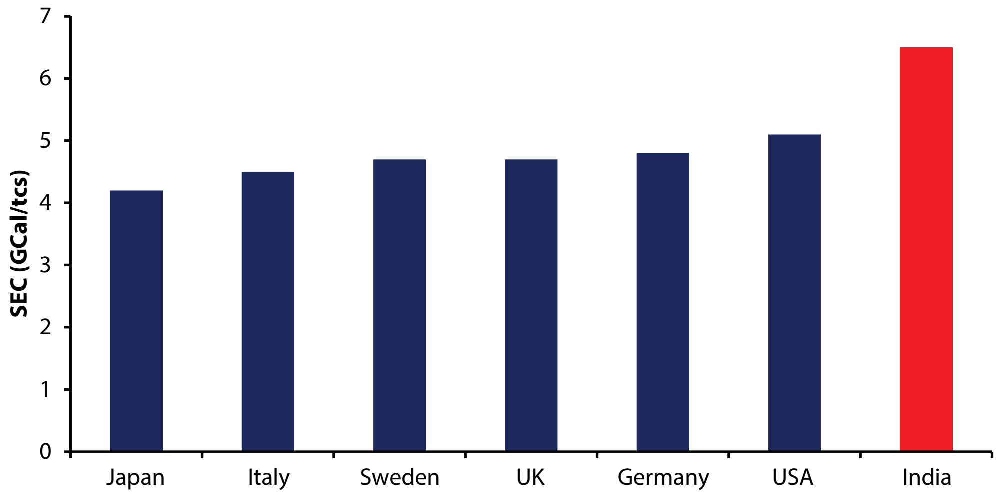


Figure 4: Average specific energy consumption of integrated steel plants by country

Source: India data updated by TERI, other countries from Samajdar (2012)

3.3 Market Structure

Since independence, an increasing share of the steel sector has been made up of private companies. The publically-owned Steel Authority of India Ltd. (SAIL) and Rashtriya Ispat Nigam Limited (RINL) still retain around a 20% share of production as of 2018–19, with private companies making up the balance. A significant number of the large steel plants were commissioned several decades ago and are in dire need of modernization, particularly those in the public sector. Figure 5 shows that the capacity-weighted average lifetime of a large steel plant is approximately 30 years in India today, illustrating the long lead-in times and replacement cycles within the industry. While many older plants are inefficient, a number of them have undergone extensive modernization to upgrade technologies. The Tata Steel facility at Jamshedpur, for example, began producing steel in 1912, with a 0.5 Mt capacity. Since then, it has undergone multiple rounds of modernization, renovation and expansion, so that it is now one of the most energy efficient plants in India, operating close to international benchmarks.

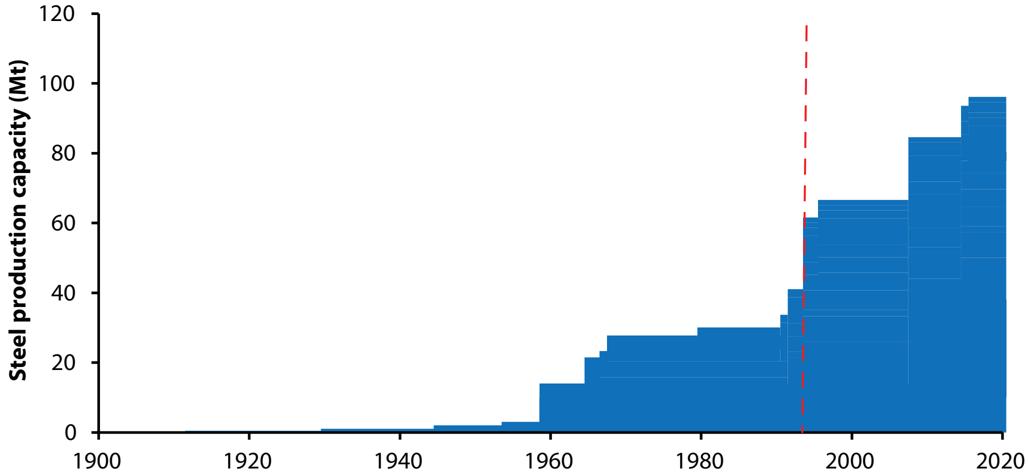


Figure 5: Production capacity of large steel plants by year of establishment

Source: TERI analysis based on data from JPC (2018)

In terms of focus on energy efficiency and improved environmental sustainability, there is significant disparity between the actions being taken by the industry leaders and the rest of the sector. Leading plants, for example, are adopting best available technologies in their plants, in line with international benchmarks. Companies such as Tata Steel are also investing heavily in R&D projects to prepare their businesses for a low carbon future. Mahindra Sanyo, in the secondary sector, is also showing leadership in this area, having signed up to the **Science-Based Targets** programme, where it aims to reduce emissions by 35% by 2030 (SBT 2018).

3.4 Steel Demand

India's steel consumption was 102.6 Mt in 2019-20. Due to adverse impact of the pandemic, the consumption decreased to 88.535 Mt in 2020-21(P), showing a decline of 14% over the previous year (MoS 2021). Despite this variation, India's true steel use[2] per capita is only 75 kg of finished steel equivalent, which is well below the global average of 224 kg (Figure 6). Developed economies' steel consumption tends to saturate at around 500 kg per capita, suggesting significant potential for Indian steel demand to grow as the country continues to develop.[3]

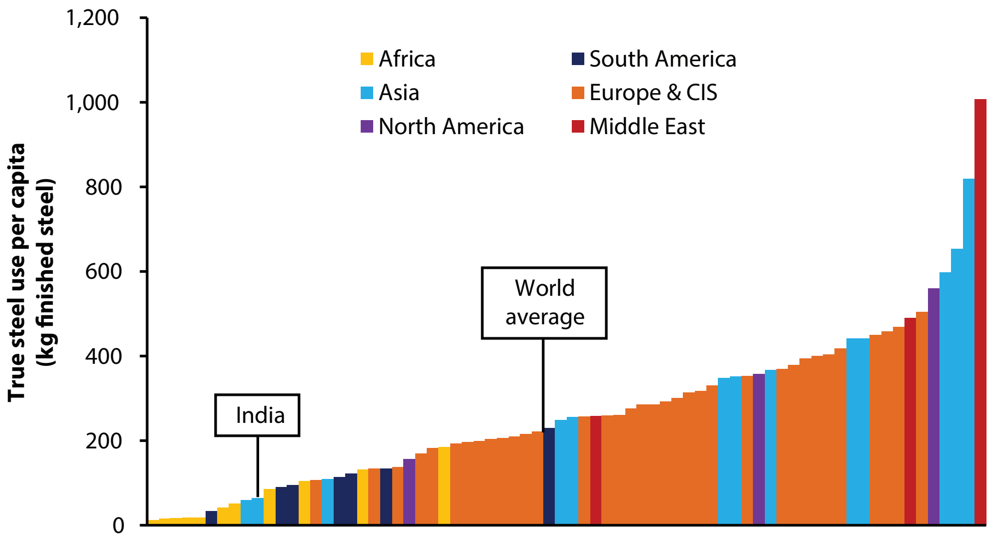


Figure 6: Per capita steel consumption by country

Source: TERI analysis based on data from WSA (2018b)

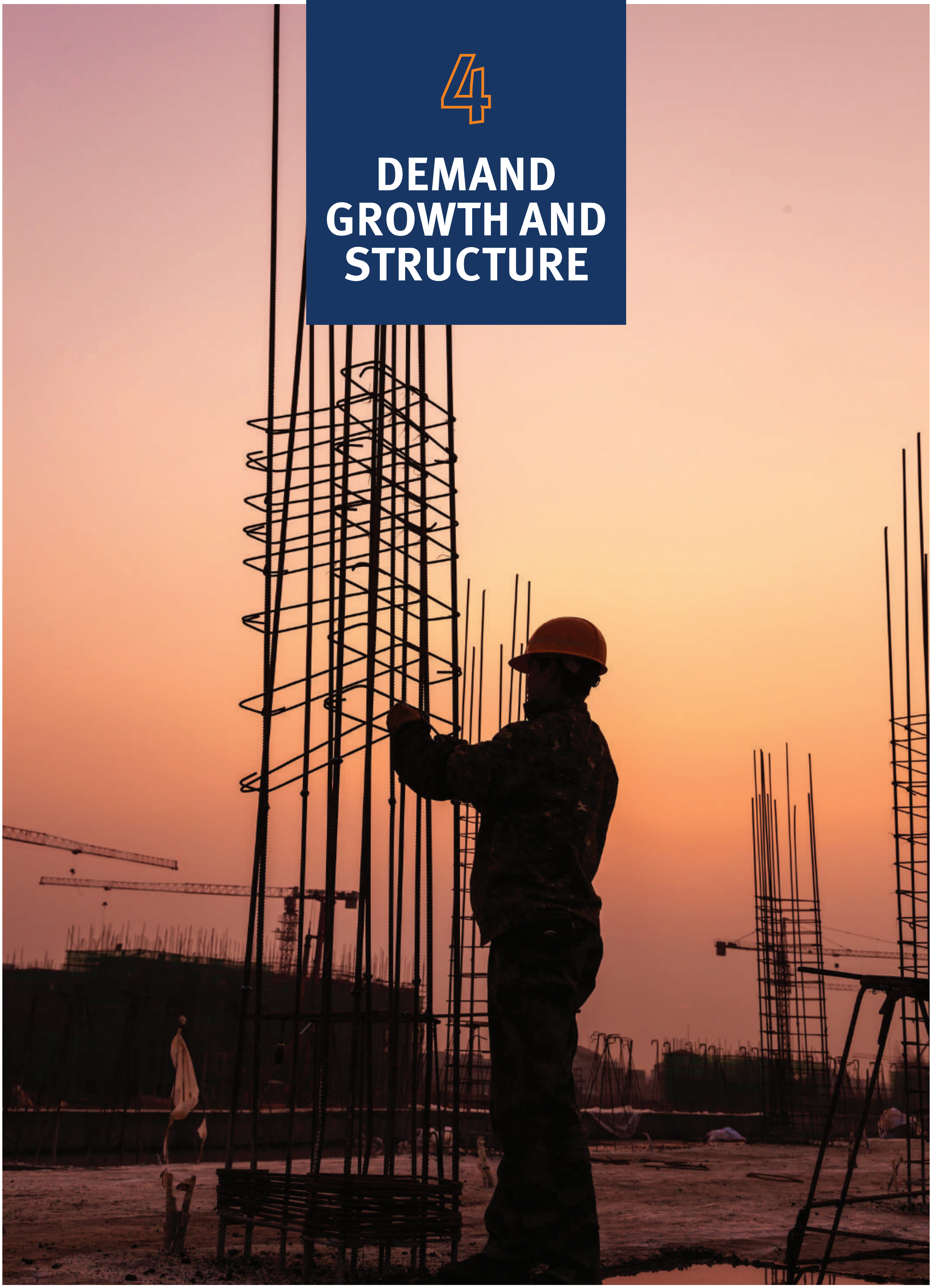
To encourage higher growth and a greater focus on energy efficient practices in the steel sector, the Ministry of Steel (MoS) launched the National Steel Policy in 2017, setting out targets for production and demand growth till 2030. The target for steel production capacity was 300 Mt for 2030–31, which represents a steel consumption per capita of 158 kg (MoS 2017). In this report, the Ministry highlighted the main sectors of steel demand, which include infrastructure and construction, engineering and fabrication, automotive and packaging. There are a number of policies that have been identified that will result in greater demand for steel, including the Pradhan Mantri Awas Yojana (the Housing for All Scheme), railway expansion, and the Smart Cities Mission. The next section will cover demand growth scenarios in detail.

2 True steel use (TSU) is apparent steel use minus net indirect exports. Apparent steel use (ASU) is production plus net imports minus net exports.

3 The analysis takes into account India-specific factors through a 'fixed-effects' econometric model. A Fixed-Effects model holds various country-specific factors, constant to account for differences across countries. For example, the model accounts for the fact that a large proportion of India's population lives in rural areas, where per capita steel consumption is much lower than in urban areas, which may not be the case in other countries.

4

DEMAND GROWTH AND STRUCTURE



Demand Growth and Structure

India is a rapidly growing economy- it has the world's second largest population, and is expected to be the largest by 2023 (OECD 2018a). Understanding the scale and pace of demand changes for key materials, such as iron and steel, is vitally important if we are to assess the sector's potential economic and environmental impact.

Covid-19 pandemic has affected several economies and industries globally and the steel industry is no exception. Indian steel industry was on growth mode until the lockdown happened in March, 2020 which deeply affected the supply as well as demand side of the sector. The supply side constraints were due to inter-state border closures, manpower shortage and workplace shutdowns. In the demand side, the weak domestic demand along with massive inventory build-up and supply chain bottlenecks resulted in production cuts and suppressed steel prices. On the optimistic part, the pandemic has actuated awareness of the approaching environmental risks in government and businesses. This has given a significant boost to both technological progress and the green transition.

A big chunk of demand will also come from rural India in coming decade. Currently, steel consumption in rural area is 17 Mt. Different development schemes such as PM Gram Sadak Yojna, PM Awas Yojna-Gramin, Deen Dayal Upadhyay Gram Jyoti Yojna, National Rural Drinking Water Supply, PM Krishi Sinchai Yojna, PM Kisan Sampada Yojna are expected to boost consumption up to 36 Mt of steel in rural India by 2030-31 (MoS 2020).

For projecting steel demand, we have adopted a top-down, econometric approach supplemented with a bottom-up, engineering approach. Top-down approaches are more widely used and are a relatively simple way of projecting material demands based on macroeconomic assumptions, such as economic growth. It is, however, difficult to develop an accurate picture of material flows with this approach, which in turn limits the detail of any circularity or demand reduction analysis. As a result, a bottom-up approach was also developed, breaking down Indian steel demand into end-uses, where possible.

4.1 Top–down Modelling

Our econometric model projects steel demand in India out to 2050, based on assumptions around the country's economic growth, levels of capital investment and structure of the economy. We have derived a relationship between steel demand and these macroeconomic indicators through the observation of data from 35 other countries between 2006 and 2016.

To select these countries, we chose those that were above a minimum geographical size, above a minimum level of industrial sector activity, and that spanned a broad range of GDP per capita. This was done to ensure that these countries could be useful comparators with India at some point in India's development pathway over the next three decades. This gave us a list of 40 countries, which were distributed both across the development cycle, as well as geographically. After some initial analysis, a further six countries[4] were removed on the basis of their exceptional characteristics, which included heavy oil dependence, abnormally high current account surpluses, or a lack of data, leaving the final list of countries at 35 (see Annex B).

The macroeconomic indicators that were tested against steel demand include Gross Domestic Product (GDP), Gross Fixed Capital Formation (GFCF), i.e., investment, and industrial Gross Value Added (GVA). These indicators are widely accepted in the literature to be reasonable predictors for material demands (POSCO 2018). Data on these indicators was obtained from the World Bank's 'World Development Indicators' database

4 These include Saudi Arabia, United Arab Emirates, South Korea, Bangladesh, Pakistan and Nigeria.

(World Bank 2017). Data on steel consumption was taken from the World Steel Association's (WSA) Statistical Yearbook (WSA 2018b).

Figure 7 shows the relationship between GDP per capita and true steel use per capita, with data from the 35 countries over the 2006–16 time period. We can observe that the relationship is relatively strong, with the level of steel consumption only starting to plateau at higher GDP per capita levels. The cluster of countries on the right-hand side of the chart represents the more developed economies, such as those in Western Europe, where the steel intensity of economic development has started to level off.

We can see however that before around $30,000 (PPP, $2011) GDP per capita, countries' steel intensity continues to grow strongly with GDP. The OECD long-term baseline scenario, which we have used as our central GDP projection in this analysis, forecasts India to reach around $25,000 per capita (PPP, $2011) by 2050 (OECD 2018b). Therefore, based on this cross-country, historical experience, it is unlikely that India's steel intensity of GDP will saturate before 2050. There are, of course, other factors which may cause this to be otherwise, such as increased substitution of steel with other materials, changes in consumer behaviour and a move to a more circular economy. All of these factors are explored fully in the scenario analysis in Section 4.3.

After testing the correlation coefficient between steel consumption and the aforementioned macroeconomic indicators, it was established that the best prediction of steel consumption could be achieved through using all indicators in a multiple regression analysis. GFCF per capita was the best predictor individually but the model was made more accurate by adding industrial GVA per capita and GDP per capita as well.

This then gives us a relationship between these three indicators and steel consumption which we can use to project future steel demand for India (Figure 8). To do so, we also developed scenarios on how GFCF, industrial GVA and GDP will change over the same time period. Long-term GDP projections, as well as industrial GVA and GFCF as a share of GDP were taken from the OECD's long-term baseline projections (OECD 2018a). This represented a central case. Population projections were also taken from the OECD, allowing us to calculate per capita figures for the above indicators out to 2050 (OECD 2016).

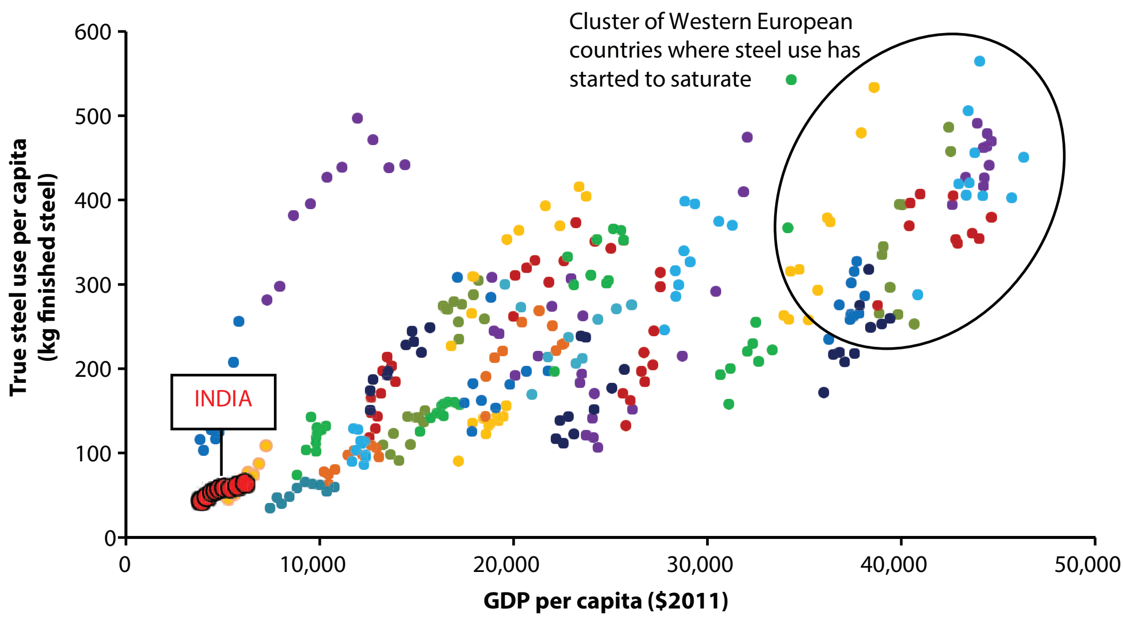


Figure 7: GDP per capita versus true steel use per capita for selected countries, 2006–16

Source: TERI analysis based on data from WSA (2018b); World Bank (2017)

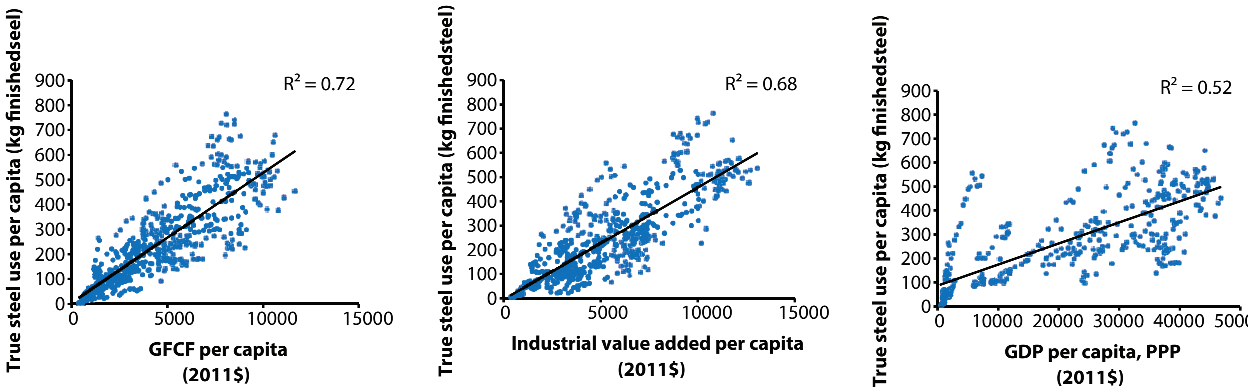


Figure 8: Steel consumption per capita versus GFCF per capita, Industrial GVA per capita and GDP per capita

Source: TERI analysis based on data from WSA (2018b); World Bank (2017)

To produce a range of scenarios, we varied core assumptions based on the international experience of countries similar to India. The assumptions used are in Table 2.

Table 2: Macroeconomic assumptions for demand scenarios

Assumption	Low		REF		High	
GDP growth	*2020–30*	*2030–50*	*2020–30*	*2030–50*	*2020–30*	*2030–50*
(growth rate p.a.)	5%	3%	6%	4%	7%	5%
Capital investment (GFCF)	*2030*	*2050*	*2030*	*2050*	*2030*	*2050*
(% of GDP)	29%	24%	31%	26%	33%	28%
Industrial growth (GVA)	*2030*	*2050*	*2030*	*2050*	*2030*	*2050*
(% of GDP)	27%	25%	28%	28%	29%	32%

Source: TERI analysis and assumptions, with reference to long-term projections from OECD (2018b)

Varying these assumptions, we were able to produce a broad spread of steel demand projections out to 2050 to reflect the uncertainty in India's macroeconomic development, which increases the further out we forecast. We narrowed down this spread to three scenarios which represent a number of plausible futures for India. These include:

- **Baseline**: This scenario uses all the central assumptions and represents a central view on steel demand out to 2050. In this scenario, steel demand grows at a similar rate relative to GDP, as compared to historical trends in India and other countries.
- **High:** This scenario uses high GDP, GFCF and GVA assumptions, reflecting a high growth, high industrialization development pathway. In this scenario, steel demand is very high as the economy continues to grow quickly out to 2050, with a greater share of this growth coming from steel-intensive industrial sectors.
- **Low:** This scenario uses low GDP, GFCF and GVA assumptions, reflecting a low growth, more service-based economy. In this scenario, steel demand is low as the rate of economic growth slows out to 2050, with a greater share of this growth coming from service sectors.

These three scenarios are plotted in Figure 9, showing the spread between our projections increasing out to 2050. In 2050, the 'High' and 'Low' scenarios are +/- 40% of our 'Baseline' scenario. It is also useful to compare these forecasts with a similar sized country's current crude steel consumption, like China. We can see here that even though we are expecting steel demand to increase rapidly over the next three decades, only in our 'High' scenario does this reach near the current Chinese consumption. It's worth noting that India will likely have a larger population than China by 2023, reflecting just how high China's current level of steel consumption is.

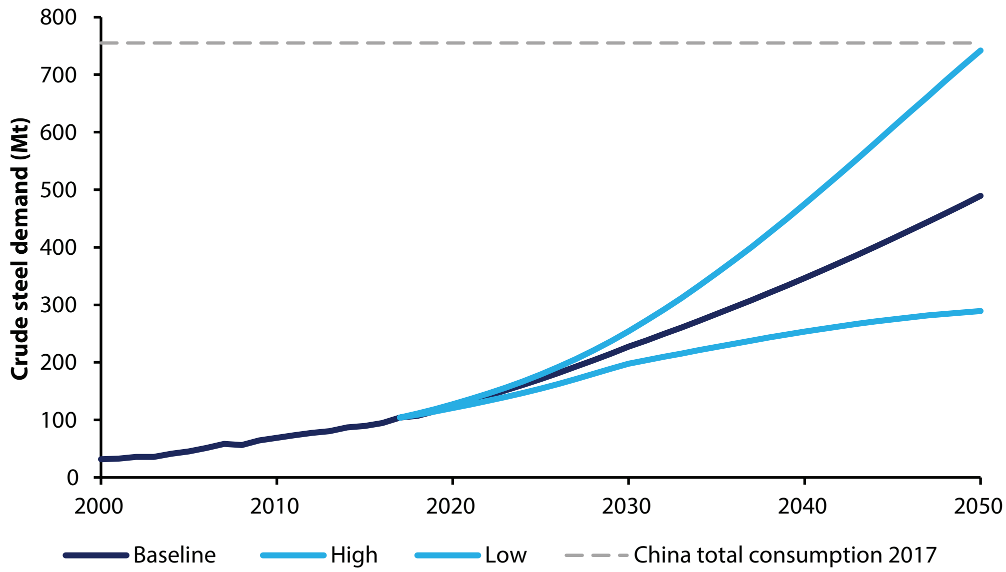


Figure 9: Scenarios for total crude steel demand (Mt), 2000–50

Source: TERI analysis based on data from WSA (2018b); World Bank (2017)

Table 3: Scenarios for total crude steel demand (Mt), 2030, 2040, 2050

Scenario	2030	2040	2050
Baseline	198	400	489
High	254	475	755
Low	131	253	289

Source: TERI analysis based on data from WSA (2018b); World Bank (2017)

To sense-check the results from this model, we can compare them with other reputable organizations' forecasts for Indian steel demand over the same period. As we can see in Figure 10, TERI's Baseline scenario is comparable with the Ministry of Steel's projections for 2030, which were included in the National Steel Policy. They are also not too dissimilar from BHP Billiton's in the near-term and the International Energy Agency's in the longer-term. They differ from Accenture's numbers to a greater extent due to the inclusion of certain 'disruption factors' in Accenture's projections, such as structural shifts and material substitution, which are not included in our baseline projections.

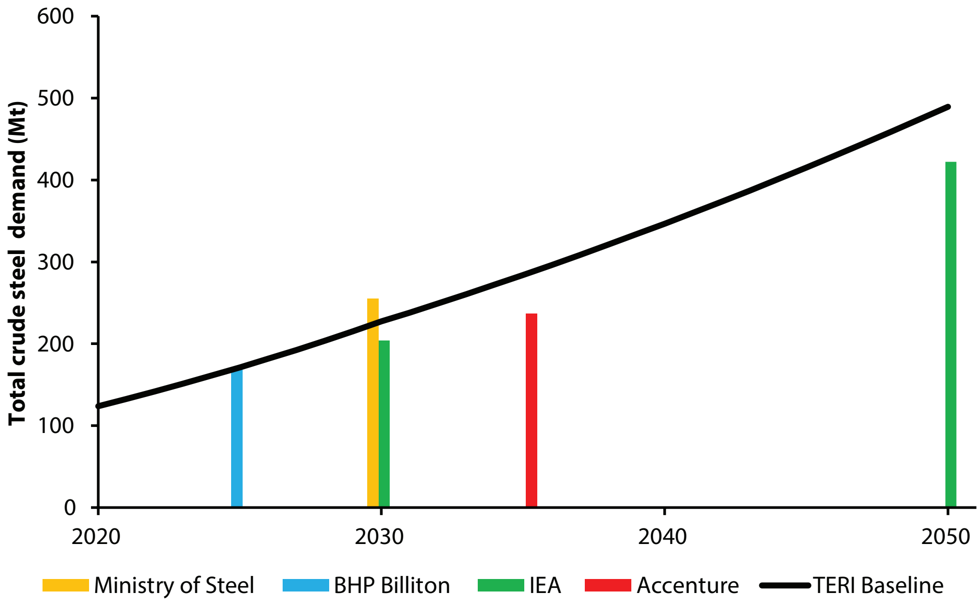


Figure 10: Comparison of different projections for Indian crude steel demand

Source: MoS (2017); Gaur and Chaliawala (2018); IEA (2019b); Accenture (2017)

4.2 Bottom–up Modelling

Having conducted a top-down, econometric projection of steel demand, we now turn to a bottom up, end-use projection of steel demand. This will allow us to develop a scenario for resource efficiency and circularity. To carry out the complementary bottom-up modelling exercise, we divided the steel sector into sub-sectors of end-use demand. These include buildings, automobiles, infrastructure, metal goods and industrial equipment. These were derived from the existing literature and the known availability of data on steel consumption (Rue du Can, Khandekar, Abhyankar, *et al*. 2019; MoS 2017; Cullen, Allwood, and Bambach 2012).The following section takes a detailed look at the buildings and automobiles sectors, outlining our approach for deriving steel demand forecasts for these end-use areas.

4.2.1 A Baseline Scenario for Automobiles

For automobiles, we have divided the sector into 2 and 3 wheelers, 4 wheelers, and trucks & buses. The trucks and buses segment also includes other forms of commercial vehicles, including, for example, tractors. Other transport sectors, such as railways, metros, shipping and aviation, are included in the infrastructure category. We gathered historical data for each vehicle category from official statistics, which we could then plot against GDP in the same historical period. Using this relationship, we could project the vehicle stock out to 2050. Multiplying this projected stock of vehicles by a steel intensity number (kg of steel per vehicle) gave us total steel consumption in the automobile sector.

Projecting linearly based on historical relationships would result in a continued and significant expansion of 2 & 3 wheelers. However, international experience shows us that, as countries become wealthier, 2 & 3 wheeler demand reduces and is replaced by demand for 4 wheelers. As a result, Figure 11 shows that the rate of growth in 2 & 3 wheelers starts to fall beyond 2030. This is replaced by an increasing number of 4 wheelers, which

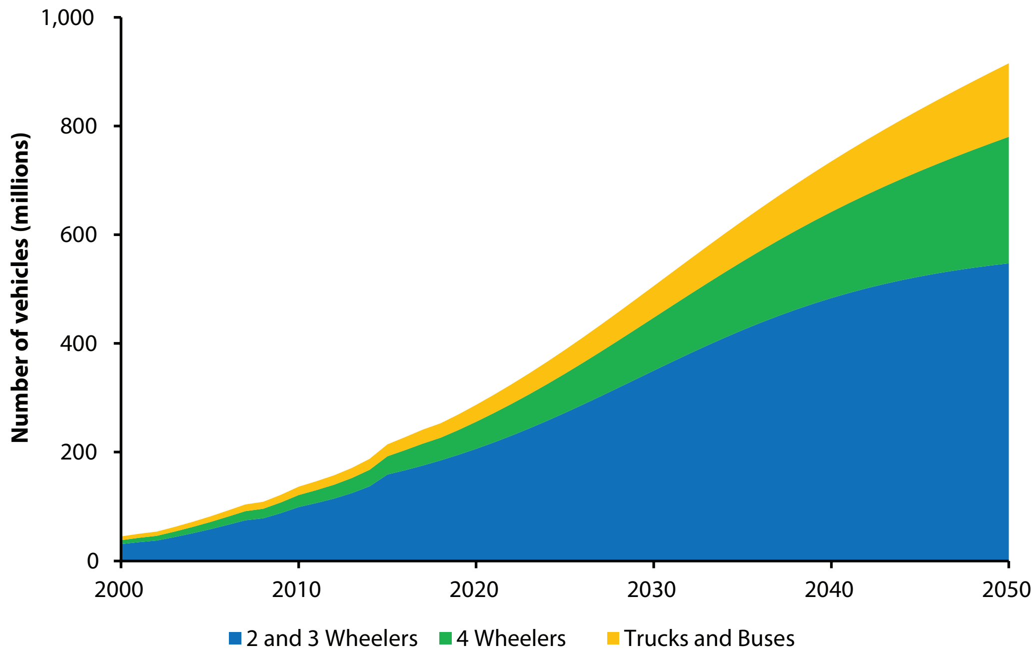


Figure 11: Projection of the stock of automobiles, 2000–50

Source: TERI analysis, based on data from MoSPI (2017b)

rises from around 30 per 1000 people today to around 140 per 1000 people by 2050. This is still well below other advanced economies in terms of number of vehicles per capita, such as the US, which has around 840 vehicles per 1000 people (US Department of Transportation 2019). Nevertheless, considering India's population density and rapid trend towards higher density urbanization, this figure seems sensible when compared with other similar countries.

We assume that demand for trucks and buses would continue to increase out to 2050, as the volume of freight and passenger traffic increases. Trucks and buses constitute a significant component of automotive steel demand, due to their size and weight. The amount of steel in the average truck or bus can be up to six times the amount of steel found in a 4-wheeler and over 30 times the amount in a 2-wheeler. For all vehicle categories, we assume that steel intensity slowly decreases out to 2050. Whilst there are several factors that might cause average steel intensity of a 4 wheeler to increase, including a switch to larger cars (e.g. compact SUVs) and higher health and safety standards, we expect that this would be outweighed by factors that reduce steel intensity. These include a switch to electric vehicles (reducing steel consumption in internal combustion engines), further light-weighting for greater fuel efficiency and the adoption of higher-strength steels.

The transport sector is undergoing a series of significant changes, making it hard to predict the world in 2050. These changes include an increase in ride-sharing and potential automation. For our baseline projections, we assume that India's vehicle numbers increase in line with historical international experience, i.e., the predominance of private vehicles as the majority means of transport. This results in a three-fold increase out from 2020 to 2050, increasing from around 17 Mt to just over 60 Mt (Figure 12).

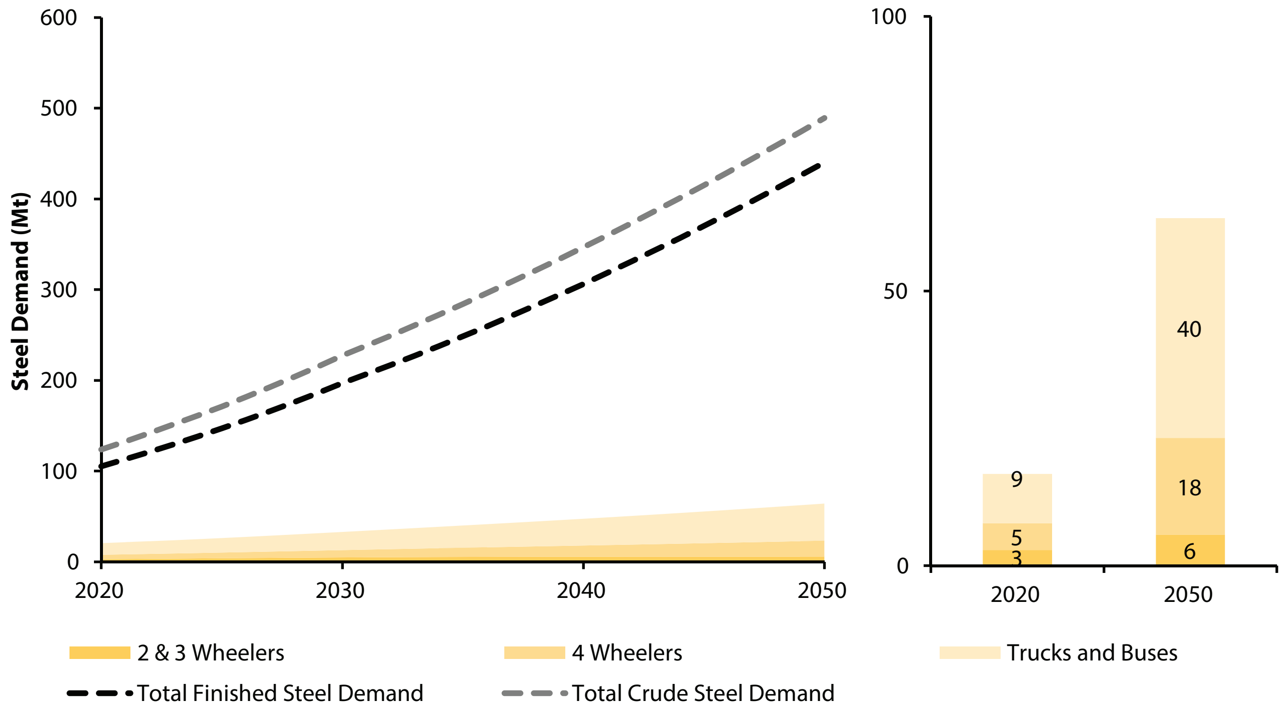


Figure 12: Steel demand projections for vehicles, 2020–50

Source: TERI analysis based on data from MoSPI (2017b)

4.2.2 A Baseline Scenario for Buildings

For buildings, we were able to divide the sub-sector into the residential and commercial segments. Nevertheless, the data was incomplete and so a residual 'other buildings' was also estimated. This included buildings that are outside the residential or commercial classification, including public sector or religious properties, for example.

To estimate demand for steel in residential buildings we needed to analyse data on the number and size of households, in order to get a total floorspace estimate (m^2), and the steel intensity of this floorspace (kg/m^2). To do so, we took historical data on household numbers and population between 1991 and 2011 and calculated the household occupancy rate. Looking at international experience on household occupancy rates, we can observe that other large middle income countries (including Brazil, China, and South Africa) all have household occupancy rates between 3.2–3.4. For India to achieve a similar household occupancy rate, it would need to fall steadily from 4.6 today, as shown in Figure 13. We expect the rate of growth in house building to slow out to 2050 as the population shifts away from rural areas, to more densely populated cities.

After forecasting household numbers, we estimate the average floorspace for residential properties to produce a total floorspace figure. We assume that the present-day average floorspace will increase to reach the levels of more developed countries. Using data from a subset of developed economies, we estimate that the average Indian household size will increase from around 47 m^2 today to 63 m^2 in 2050 (Times of India 2008; Odysee-Mure 2017). Multiplying these figures by the total household numbers gives us a total floorspace number for the residential sector in India. This also allows us to calculate floorspace per capita, which we could compare with other countries to help verify the estimate (Eom, Le, Pl, *et al.* 2012). Even in 2050, we expect India to have a lower floorspace per capita figure, largely due its to high population density, still relatively high household occupancy rate, and the rural to urban shift.

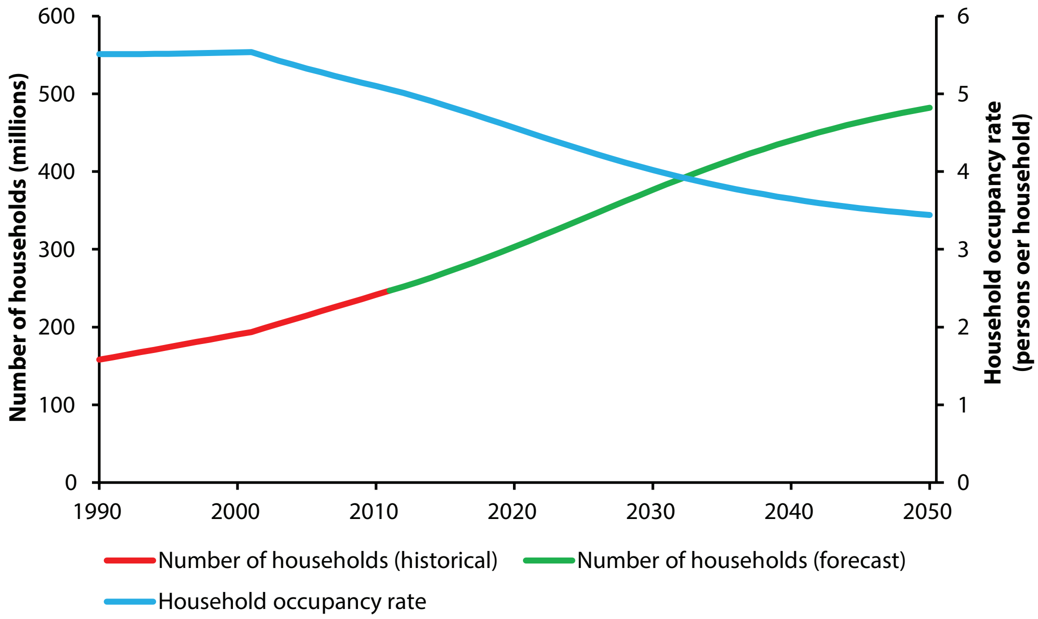


Figure 13: Projections of household occupancy rate and number of households, 2000–50

Source: TERI analysis based on data from MoSPI (2018); Eom, Le, Pl, et al. (2012)

In order to estimate steel demand, we obtained estimates of steel intensity per m^2 for residential buildings. Steel intensity in residential construction is relatively low in India today due to lax buildings standards and a high number of low-rise 'kutcha' or 'semi-pucca' houses, which are built with low quality materials. Steel intensity is expected to increase as incomes rise, with Indian houses coming closer to international build quality standards. A key trend will also be urbanization, which will drive a shift from detached or semi-detached low-rise construction towards much more steel-intensive high-rise construction. We estimate that steel intensity will increase from around 20 kg/m^2 today to 45 kg/m^2 by 2050 (Thiruvengadam, Wason, and Gayathri 2004; SteelConstruction.info, 2016; CBRI Roorkee 2019). Whilst it is difficult to obtain India-specific data, particularly around future expectations for the industry, we can assume that current steel use will start to converge with international standards out to 2050.

A similar approach was taken for commercial buildings, whereby we obtained data on commercial floorspace, as data on number of commercial buildings was not available. It's worth noting that floorspace data for the commercial buildings sector is very difficult to obtain and so these estimates are likely to be less robust than the residential estimates. In India, as with other developing countries, commercial space is often also registered as residential space (e.g., a shop front at the front of a house, using rooms for commercial storage, etc.) making classification challenging.

The main source of data for commercial floorspace is a report carried out by the International Resources Group (IRG) on behalf of USAID and the Bureau of Energy Efficiency (BEE) (IRG 2010). For this report, IRG undertook surveys and attempted to cross-reference floorspace with electricity consumption data making it more robust than the other broad brush estimates produced by other organizations. At their most recent data point, in 2010, they estimate that there is 659 m^2 of commercial floorspace in India, or around 0.5 m^2 per capita (IRG 2010). Using analysis showing the relationship between GDP per capita and commercial floorspace per capita, we estimate that India's commercial floorspace per capita will increase to just below 6 m^2 by 2050 (Eom, Le, Pl, *et al.* 2012) (Figure 14). Whilst still very low when compared internationally, this represents a fast growth rate of 7% per annum.[5]

5 The low figure for 2050 commercial floorspace per capita also represents the likely continuation of some dual purpose floorspace in India.

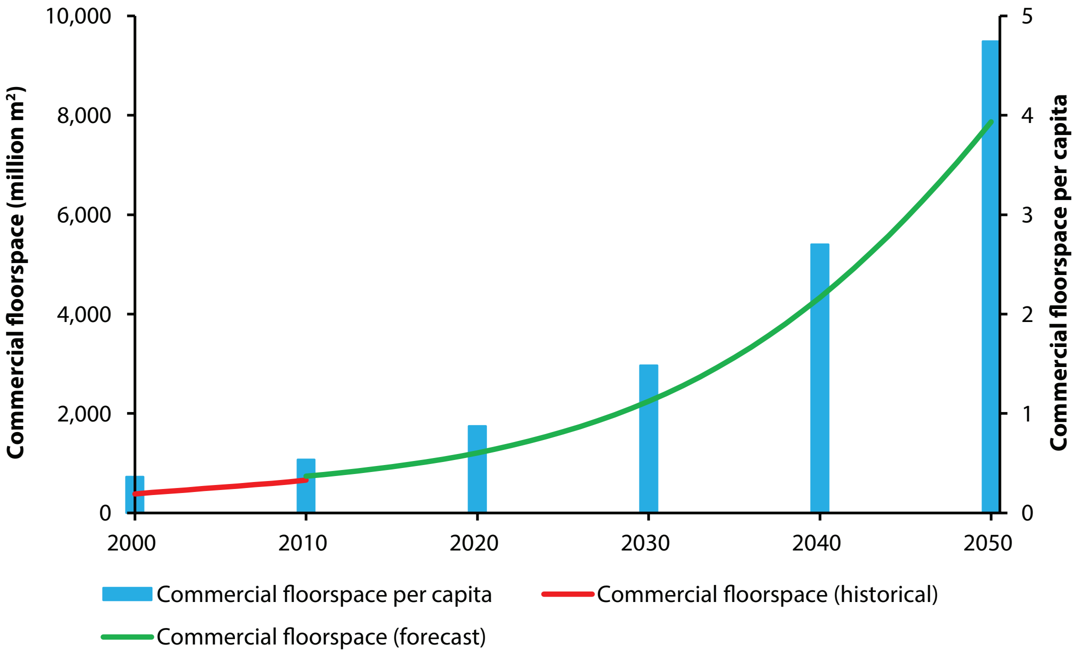


Figure 14: Projection of commercial floorspace per capita and total commercial floorspace, 2000–50

Source: TERI analysis based on data from IRG (2010); Eom, Le, Pl, et al. (2012)

With regards to steel intensity, we estimate that steel intensity of commercial floorspace will increase from around 38 kg/m^2 to 75 kg/m^2 (Thiruvengadam, Wason, and Gayathri 2004; SteelConstruction.info 2016; CBRI Roorkee 2019). As with residential properties, we have assumed that current steel use in commercial properties will start to converge with international standards by 2050.

For both residential and commercial properties, we have also conducted a stock-flow analysis, whereby each year a proportion of the stock will need to be replaced based on assumptions around building lifetimes. This will be especially important as we model potential demand reduction measures, one of which could include improving build quality and thus longer building lifetimes. We assume that both residential and commercial properties have an average lifetime of 60 years based on discussions with industry experts.

The combination of floorspace projections with steel intensities can allow us to produce steel consumption projections for the buildings sector. Based on existing literature on the breakdown of steel consumption in India and internationally, we expect the buildings' share of steel to fall from around 37% today to 35% by 2050 (MoS 2017; Cullen, Allwood, & Bambach 2012). Using this share in combination with the top-down estimates has allowed us to calculate an 'other buildings' category which will pick up all other buildings that have not been covered in historical household and commercial buildings statistics. This could include some industrial properties or public sector buildings. In these projections, we see steel demand for buildings increase more than four-fold from 33 Mt in 2020 to over 150 Mt by 2050, increasing at a CAGR of 5% (Figure 15).

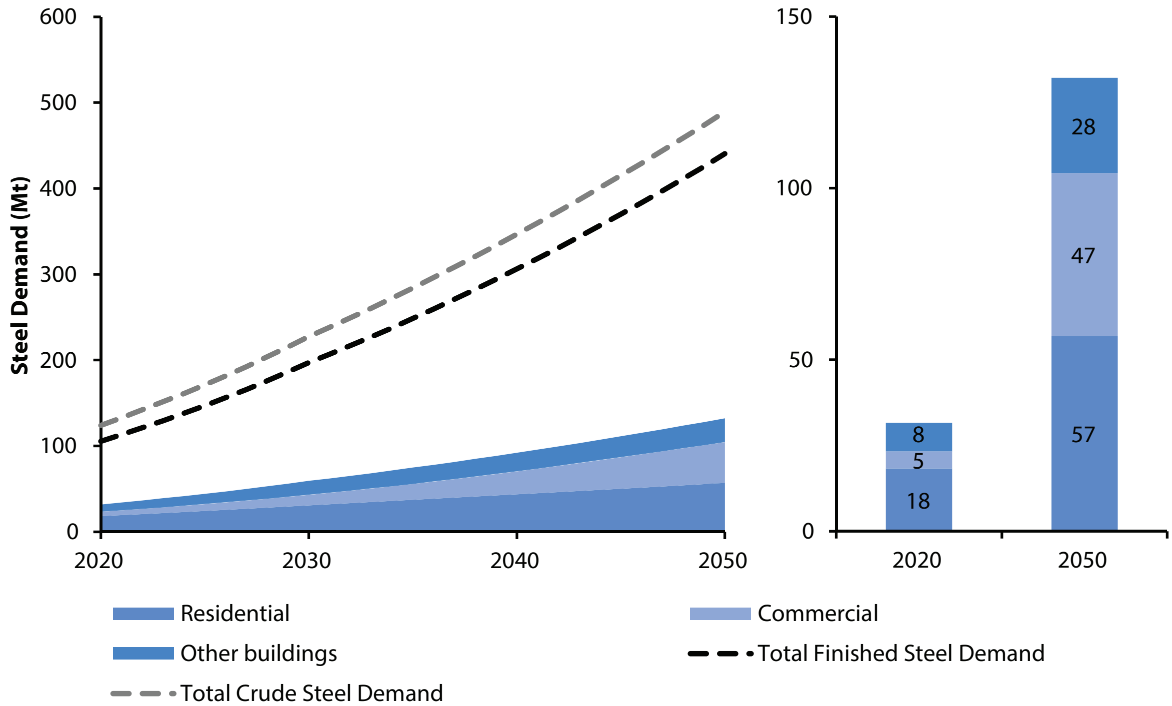


Figure 15: Projection of steel demand from buildings, 2020–50

Source: TERI analysis based on data from (Thiruvengadam, Wason, and Gayathri 2004; SteelConstruction.info 2016; CBRI Roorkee 2019)

4.3 Scenarios for Resource Efficiency

The previous sections laid out a series of scenarios, assuming that steel demand in India will grow based on domestic and international historical experience. However, the past won't necessarily hold true for the future. In the automobiles sector, potential structural shifts include the impact of ridesharing and policies to reduce car use in city centres (NITI Aayog 2018). With regards to buildings and construction, various governments and institutions are exploring the use of higher-strength steels, allowing less material to be used (Nippon Steel 2015). The term which captures these types of impacts is resource efficiency; or achieving the same or better end-use or service whilst using fewer resources.

Improving resource efficiency and encouraging greater levels of material circularity is vital for mitigating negative environmental impacts as India continues to grow. This includes encouraging greater use of scrap, which reduces the amount of raw material required for primary steel production, resulting in positive knock-on effects for energy and emissions.

Whilst scrap is an important and valuable resource, there are several barriers to increasing its use in India, including (ETC 2018):

- Losses in the supply-chain, including excessively corroded steel at end-of-use and losses in the fabrication and re-melting processes.
- The issue of 'down-cycling', whereby recycled steel is lower quality, and therefore its lower value limits the extent to which it can be used again in the economy.

- Steel can become contaminated, most commonly with other metals (such as copper), limiting where it can be re-used. This is particularly problematic for the automotive industry, where copper wiring is left in the vehicle as it is scrapped.

The main scrap-based production route is the electric arc furnace (EAF). If we compare the raw materials, energy and emissions from the scrap-based route with a primary steelmaking process, such as a blast furnace with a basic oxygen furnace (BF-BOF), we can clearly see the benefits of greater circularity in the steel sector.

Figure 16 shows significant savings across materials, energy and emissions, representing benefits for the economy through lower import dependency of resources such as coking coal (covered in more detail in Section 5.4). This also translates into significant benefits for the environment, with overall CO_2 emissions reduced by around 85%. Moreover, this analysis only captures the reduced energy and emissions benefits from within the plant boundary. There are further benefits from reduced extraction of raw materials, such as iron ore, which will have significant land-use and biodiversity benefits from avoiding deforestation for mining.

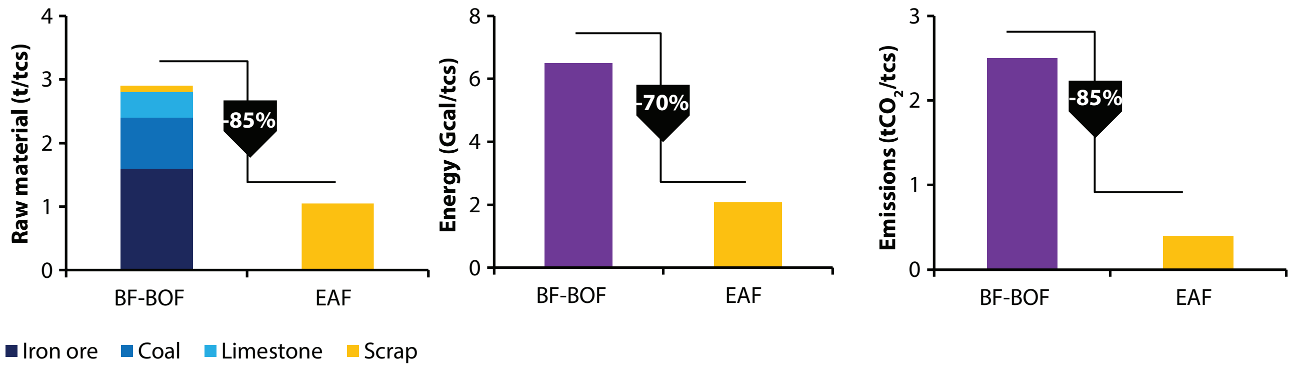


Figure 16: Material, energy, and emissions benefits of scrap-based production

Source: TERI analysis based on data from BEE (2018); MoS (2017). Assuming an emissions intensity of electricity of 700 gCO_2/kWh.

Resource efficiency and material circularity are important not just within the steel sector but also between the steel sector and other sectors. For example, today, steel slag is used in construction either as an aggregate for roads or it can be added to cement and concrete as a substitute for lime. Around 0.3 tonnes of slag by-product are produced for every tonne of crude steel, indicating how significant a resource it is (Bhattacharya and Kapur 2019).

There are a number of factors which can have an impact on resource efficiency. These are outlined in Table 4 below.

Table 4: Resource-efficiency measures

Metric	Description
Lifetime	Increasing the lifetime of a product through higher build standards and higher quality input materials can reduce the number of products purchased.
Recycle rate	Higher recycling rates reduce the amount of virgin steel required for manufacturing, reducing environmental impacts from processes such as mining. Processing recycled steel also requires less energy.
Steel intensity	Steel intensity can be reduced in products through substitution with other materials e.g. aluminium or plastics or less steel of higher grades can be used.
Per capita	The amount of steel use per person may be impacted through lower private ownership of, for example vehicles through shifts to ride-sharing or public transport.

In this section, we will explore the impact of different resource efficiency measures in the automotive and buildings sectors, through a detailed stock-flow analysis. Using this analysis, we willl derive some economy-wide resource efficiency scenarios, which can illustrate the potential impact of different policies to improve resource efficiency.

4.3.1 Automobiles

For the automobiles sector, we divided the sector into three sub-sectors as in the previous section. These include 2 and 3 wheelers, 4 wheelers, and trucks and buses. Our *Baseline* scenario in the stock-flow analysis is the central scenario taken from the previous section. Resource efficiency measures are then applied to this scenario to estimate the impact of, for example, increasing vehicle lifetime or reducing the intensity of steel use in vehicle manufacture.

To illustrate the impact of different resource efficiency measures, we have devised a scenario which we believe falls in line with current policies and structural trends seen around the world. Although not all of these measures are being implemented in India today, it is possible that these could be achieved over the 2050 time horizon. Given the rapid rate of infrastructure growth required in India, the impact of resource efficiency measures are comparatively less when you compare them with more advanced economies.

Table 5: Automobile resource efficiency assumptions

Scenario / Metric	Baseline	Resource efficiency
Lifetime	Base	plus 10%
Recycle rate	80%	85%
Steel intensity	Base	minus 20%
Per capita	Base	minus 20%

Table 5 shows the assumptions used to define the resource efficiency scenarios for the automobile sector. For the Baseline scenario, **lifetime** is assumed to be on average 12.5 years for 2, 3 and 4 wheelers and 20 years for buses. Whilst this lifetime for buses appears high when compared with international standards (USA is closer to 12 years), this is taking into consideration India's tendency to run buses for longer periods to extract maximum value. The upcoming Vehicle Scrapping Policy, intends to limit the lifetime of buses and other commercial vehicles to 20 years (Times of India 2018). In the *Resource efficiency* scenario, we increase the lifetimes by 10%.

With regards to the **recycle rate** (i.e., how much of the car's steel is recycled), we assume that India's *Baseline* recycle rate is slightly below international standards at around 80%. Most of the recycling of vehicles in India is carried out by the informal sector in India, where a large amount of manual labour is used, compared with automated processes in more developed countries. As a result, this can make it more cost-effective to separate some materials from one another, due to low labour costs. On the other hand, manual processes can also limit the amount of separation that is otherwise possible using advanced machinery. As a result, after discussion with sector experts, we think 80% is suitable based on the available information. This would increase to current international standards in the *Resource efficiency* scenario (WSA 2018a). Automobiles are more able to control quality on automated production lines and will need to design in the ability to recycle in future.

For **steel intensity**, we assume a slight increase out to 2050 in the *Baseline*, as a result of a shift towards larger, more luxury vehicles, as is the international experience (IEA 2019d). In the *Resource efficiency* scenario, this would fall by 20%, reflecting the high potential of plastics, aluminium and higher-strength steels to replace large sections of vehicles (Material Economics 2018).

Lastly, **per capita** vehicle consumption reflects the impacts of structural shifts within the transport sector. These include a greater role for ride-sharing, increased penetration of high quality of public transport and more cycling and walking within densely populated urban areas. We assume a reduction of 20% in the *Resource efficiency* scenario. Given India's population density and high labour supply, there seems to be a particularly large potential for ride sharing to displace personal vehicle ownership, and hence reduce the total vehicle stock and associated steel consumption.

The combined result of these measures is illustrated in Figure 17. This analysis shows that under current trends and in-line with policies relatively common in advanced economies, India could mitigate the increase in steel demand in the automobile sector by 35% by 2050.

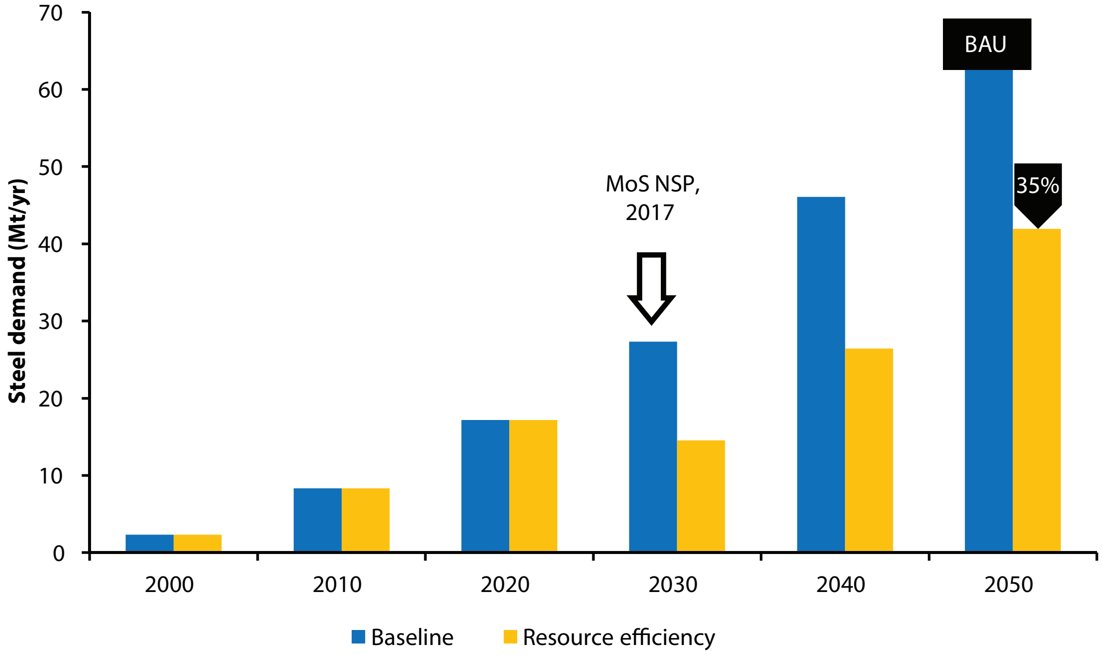


Figure 17: Resource efficiency scenarios in the automobile sector

Source: TERI analysis based on data from Material Economics (2018); WSA (2018a)

Whilst ambitious, these estimates show less reduction in steel demand than assessments at the global level (Material Economics 2018). Nevertheless, this is to be expected, as India's demand for automobiles is set to expand significantly compared with the global average to satisfy transport demands.

4.3.2 Buildings

For buildings, we have conducted stock-flow analysis for the residential and commercial sectors. Our *Baseline* scenario has been taken from the bottom-up modelling in Section 4.2. Resource efficiency measures are then applied to this scenario to estimate the impact of, for example, increasing building lifetime or using less but higher quality steels.

As with the automobiles sector, we have devised a scenario for the buildings sector to test the impact of resource efficiency measures (Figure 18).

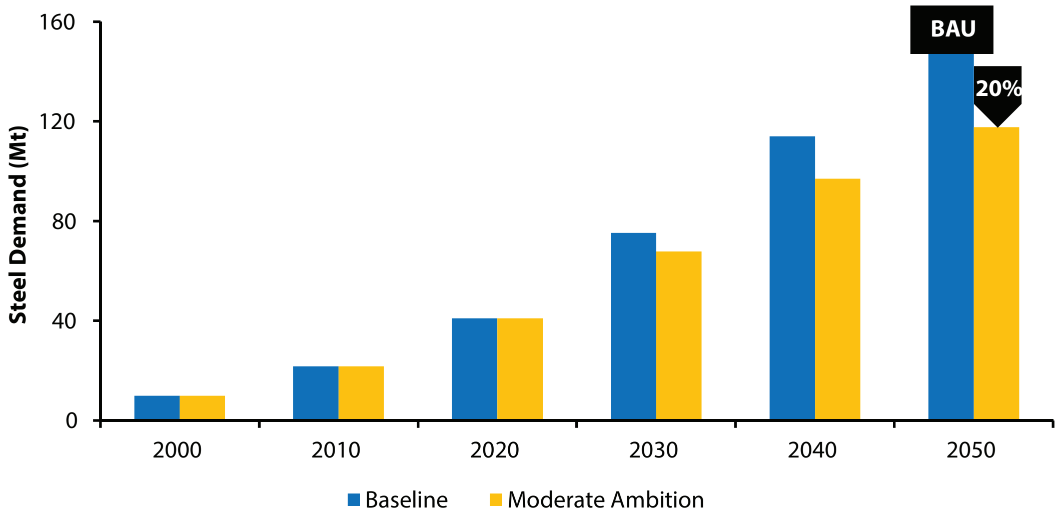


Figure 18: Resource efficiency scenarios in the buildings sector

Source: TERI analysis based on data from Thiruvengadam, Wason, & Gayathri (2004); Material Economics (2018)

Table 6 shows the assumptions used to define the *Resource efficiency* scenario for the buildings sector. For the *Baseline* scenario, the **lifetime** is assumed to be on average 60 years for both residential and commercial properties. In the *Resource efficiency* scenario, we increase the lifetimes by 10% (CBRI 2019).

With regards to the **recycle rate** (i.e., how much of the building's steel is recycled), we assume that India has a relatively high rate. Structural steel used in buildings tends to be low quality, which limits its use elsewhere in the economy. It is often steel that has been previously recycled, or 'down-cycled', i.e., the recycling process has resulted in the steel becoming contaminated with lower quality materials. As a result, it's recycle value tends to be relatively low. More ambitious action to guarantee effective material segregation throughout the supply chain would be needed to limit the effects of contamination and down-cycling.

For **steel intensity** in buildings, we assume a fairly significant increase out to 2050 in the *Baseline* scenario, as a result of a shift towards the use of steel frames and steel-reinforced concrete (The Hindu 2019). In the *Resource efficiency* scenario, this increase would be mitigated by 20%, reflecting greater use of alternative materials, such as cross-laminated timber and bamboo in buildings. These have the potential to be adopted even in mid-rise, urban buildings, satisfying demand from the rural-urban shift. Nevertheless, the amount of substitution out to 2050 is limited by the need to maintain building safety standards in a country where a significant proportion of buildings are affected by seismic activity and the availability of truly sustainable timber and bamboo (Thiruvengadam, Wason, & Gayathri 2004).

Table 6: Buildings resource efficiency assumptions

Scenario / Metric	Baseline	Resource efficiency
Lifetime	Base	plus 10%
Recycle rate	50%	60%
Steel intensity	Base	minus 20%
Per capita	Base	minus 5%

Lastly, **per capita** demand for floorspace reflects the impacts of structural shifts within the buildings sector. The growth in floorspace per capita is significant in the baseline, as India's building sizes are well below the international average and below a country with its GDP, due to other factors, such as population density. In the *Resource efficiency* scenario, we see this increase mitigated by 5%, which is entirely in the commercial sector. This would be a result of higher rural to urban shifts and more efficient use of space in urban areas, such as the proliferation of co-working spaces, more remote working and a greater role for internet-based businesses without a physical shop presence.

Again, these estimates are ambitious but fall below conclusions from analysis at the global level (Material Economics 2018). Unlike many developed economies, we expect rapid growth from the buildings sector and any demand reduction potential is limited when compared with other sectors, given the low baseline. Commercial buildings, in particular, are set to expand significantly, and avoiding much of this additional consumption will be very difficult without widespread availability of new materials. There are nevertheless significant uncertainties in estimating demands out to 2050 and macro-trends, such as urbanization and industrialization, will be key drivers behind the scale and pace of future building demand, and associated steel demand.

4.4 Demand Scenarios: Synthesis

From this top–down and bottom–up approach, we can estimate the sectoral split in steel demand across the economy and the subsequent impact of resource efficiency measures. The final sectoral breakdown for steel demand out to 2050 is shown in Figure 19. We expect significant growth in all sectors but the most rapid expansion occurs in infrastructure and buildings.

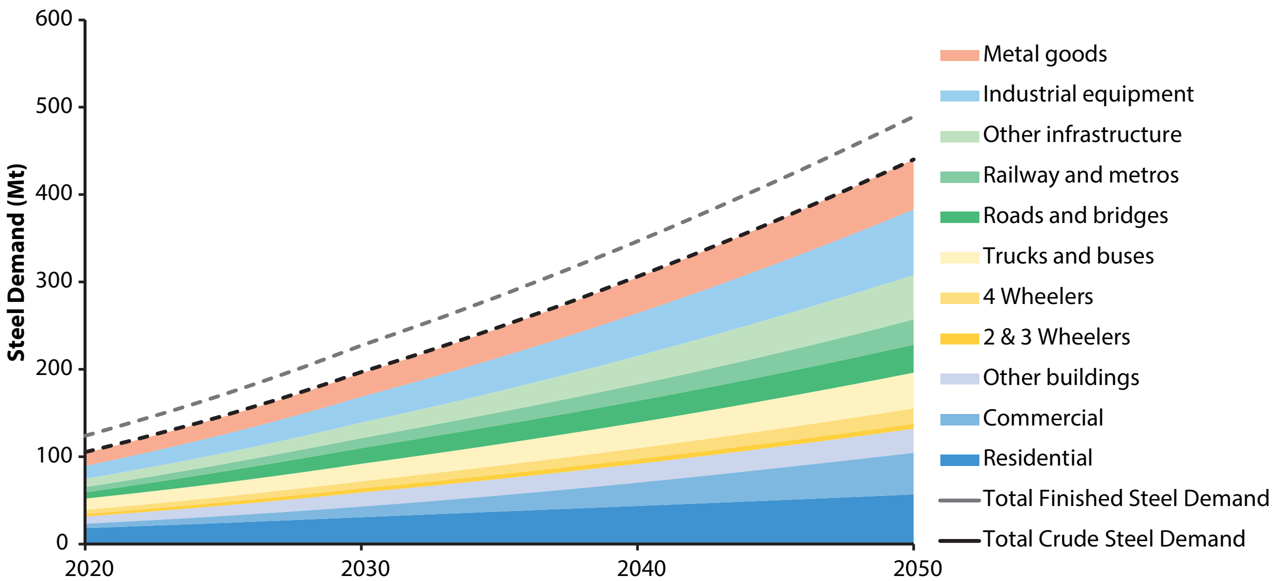


Figure 19: Steel demand projections by category, 2020–50

Source: TERI analysis

To estimate steel use in the infrastructure, metal goods, and industrial equipment categories, we conducted an initial literature search for data on, for example, metal goods sales. As a lot of this data is incomplete, insufficiently disaggregated, proprietary and /or commercially sensitive, it was not possible to gather detailed data for these categories. As a result, we have resorted to estimating steel use for industrial equipment by making an assumption of the share industrial equipment in total steel demand from our top-down projections. These shares are derived from Indian and international literature (MoS 2017; Cullen, Allwood, and Bambach 2012).

From this sectoral breakdown, we can extend our stock-flow analysis to the economy as a whole, applying resource efficiency measures to provide us with two final demand scenarios. The *Baseline* and *Resource efficiency* scenarios are shown in Figure 20.

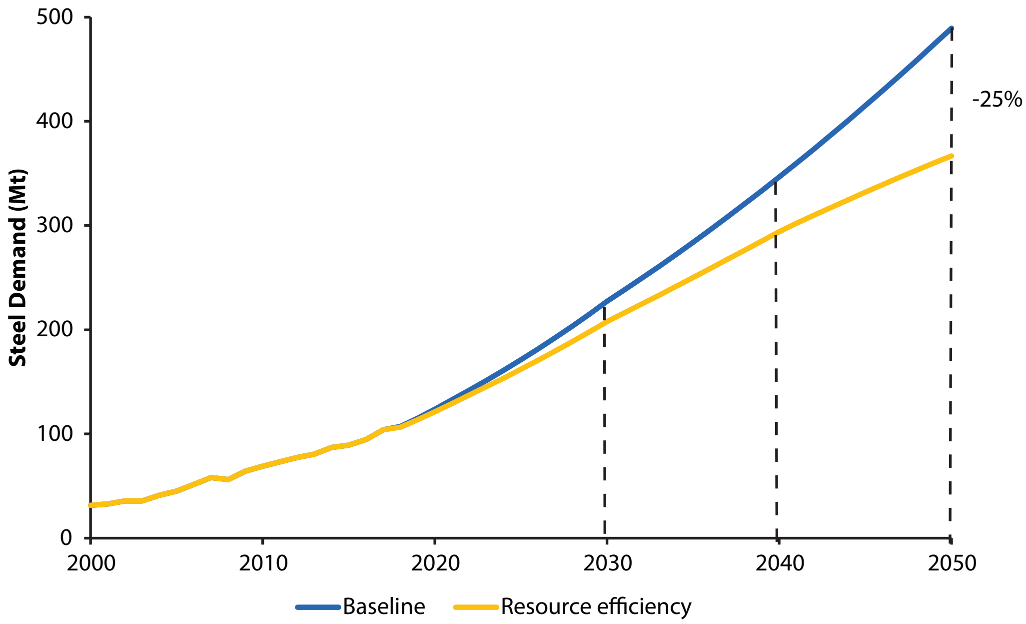


Figure 20: Steel demand scenarios including resource efficiency, 2000–50

Source: TERI analysis based on data from (MoS 2017; Cullen, Allwood, & Bambach 2012)

By 2030, in our *Baseline* scenario, we expect steel demand to more than double versus today, increasing the steel use per capita to 150 kg. Under the *Resource efficiency* scenario, steel use per capita is similar over this time frame, given the time taken for resource efficiency measures to have a substantial impact.

By 2050, in the *Baseline* scenario, we expect steel demand per capita to nearly quadruple to 295 kg per capita. This would make it similar to middle to high income economies today, being equivalent to the average true steel use per capita across the European Union (WSA 2018b). Whilst the growth rate implied by these projections is high (5% CAGR), we believe this is plausible, given the vast amount of steel that India still requires to develop. In combining the top-down assessment with a bottom-up analysis, we have been able to identify the key areas which will drive future Indian steel demand, to sense-check these projections.

Applying resource efficiency measures at the economy-wide level, we estimate that Indian steel demand could be reduced by 25% when compared with the baseline. Further work needs to be done to assess the likely trajectory for resource efficiency measures and the impact of resource efficiency policies on different sub-sectors but these represent a first estimate, based on the available literature (Material Economics 2018).

The substantial reductions in steel demand when compared with the baseline would still see steel demand growing strongly in 2050. If we compare steel intensity of GDP in these scenarios, along with historical cross-country data, we can see from Figure 21 how the *Baseline* scenario broadly follows the international experience. The *Resource efficiency* scenario would result in a lower steel intensity as a proportion of GDP but is not outside the international and historical data.

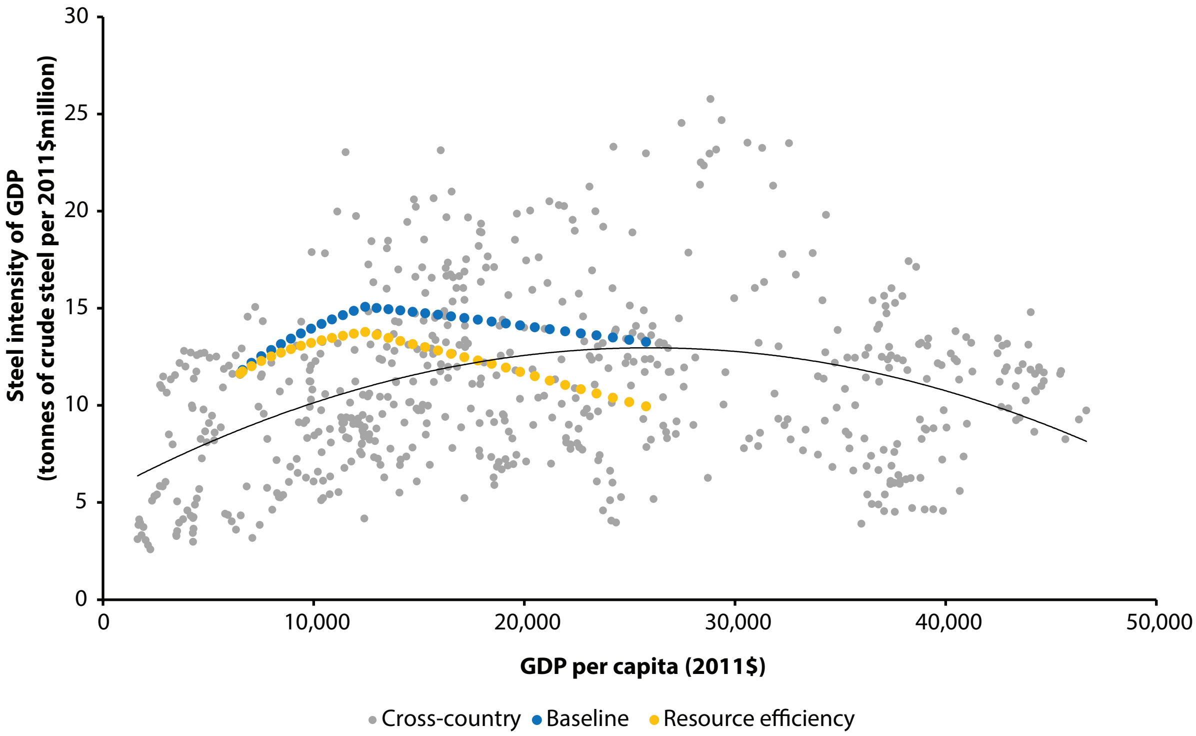


Figure 21: Steel intensity of GDP, historical cross country experience versus projected scenarios for India

Source: TERI analysis based on data from WSA (2018b); World Bank (2017); steel intensity of GDP is based on true steel use (TSU) data.

Table 7 provides additional metrics implied by these projections, covering crude steel capacity, crude steel demand / production, finished steel demand and per capita crude steel consumption. These will be used in subsequent analysis as we start to assess the energy and emissions impacts of these various demand scenarios.

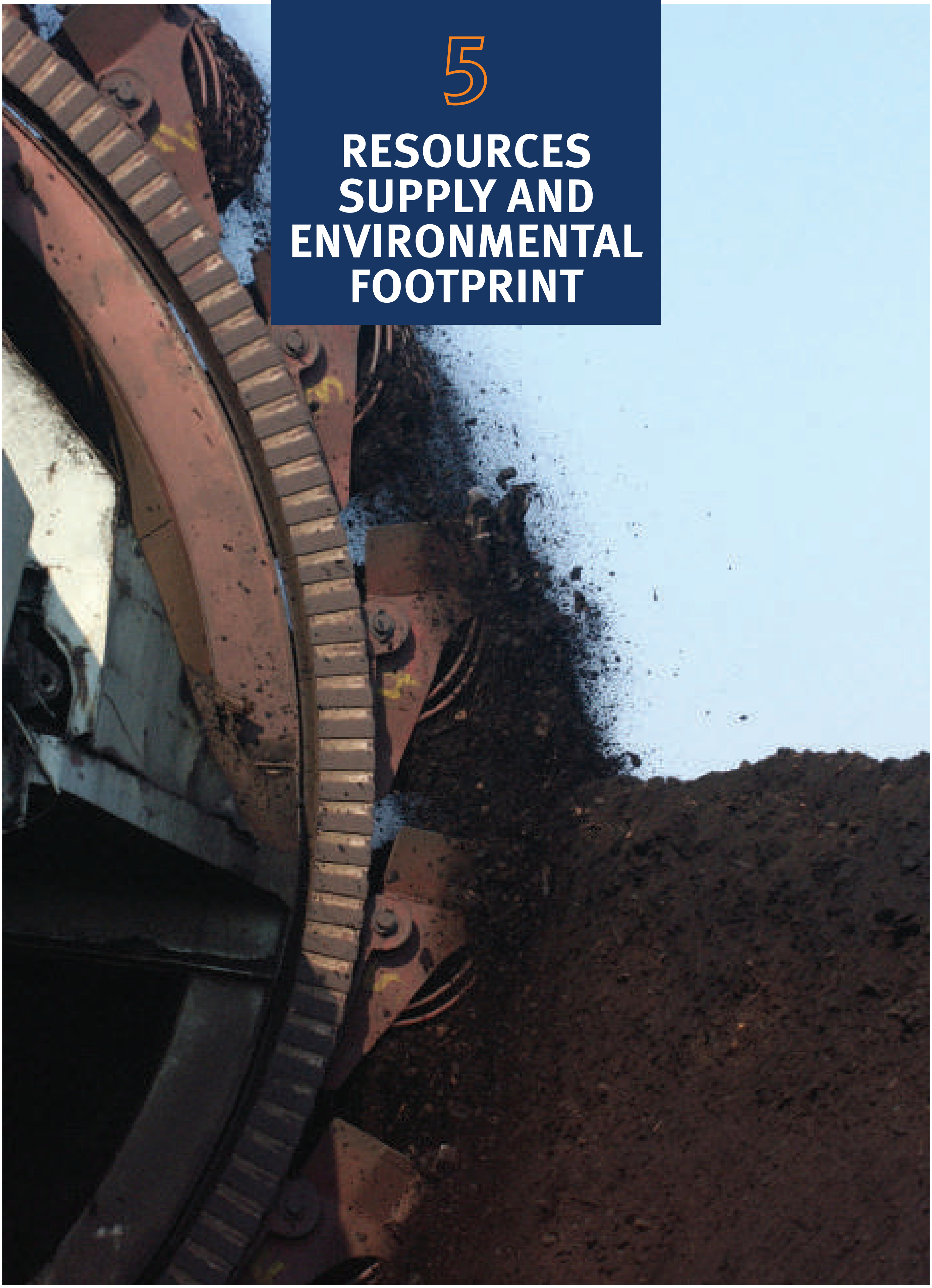
Table 7: Steel demand metrics, 2030 and 2050

Metric	Unit	Scenario	2030	2050
Crude steel capacity	Mt	Baseline	245	528
		Resource efficiency	224	396
Crude steel demand / production	Mt/yr	Baseline	227	489
		Resource efficiency	208	367
Finished steel demand / production	Mt/yr	Baseline	205	440
		Resource efficiency	187	330
Per capita crude steel consumption	kg/per capita	Baseline	150	295
		Resource efficiency	137	221

Source: TERI analysis based on data from WSA (2018b); World Bank (2017)

5

RESOURCES SUPPLY AND ENVIRONMENTAL FOOTPRINT



Resources Supply and Environmental Footprint

This section will cover the resources required to meet the levels of demand laid out above. This includes how much energy is required and the role of energy efficiency measures in reducing energy and emissions. It will also provide an assessment of the impact on key raw materials, covering coking coal and iron ore.

5.1 Production Scenario

To calculate the levels of energy and resources required under different scenarios out to 2050, it is first necessary to establish a share of production for the different steelmaking technologies (see Figure 22). After reviewing relevant literature and discussing with sector experts, we arrived at the scenario below for production route shares for our baseline. This represents an illustrative scenario for how the steel market might develop if we assume no radical change in policy and that the majority of steel demand is met through domestic capacity expansion, in line with an ambitious 'Make in India' program (MoS 2018).

Here we have simplified the routes down to BF-BOF and EAF/IF. Under the EAF/IF route, electric arc furnaces and induction furnaces are fed by a mixture direct reduced iron (DRI) and scrap. The amount of scrap is assumed to increase substantially over time, as shown in Figure 23, taking into account recent drives towards increased scrap utilization.

We have assumed that the share of BF-BOF will increase out to 2030, to satisfy the rapid capacity growth requirements. Most large steel companies favour the BF-BOF route as a means to add significant capacity and this constitutes most of the near-term project pipeline. New integrated BF-BOF plants can also be designed to higher levels of efficiency, with lower environmental impact versus the coal-based Direct Reduction route.

Moreover, the limited availability of scrap in the near-term will necessitate that primary steelmaking continues in the BF-BOF route. Beyond 2030, the increasing share of scrap will start to displace primary steelmaking to a greater extent, which is reflected in the peaking of BF-BOF capacity in the 2030s. The growth in steel demand throughout the 2010s and 2020s will mean that greater amounts of recycled steel will be available for use in EAFs during this later period.

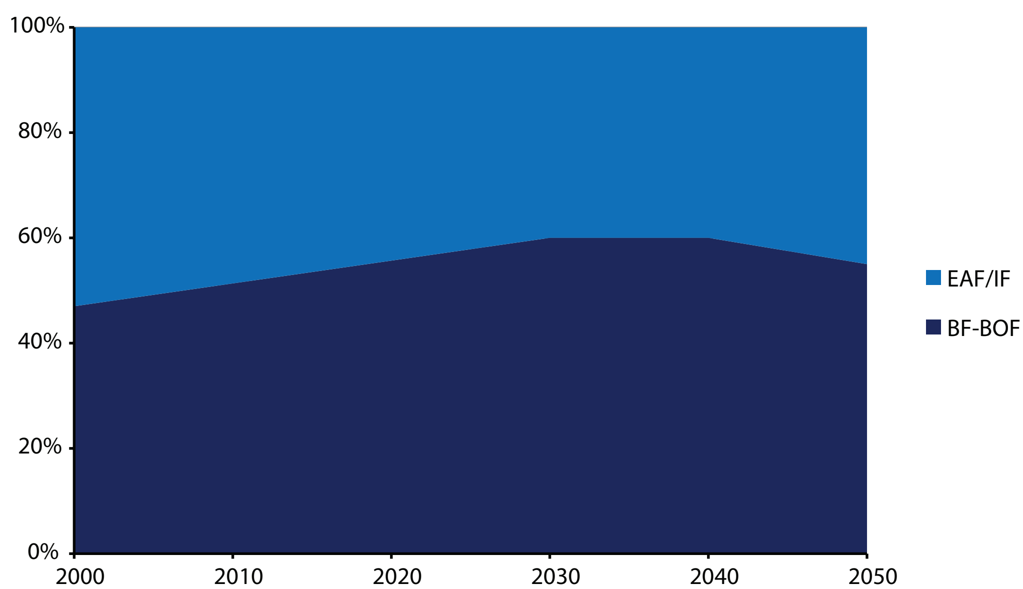


Figure 22: Production route shares by technology, 2000–50

Source: TERI analysis based on data from MoS (2017)

The increasing availability of scrap plays an important role in reducing the amount of energy used for steelmaking, as this can be added to both routes to varying extents. We assume that scrap use in the BF-BOF route increases from an average of around 10% today to 20–25% by 2050, which helps increase the efficiency of the process. Whilst there are some space constraints for the integration of scrap facilities in existing plants, by 2050, we assume that all new plants will have scrap handling equipment integrated from the outset. We assume the remaining scrap is used in EAF/IFs.

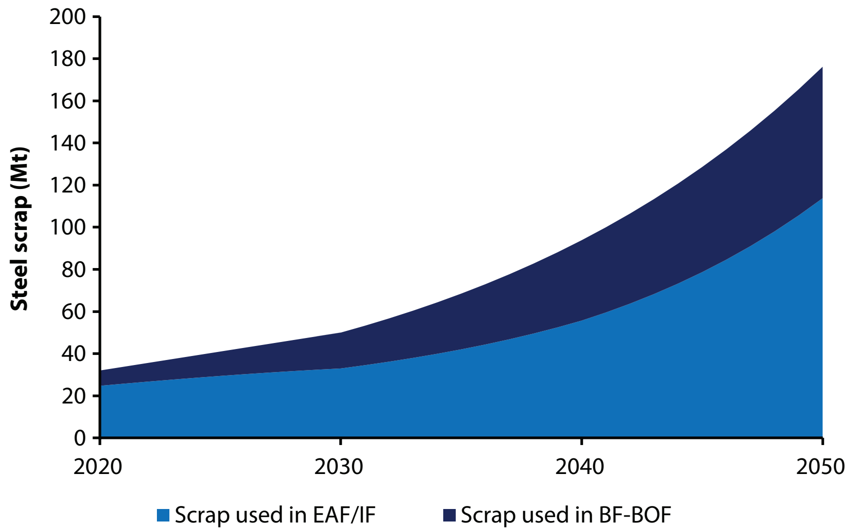


Figure 23: Scrap steel availability and use, 2000–50

Source: TERI analysis based on data from MoS (2017)

The split of capacities for the *Baseline* demand scenario are shown in Table 8. If we assume that all increased steel demand is met through domestic capacity increases, this would result in an increase from 138 Mt today to 245 Mt by 2030 and over 500 Mt by 2050. As the steel industry is expected to grow rapidly out to 2050, it is assumed that the utilisation of existing stock increases from around 75–80% up to 90–95% by 2050. We assume that BF-BOF plants operate at higher capacity utilization rates versus DR-EAF, as their operation is less flexible.

Table 8: Production capacity by route

	2030	2040	2050
BF-BOF	144	219	283
EAF/IF	101	154	245
Total	245	373	528

Source: TERI analysis based on data from MoS (2017)

This represents significant capacity expansion in a relatively short period of time; a significant challenge for the sector given the long lead-in times for commissioning such facilities. To meet this level of capacity expansion, it is likely that utilization rates of existing stock would first have to increase, so that ISPs are closer to 95% utilization and smaller facilities around 90% (up from approximately 80–85% and 60–65%, respectively). There is also significant potential to build additional capacity on brownfield sites currently owned by steel companies, i.e., plant expansions. Many of the existing steel plants, particularly those within the public sector, sit on large sites which could be expanded without the added delays of land acquisition and associated approvals. According to the OECD, there is currently around 30 Mt of steel capacity in the pipeline for the early 2020s, with the bulk being delivered by Tata Steel and JSW (OECD 2019a).

Despite this potential, meeting such rapid demand increases through domestic supplies will be extremely challenging. We explore the potential role of imports in the Indian steel sector in Section 6.

5.2 Energy Demand

After establishing a plausible route breakdown for production capacities, we can now begin to understand the impact of increasing steel demand on energy use. The Indian steel industry is currently one of the most energy-intensive in the world, with energy use around 40% higher than the global average (Samajdar 2012). This is largely down to the use of old technology and the use of smaller, less efficient coal-based DR facilities. When compared with international benchmarks in Figure 4, it can be seen that there is significant potential for energy savings through deploying best available technologies (BAT).

To drive a reduction in energy use in the steel sector, one of the major initiatives undertaken by the Government of India is the Perform Achieve and Trade (PAT) scheme. PAT is a regulatory instrument under the National Mission on Enhanced Energy Efficiency (NMEEE) that focuses on reducing specific energy consumption (SEC) in energy-intensive industries. The iron & steel sector is one of 13 industry sub-sectors covered under the five PAT cycles that have taken place so far. A total of 163 iron and steel units have been covered under the PAT scheme until now. The achievements of PAT cycles are outlined in Table 9.

Table 9: Energy savings from the iron and steel sector under the PAT scheme

PAT cycles	No. of units covered	Energy demand (Mtoe)	Reduction target (Mtoe)	Savings achieved (Mtoe)
Cycle -1	67	25.32	1.486	2.10
Cycle- 2	71*	40.44	2.37	2.913
Cycle- 3	29	7.648	0.457	0.735

Source: MoS (2021)

(Number of units indicated against PAT cycle-2 is inclusive of PAT cycle-1 units)*

To help understand the potential for energy efficiency for the Indian steel sector, TERI has undertaken an assessment of different measures for the BF-BOF and DR-EAF routes. These have been compiled from a number of sources, including the Japan Iron and Steel Foundation (JISF), UK Iron and Steel Sector Roadmaps, the Indian Bureau of Energy Efficiency (BEE) and the Confederation of Indian Industry (CII). We have then tested this analysis with industry experts to ensure the energy savings presented here are plausible.

Figure 24 shows the energy savings potential for a typical BF-BOF plant, where the range of most inefficient plants is shown on the left. Whilst an average inefficient plant in India will have an SEC around 7.1 Gca/tcs, there is a long tail of even more inefficient plants, whose energy consumption can be as high as 9.0 Gcal/tcs.

There are a number of older plants in dire need of modernization and by applying even the already widely adopted efficiency technologies, these plants can substantially improve their energy efficiency. Beyond those measures which are already widely adopted in India, there are significant savings available to reach BAT (best available technologies). Our analysis suggests that, theoretically, energy use can be reduced by up to 2.5 Gcal/tcs for the average BF-BOF plant.

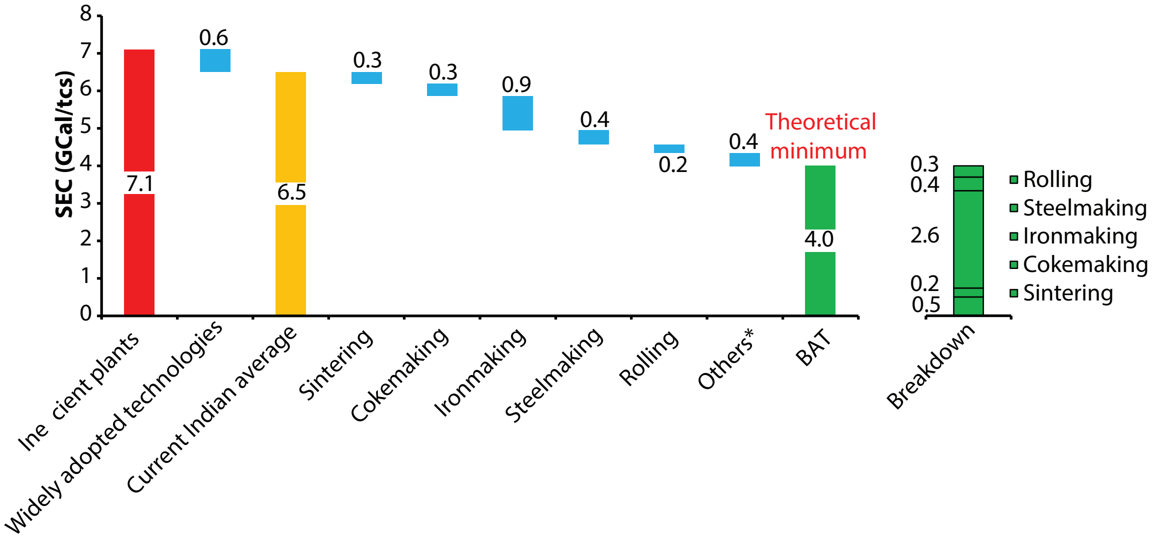


Figure 24: Energy efficiency measures for the BF-BOF route

Source: WSP, Parsons Brinckerhoff and DNV GL (2015); JISF (2014); CII (2013); Morrow, Hasanbeigi, Sathaye, & Xu (2014); BEE (2018)

However, these measures might not be practically possible to adopt in existing plants for a number of reasons, including a lack of space, insufficient capital for investment, non-availability of technology and an inability to retrofit with older technology. Moreover, even when installed, these SECs might be difficult to achieve if the plants are running below optimal utilization, as can be seen currently.

Nevertheless, by 2050, we assume on the basis of our estimation that these measures would be adopted, as most of these issues could be overcome when building new facilities. Indeed, many steel companies in India are confident that they can build plants to operate at international benchmarks when building greenfield sites.

A full list of the energy efficiency measures is contained in Annex C, including an assessment of their adoption status within India.

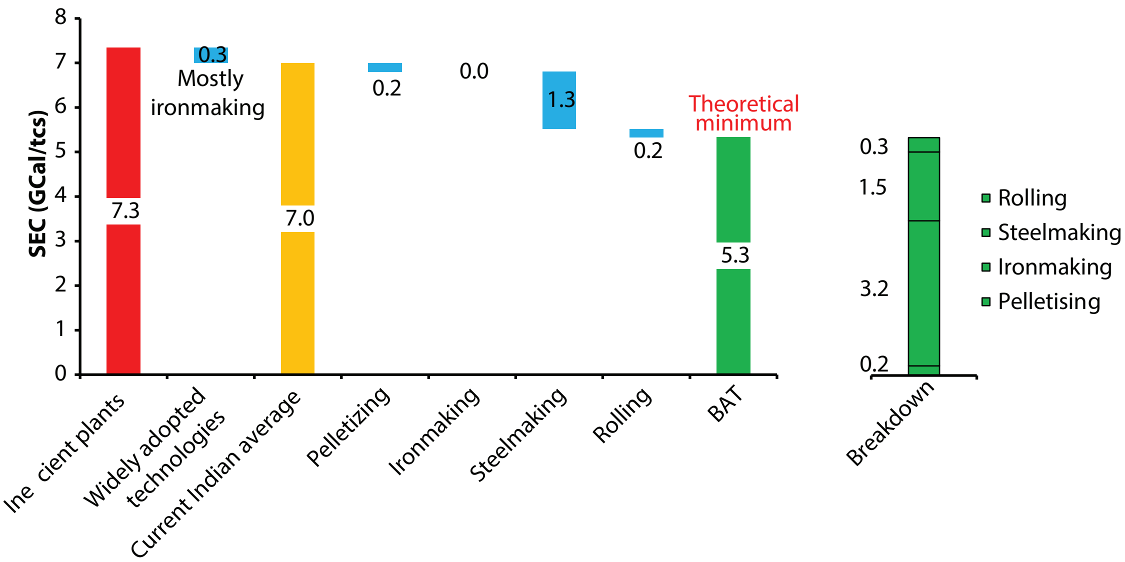


Figure 25: Energy efficiency measures for the coal-based DR-EAF/IF route

Source: WSP, Parsons Brinckerhoff and DNV GL (2015); JISF (2014); CII (2013); Morrow, Hasanbeigi, Sathaye, & Xu (2014); BEE (2018)

Figure 25 shows the energy savings potential for a typical DR-EAF plant. As we can see from these SEC numbers, the DR-EAF/IF route is typically more energy-intensive than the BF-BOF route and the potential for energy savings is more limited. The most widely adopted technologies are in the iron-making part of the process. Beyond those measures which are already widely adopted in India, we can see that significant savings are possible along the other parts of the steelmaking process. Our analysis suggests energy use can be reduced by up to 1.7 Gcal/tcs for the average DR-EAF plant.

Applying these numbers to the steel sector as a whole, we can start to understand the overall energy use out to 2050 and the impact energy efficiency measures can have. Conducting a bottom-up assessment, we estimate that energy demand in the iron and steel sector is around 72 Mtoe in 2018–19. Based on baseline assumptions, we estimate that energy consumption increases to nearly 80 Mtoe by 2020.

From 2020 onwards, we present two alternative scenarios for energy efficiency; the *Baseline* and a full-scale adoption of best available technologies (or **BAT)**. In the Baseline scenario, energy efficiency in the iron and steel sector continues to improve out to 2050, assuming a successful continuation of the PAT scheme and other cost-effective modernization. This results in a steady improvement in average SEC from 6.5 Gcal/tcs in 2020 to 5.5 Gcal/tcs by 2050 for the BF-BOF route and from 7.0 Gcal/tcs to 6.2 Gcal/tcs for the DR-EAF route.

For the BAT scenario, we assume that energy efficiency measures are introduced sooner and both the BF-BOF and DR-EAF route achieve significantly lower energy consumption by 2050. As a result, we project energy consumption falling from 6.5 Gcal/tcs in 2020 to 4.0 Gcal/tcs by 2050 for the BF-BOF route and from 7.0 Gcal/tcs to 5.3 Gcal/tcs for the DR-EAF route.

Figure 26 shows the difference between these two scenarios and the resulting impact of more ambitious energy efficiency measures. By 2030, the steel sector could be saving up to 25 Mtoe per year, increasing up to 38 Mtoe by 2040 and 50 Mtoe by 2050. Cumulatively, this represents an energy saving of nearly 900 Mtoe.

This analysis highlights the importance of driving forward energy efficiency measures to reach BAT benchmarks as soon as possible. This will require increased assistance to different sector players, alongside the PAT scheme. Initiatives such as SAMEEEKSHA (Small and Medium Enterprises Energy Efficiency Knowledge Sharing) have been

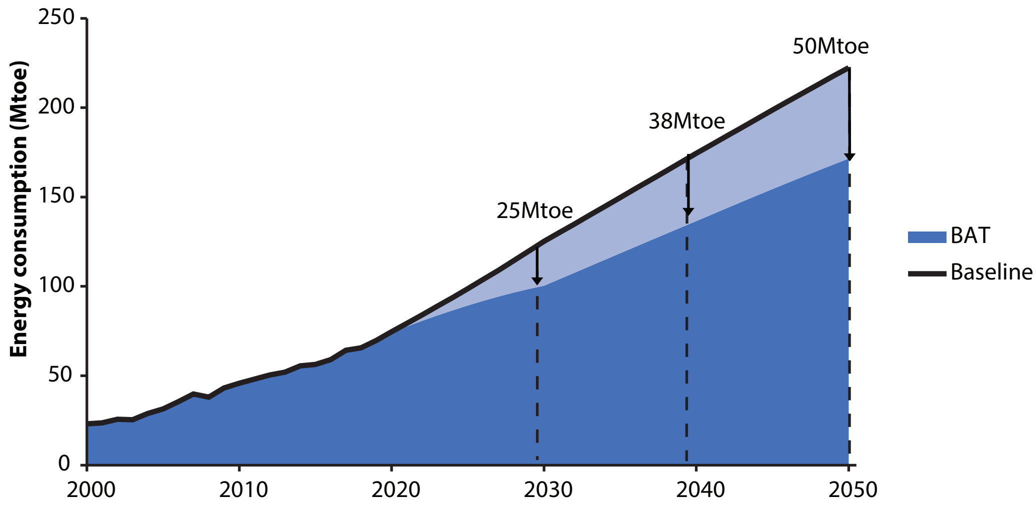


Figure 26: Energy consumption impact efficiency measures, 2000–50

Source: WSP, Parsons Brinckerhoff and DNV GL (2015); JISF (2014); CII (2013); Morrow, Hasanbeigi, Sathaye, & Xu (2014); BEE (2018) vital in sharing learning and experience among MSME units for improving their energy efficiency. The Energy Conservation Guidelines (ECG), prepared by the Bureau of Energy Efficiency (BEE) with support from TERI, are for both large industrial units and MSMEs. These guidelines are also designed to drive industry towards the adoption of best available energy efficiency technologies.

It's also worth noting that as the sector moves towards the BAT benchmarks, the energy savings measures will be harder to deploy than those in the past, as most of the easier measures with shorter payback periods will have already been adopted.

5.3 Emissions Impact

Through understanding the specific energy consumption of the different production routes and the proportions of fuels used in each route, we can calculate emissions intensities per tonne of crude steel. From this, we can estimate total emissions from the steel sector.

We estimate that emissions increase to just around 250 $MtCO_2$ by 2020, based on expected steel demand growth. Under the Baseline scenario, emissions would increase from this level to 798 $MtCO_2$ per annum by 2050, or nearly half of India's total CO_2 emissions today (GoI 2018). This represents a trebling of emissions from the sector, a level that would be very difficult to make compatible with global efforts to mitigate the negative impacts of climate change.

As more advanced energy efficiency technologies are deployed in the BAT scenario, out to 2050, the emissions reduction compared to the baseline increases. By 2050, emissions have been reduced from 798 $MtCO_2$ per annum to 687 $MtCO_2$, a saving of nearly 14% (Figure 27).

Despite these efforts, emissions from the iron and steel sector are still significant in 2050 and rising. They are 3 times what they were in 2015 and equivalent to around a third of India's emissions today (GoI 2018). So what other measures are available to mitigate emissions?

As explored in the previous section, resource efficiency, as well as energy efficiency, could play an important role in reducing emissions. The measures won't be entirely additive, as energy efficiency will result in fewer total emissions savings if less steel is being demanded but the potential is still significant. It is more beneficial for the economy as a whole if less energy is demanded, due to waste being reduced in the first place.

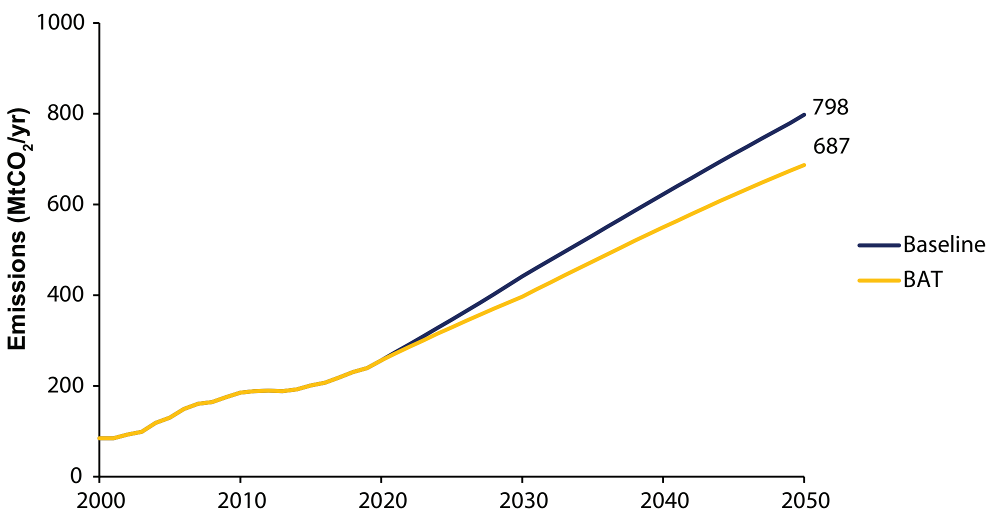


Figure 27: Emissions impact of energy efficiency measures, 2000–50

Source : TERI analysis

In Figure 28, we can see the impact of reducing steel consumption, whilst improving energy efficiency. Deploying best available technologies, as well as improving resource efficiency could see emissions from the steel sector peaking around 2050 at 515 $MtCO_2$.

These scenarios illustrate the potential of known technologies and measures to drastically improve the overall efficiency of steel production and use in India. Deploying best available technologies and adopting resource efficiency measures are well within the scope of existing policy thinking. The aforementioned PAT scheme, as well

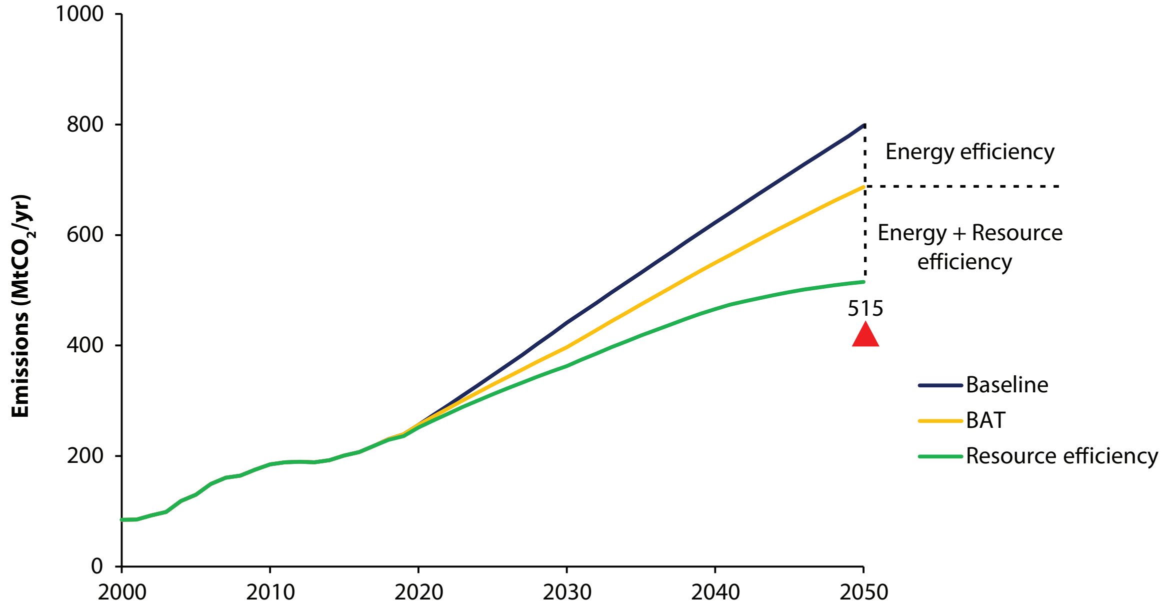


Figure 28: Emissions impact of energy efficiency and resource efficiency

Source: TERI analysis

as the Ministry of Steel's Steel Scrap Recycling Policy and the Government of India's broader Resource Efficiency Strategy, all provide the first steps towards a more energy and resource efficient steel sector. Nonetheless, there are still significant barriers to be overcome if the sector is to achieve these goals. Replacement cycles are long, the sector is facing intense global competition and growth in India is rapid. This confluence of issues mean long-term planning is vital.

5.4 Key Resources

Beyond overall energy and emissions estimates, it's also useful to understand the impact of these energy and resource efficiency measures on key resources. For the steel sector, two key inputs which have significant economic and environmental consequences are coking coal and iron ore. In the former, India has significant import dependence at great cost to the steel industry. Understanding how this dependence could change in the future is vital to understand the broader issues within the sector. India has large deposits of iron ore but the qualities vary. Also much of the land containing iron ore is currently forested. Significant expansions in primary steelmaking from iron ore will likely result in large-scale deforestation of environmentally valuable areas and the potential relocation of communities.

5.4.1 Coking Coal

The Indian iron & steel sector currently uses just over 60 Mt of coking coal per annum, of which around 80% is imported (CRISIL 2018; MoCI 2019). Whilst India has significant coking coal reserves, much of this is of insufficient quality to be used for steelmaking, or is located underneath developed areas and forested areas (Firoz 2014). There is some potential to increase domestic coking coal production, and Coal India has set out plans to increase these supplies out to 2030 (CIL 2018). Nevertheless, there is some scepticism about how quickly these resources could be scaled up and how sufficient they will be for a steel industry demanding higher quality metallurgical coal. As a result, import dependence for coking coal is likely to only increase, having implications for energy security and India's balance of payments.

Moreover, prices of coking coal have increased significantly in recent years, rising from around $90/tonne in 2015 to $195/tonne in 2018 (CRISIL 2018). Whilst prices are expected to fall slightly, they will likely remain far above their 2015 low. The cost of coking coal imports to the Indian economy was 720 billion rupees in 2018–19, or 10.3 billion USD. This equates to about 5.6% of India's total goods trade deficit, a substantial share (Department of Commerce and Industry 2019). As the sector expands, and the demand for coking coal along with it, these costs will only increase.

Figure 29 shows the extent to which India's import dependence will increase under our Baseline scenario, where the BF-BOF route constitutes 55% of estimated capacity by 2050. Along with some energy efficiency improvements, we assume the coking coal consumption decreases to 700 kg per tonne of crude steel by 2050 (WSA 2019a). We have also assumed that domestic production will increase from just below 15 Mt today to around 30 Mt by 2050, reflecting an optimistic scenario based on expert views and the available literature (CRISIL 2018; Firoz 2014). By 2030, India's import dependence could increase to nearly 90% and remain around that level out to 2050. This scenario would see India spending $19 bn–$23 bn on coking coal imports by 2030, assuming a price between $150–$180/tonne. This could rise to $33 bn–$40 bn by 2050, assuming the same price range. As with any globally traded commodity, there is significant uncertainty around the future price and availability of coking coal but this analysis shows that under current expansion plans, India is set to increase and maintain a high level of import dependence at significant cost to the economy.

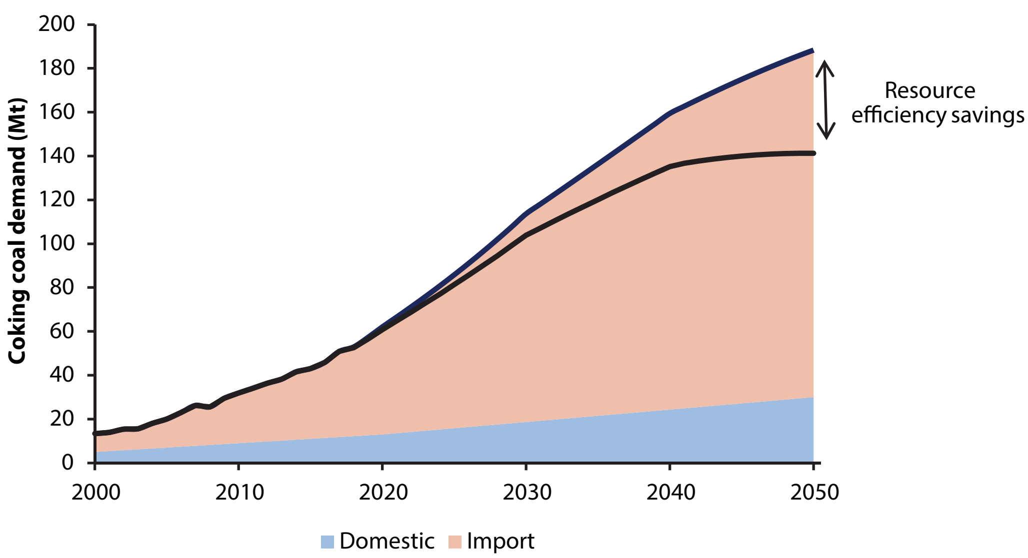


Figure 29: Coking coal demand and import share

Source : TERI analysis

Greater levels of resource efficiency could reduce import dependence, as shown on the chart. Applying the measures under our *Resource efficiency* scenario would reduce coking coal import by around 25% by 2050. One of the options for further reducing the reliance on coking coal for use in the BF-BOF route is a shift to smelting reduction processes, such as HIsarna, for new plants. These processes are discussed further in Section 7.

5.4.2 Iron ore

Along with coking coal, iron ore is also a vital resource for the expansion of the steel industry. Historically, the Indian steel industry has been able to source most of its iron ore domestically, and indeed India is a small net exporter of iron ore. However, as primary production increases rapidly, there are concerns over the ability for domestic iron ore mining and supply to keep pace. This is for several reasons, including environmental constraints, mining caps, lack of infrastructure for transporting iron ore and opposition from local populations.

The domestic iron ore industry is highly fragmented, with 294 mines operating in 2017–18, with 35 public and 259 private. The private mines tend to be far smaller, only contributing to 65% the total production, despite the large number of mines. Captive mines were responsible for 30% of the production, with non-captive mines making the balance (IBM 2018).

Table 10: Iron ore reserves in India

Ore type	Reserves (Mt)	Remaining resources (Mt)	Total resources (Mt)
Haematite	5,422	17,065	22,487
Magnetite	53	10,736	10,789
Total	5,475	27,801	33,276

Source: IBM (2018)

India still has large quantities of domestic reserves, with over 17,000 Mt of Haematite and nearly 11,000 Mt of Magnetite remaining (see Table 10). Based on our analysis, under the *Baseline* scenario, the steel sector would demand around 12,000 Mt of iron ore out to 2050, or around 10,000 under the *Resource efficiency* scenario. We can, therefore, assume that India has sufficient iron ore resources for the long term.

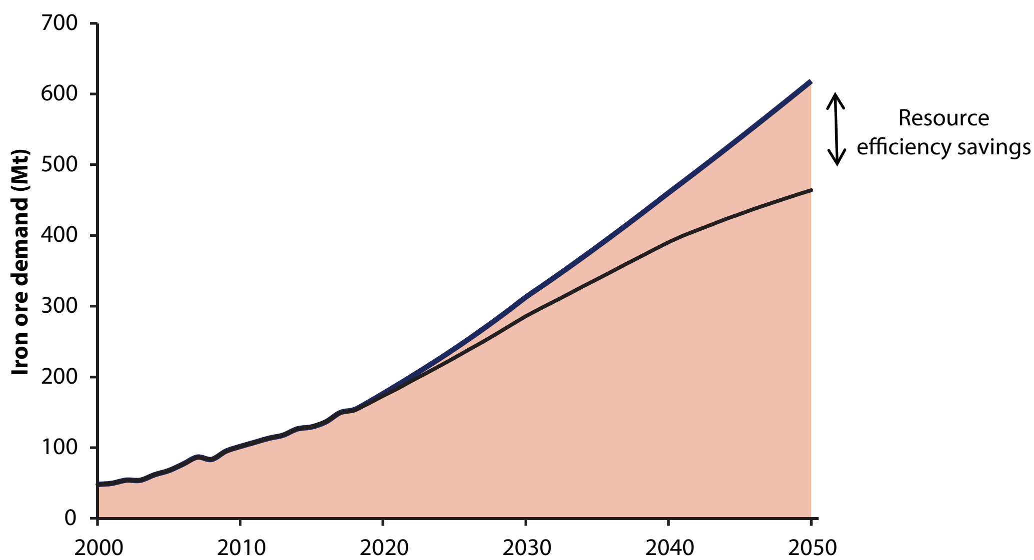


Figure 30: Iron ore demand, 2000–50

Source: TERI analysis

6

TRADE AND COMPETITIVENESS

Trade and Competitiveness

The iron and steel sector is an economically and a socially important sector, and policymakers are particularly sensitive to perceived risks to its competitiveness. By raising energy costs, it is sometimes proposed that climate policy may adversely affect the economic competitiveness of the iron and steel sector. In discussing this proposition, it is necessary to make a distinction between three different aspects of economic competitiveness:

- *Within sector, domestic competition*: This refers to the degree of competition within the sector, which in turn influences the capacity of producers to pass on incremental costs to final consumers. As a large, capital intensive sector, the iron and steel sector, particularly the production of crude steel, tends to be dominated by a few large firms. *A priori,* this would imply a lower degree of domestic competition within sector, and facilitate the pass through of incremental costs to consumers (we discuss this proposition below).
- *Between sector, domestic competition*: This depends on the degree of substitution between the products of different sectors. Generally, we would expect a relatively low degree of substitution for the products of the iron and steel sector, although there is an increasing use of aluminium in certain sectors.
- *International competition*: This depends on the degree of tradability of the outputs of the sector, the drivers of comparative advantage (labour, land, energy, finance, and transport costs), the degree of product differentiation, the premium placed on quality, and the premium placed on the proximity of production and demand.

This section discusses the aspects of trade and competitiveness with reference to the Indian iron and steel sector. Section 6.1 discusses the characteristics of the iron and steel sector as they pertain to competitiveness. Section 6.2 analyses the current commercial relationships of India in the iron and steel sector, and draws conclusions in terms of the apparent competitiveness of the Indian iron and steel sector. Section 6.3 discusses the outlook for the global market for iron and steel, particularly with respect to some of India's most significant trading partners.

6.1 The Characteristics of the Iron and Steel Sector

6.1.1 Energy Intensity

The operating costs of the iron and steel sector are dominated by large expenditures on fuels and materials as inputs to the production process. The Annual Survey of Industries (ASI) is the main source of data on Indian industrial sectors. On the basis of the ASI we calculate the energy intensity of production, defined as the cost of fuels consumed divided by the value of total output. We plot this against the cumulative sectoral share in total value added.

It can be seen from Figure 31 that sectors accounting for more than 80% of total industrial value added have an energy intensity of less than 10%. Thereafter, sectoral energy intensity rises rapidly. The iron and steel sector has a sectoral energy intensity of just over 10%, making it the eighth most energy intensive sector. It is exceeded by sectors like the manufacture of non-metallic minerals; manufacture of pulp and paper; and manufacture of fertilizers and nitrogenous compounds. The energy intensity of the Indian iron and steel industry appears to be a little higher than other countries, with energy costs over production value averaging 7.5% for four major European steel producers (Eurostat 2019). It is even lower in the case of the United States, at 1.4% (US Census Bureau 2017). The differences may be due to the cost of fuels (e.g., cheap natural gas in the US), degree of value addition in outputs, energy intensity of production, the structure of production (i.e., the scrap-based EAF route is much more energy efficient than the BF-BOF route), as well as statistical variations in the way certain inputs are classified.[6]

[6] For example, it could be that the different statistical agencies classify coking coal differently, either as a material input to production, or a fuel input. However, across the three jurisdictions assessed, material inputs, as a share of total output value, are broadly similar. In the case of India, material inputs account for 64.8% of the value of total output, 60% in the EU, and 62% in the case of the US (Eurostat 2019; MOSPI 2017a; US Census Bureau 2017). Thus, it would seem that this discrepancy cannot account for the large difference between the share of fuel as a share of output value in the US versus India and the EU.

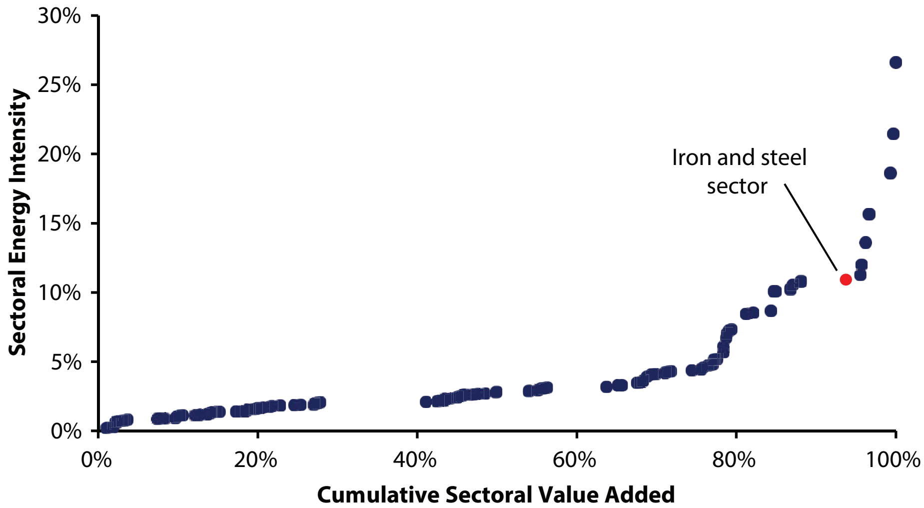


Figure 31: Sectoral energy intensity versus cumulative sectoral value added

Source: TERI analysis based on data from ASI 2016–17 (MOSPI 2017a)

Other major input costs (with average figures) include material inputs (65% of output value), labour costs (4.3% of total value), and other costs (6.8% of total value). There is significant variation between companies in terms of share of output value for these different inputs. It is also worth noting the difference in labour costs as a share total output between different jurisdictions, which at 12% in the US and the EU is more than three times the share in India.

Energy costs are an important determinant of the costs of production, but by no means the only determinant. Large disparities exist between countries with low- and high-cost energy and low and high labour costs.

6.1.2 Trade Intensity

Trade intensity is another important determinant of the perceived risk of climate policy impacts on industrial competitiveness. Following standard practice, we define trade intensity as the sum of imports and exports over the sum of imports, exports, and domestic production. We focus on the trade intensity of the iron and steel sector itself, rather than that of downstream sectors like transport equipment manufacture, which embody iron and steel in their products. Because of the large cumulative value addition in downstream products, the value of embodied iron and steel is generally low, in the order of 1–2% for a car produced in India for example (see Section 7.2.2 below). Hence, competitiveness concerns are mainly in the upstream sector of iron and steel production.

We start by calculating the trade intensity of the iron and steel sector in physical terms, with imports, exports, and domestic production expressed in tonnes. According to data from the World Steel Association, the trade intensity of crude steel has been broadly stable at slightly less than 20% (see Figure 32). On the other hand, the trade intensity of lower value- added iron products is far lower, at less than 5%. This is due to these products having lower value added, and, therefore, the mass to value ratio makes transporting such goods long distance less favourable.

We now turn to calculating monetary trade intensity. For this, we take monetary domestic production values for the iron and steel sector from the Annual Survey of Industries, and monetary import and export values from the Department of Commerce's Export Import Data Bank. According to this analysis, the monetary trade intensity of the iron and steel sector is comparable to the physical estimate. It has also been broadly stable over time. Figure 32 shows the results of this analysis.

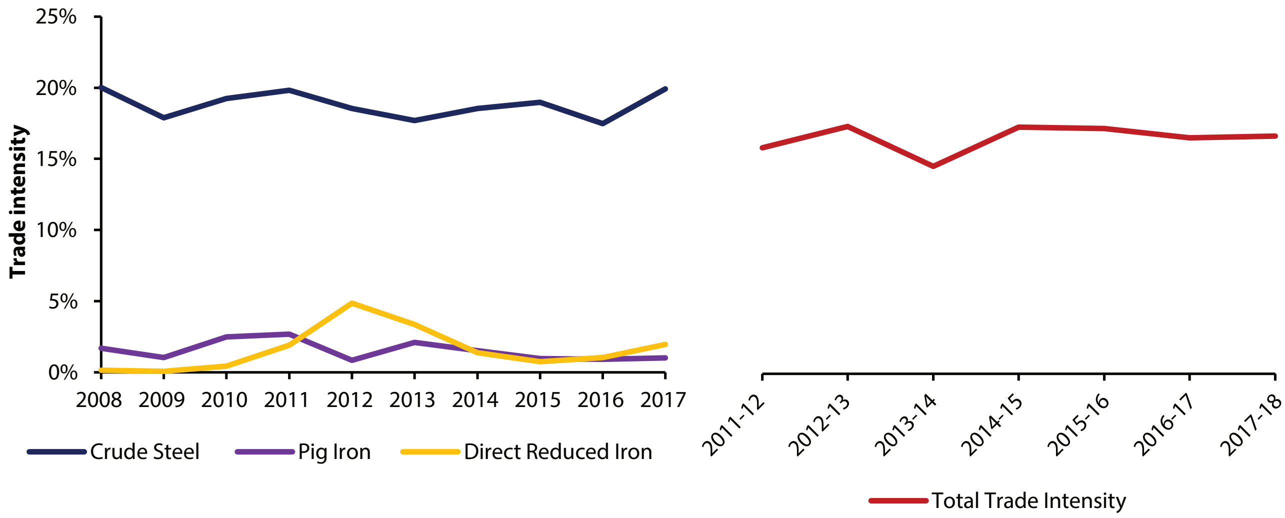


Figure 32: Trade intensity of the iron and steel sector

Source: TERI analysis based on data from MOSPI (various years); WSA (2018c); Department of Commerce and Industry (2019)

Therefore, the iron and steel sector is among the more trade intensive industrial sectors. Consequently, trade competitiveness can be considered a serious concern.

6.1.3 Financial Characteristics

In this section, we analyse several financial characteristics of the Indian iron and steel sector, which may impact on its ability to pass on incremental costs, invest in innovation and new capacity, or compete internationally. Using ASI data, we look at the following metrics:

- *Profit margins*: This is defined as profits over total revenues, and may give an idea of both the current financial health of the sector and its capacity to invest in innovation or new capacity.
- *Investment intensity*: This is defined as the sector's net fixed capital formation (i.e. gross fixed capital formation net of depreciation) over total revenues. This metric may suggest the current level of investment in new capacity or equipment, as well as give an indication of the ability to raise this investment in the future.
- *Interest coverage ratio*: The formula for interest coverage ratio is earnings before interest and tax (EBIT) over total interest expenses. As the ASI does not give EBIT, we take a close proxy, namely net value added.

For each of these indicators, we present one plot below which shows the average value for each sector over the last seven years of ASI data (2010–17). In each case, we sort the data from the lowest to the highest values and highlight where the iron and steel sector is located in this distribution. Figure 33 presents the results.

As can be seen, the iron and steel sector has been among the poorer financial performers in the sectors covered by the ASI. It is towards the bottom in terms of average profit margin, at 1.7% on average over the last 7 years. It is also towards the bottom on the interest coverage ratio (2.85). This means that annual net value added was only 2.85 times annual interest payments, on average, across the period. It is, however, among the top of the sectoral distribution in terms of investment intensity, with net gross fixed capital formation averaging 5.6% of total revenues across the period studied.

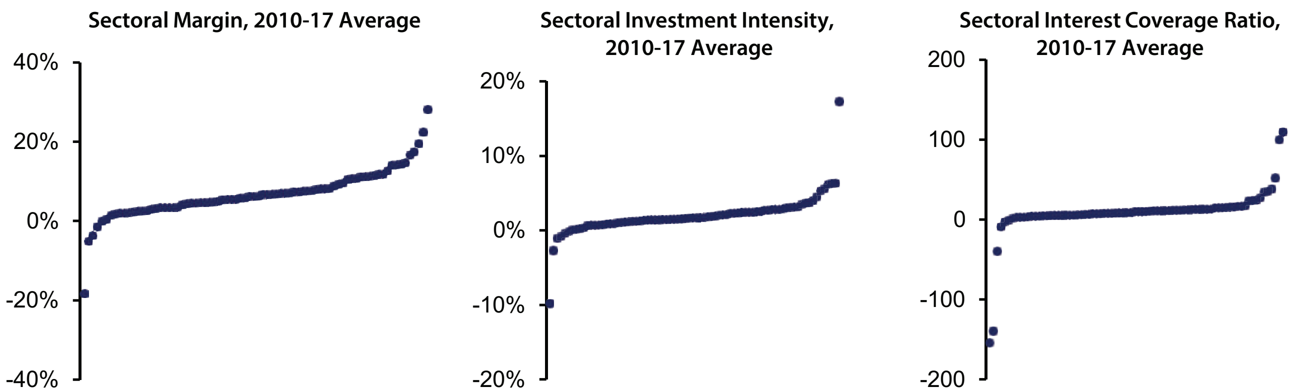


Figure 33: Financial performance of the Indian iron and steel sector relative to other ASI sectors

Source: TERI based on data from ASI (MoSPI, various years)

Having looked at the average values for each indicator across all the ASI sectors, we now plot the trend for just the iron and steel sector across 2010–17. The results are shown in Figure 34 below. There has been a generally declining trend over the 7 years analysed across all indicators. In the case of profit margin and interest coverage ratio, there has been a rebound since 2015 but insufficient to take these indicators back to the levels seen in the earlier years of the period analysed.

To conclude this section: the Indian iron and steel sector seems to be financially fragile, with narrow profit margins, declining investment intensities, and an increasing interest burden. Of course, the iron and steel sector is highly cyclical, and upswings and downswings are a normal feature of this industry. In addition to domestic issues, the international environment has also been volatile, including in the global steel market. This being said, it is clear there might be limited capacity to undertake large and risky investments, which may challenge domestic or international competitiveness, given the environment of narrow profit margins, high interest burdens, and stagnant investments.

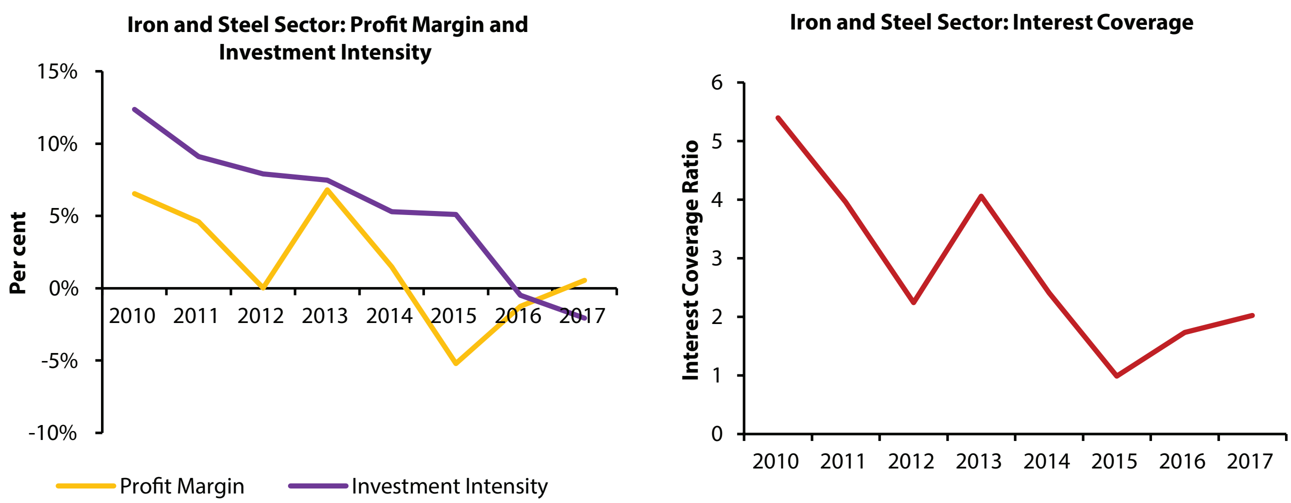


Figure 34: Trend of the iron and steel sector on several financial performance metrics

Source: TERI analysis based on ASI data

6.1.4 Sector Characteristics Summary

The iron and steel sector is characterized by a relatively high energy and trade intensity among industrial sectors. This combination makes it one of the important sectors at risk of so-called 'carbon leakage'[7] or adverse international competitiveness impacts from unilateral, stringent climate policies. At the same time, the iron and steel sector is a highly cyclical, capital intensive sector. In recent years in India, it has suffered from low profitability, high interest burdens, and declining investment intensity. All of these factors may be barriers to the implementation of ambitious innovation and decarbonization policies in the sector.

6.2 India's Commercial Position in the Iron and Steel Sector

6.2.1 Overview

Having reviewed some of the basic characteristics of the iron and steel sector, we now turn to a brief analysis of India's commercial relationships in the sector. We use the data of the Department of Commerce and Industry in order to build a picture of India's trading relationships for iron and steel (Department of Commerce and Industry 2019). The iron and steel sector is defined as all sub-sectors falling within the Harmonized System (HS) in Chapter 72 "Iron and Steel". It excludes iron ores and coking coals, which are listed under Chapters 26 and 27 respectively, of the HS system of product classification.

India's overall trade balance within the iron and steel sector was generally negative from 2010–11 to 2018–19. A small positive trade balance was achieved only in 2013–14, 2016–17, and 2017–18. The iron and steel sector recorded a steeply negative trade balance in 2011–12 and 2012-13, and again in 2014–15 and 2015–16. The periods of net export (positive balance) appear to coincide with periods of domestic weakness in investment in key major steel consuming infrastructure sectors. For example, construction investment was negative in 2013–14 and 2016–17, and investment in road transport infrastructure was sharply negative in 2013–14 and moderate in 2016–17 (MOSPI 2019b). On the other hand, at least one period of sharply negative trade balance in the iron and steel sector coincided with the period of Chinese industrial slowdown in 2015–16 and severe overcapacity in the global steel market. Therefore, while India's trade balance in the iron and steel sector fluctuates depending on the domestic and international macro-environment, it has, broadly speaking, been substantially negative across the period that has been assessed here.

India's trade deficit has averaged 160.5 billion in nominal rupees across the period in 2010–11 to 2018–19, equating to roughly 2.35 billion USD.[8] Over time, the iron and steel sector trade deficit accounted for about 1.8% of India's total goods trade deficit on average, and peaked at 4.9% in 2015–16. Thus, the iron and steel sector is a significant factor within India's overall trade deficit. If we add in the import of coking coal, then the total share of the iron and steel sector in India's manufacturing goods deficit was about 7.4%.

6.2.2 Analysis by Product

We now turn to analysing India's trade relationships by product. The figure below presents India's average trade balance per sector across the period 2010–11 to 2018–19, sorted from low (net imports) to high (net exports). In Figure 35, each sector is colour coded according to the level of technological intensity. Generally, sectors which do not involve processing above rolling or drawing into wires, or do not involve alloying are classified as 'low tech'. Sectors which involve physical processing but not alloying are classified as 'medium tech', and sectors that involve both alloying and physical processing are classified as 'high tech'. The annex presents a table of each subsector code, description, and technological classification.

7 Carbon leakage refers to an increase in greenhouse gas emissions in one country as a result of policy causing a reduction in emissions in another country.

8 Calculated at an exchange rate of 68 INR per USD

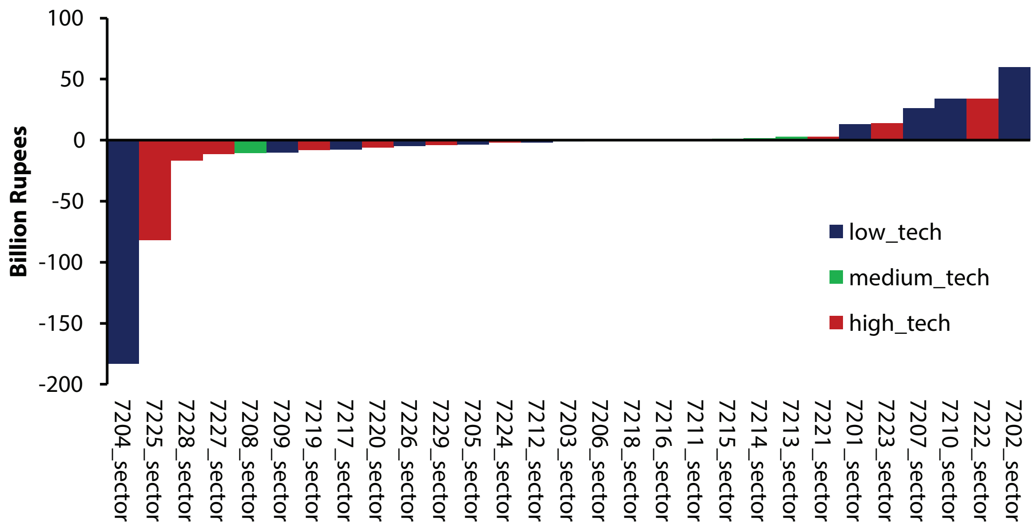


Figure 35: India's net iron and steel trade balance by subsector: 2011–12 to 2018–19 average

Source: TERI analysis based on the data from Department of Commerce and Industry (2019)

The figure above makes clear how exceptional India's imports of scrap (code 7204) are in the context of its overall trade balance in iron and steel subsectors. With the exception of scrap imports, the other major sectors in which India tends to have a sizeable trade deficit are subsectors that we have classified as having a high technological intensity. These include: flat rolled products of alloyed steel (code 7225), bars, rods and sections of alloyed steel (7228), and bars and rods, hot-rolled, in irregularly wound coils, of other alloy steel (7227). On the other hand, India tends to be an exporter of products that we have classified as having a lower technological intensity. These include: ferro-alloys (7202), flat-rolled products of iron or non-alloy steel (7210), or semi-finished products of iron or non-alloy steel (7207).

It, therefore, appears clear that India's comparative advantage lies at the lower end of the technology spectrum, and that it has a higher dependency on imported products in higher technology subsectors.

6.2.3 Analysis by Trade Partner

6.2.3.1 Overview by Commodity Group

In this subsection, we provide analysis of India's net trade balance in the broad commodity group 'iron and steel' (HS Code 72). This is to identify India's largest trading partners, in terms of both net import and net export and how stable these relationships have been over time. In the following subsection we then analyse these major trading relationships in more detail by product category.

Figure 36 shows the results. As can be seen, India has been an exporter to a number of countries within the region (Nepal, Bangladesh, Vietnam, Iran), as well as several European countries (Italy, Belgium, Spain). On the other hand, India's net imports are much more concentrated, with essentially only the East Asian industrial powerhouses playing a significant role (South Korea, China, Japan). China's net exports to India have been more volatile than those of South Korea or Japan, with a surge in net exports during notably a period of domestic industrial weakness and iron and steel overcapacity in China (FY2014–15 to FY2015–16). Sustained exports from South Korea and Japan can, in part, be attributed to the Comprehensive Economic Partnership Agreements which India has with both countries, which has resulted in a steady reduction on import duties for iron and steel.

As the Chinese economy recovered on the back of substantial domestic infrastructure stimulus, net exports subsequently reduced. This period of net export surge also corresponded to a period of financial weakness in Indian industry, with indicators like profit margin and interest coverage ratio declining (from low levels) in FY15–16, in particular (see Figure 35). This indicates that exposure to global steel sector overcapacity, driven largely by China, has disrupted the Indian steel market, and put pressure on domestic firms.

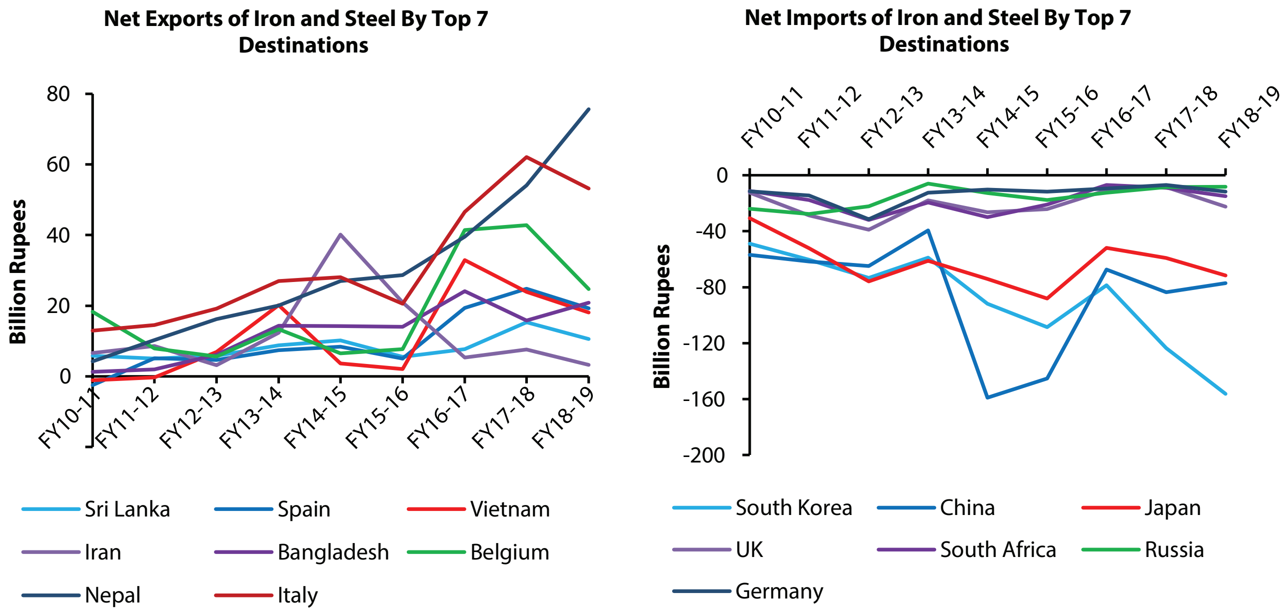


Figure 36: Net exports and imports of iron and steel products by major trading partner

Source: TERI analysis based on the data from Department of Commerce and Industry (2019)

6.2.4 Detailed Analysis by Major Trading Partner

6.2.4.1 Imports

Figure 37 shows India's imports by 4-digit product from the 3 largest import origin countries in 2017 and 2018, namely South Korea, China, and Japan. The x-axis displays the product code, while the y-axis displays India's net trade with the country in question for each product, in million USD.[9] The first aspect worth noting is that India is a deficit country in similar subsectors across the three countries. These products fall into three broad groups, as follows:

- HS codes 7207 to 7210: these refer to semi-finished products of iron or non-alloy steel (code 7207), and various flat-rolled products of iron or non-alloy steel of a width of 600 mm or more (codes 7208, 7209, 7210).
- HS codes 7218 to 7221: these refer to various products of stainless steel, in particular ingots and other primary forms (code 7218), flat-rolled products of a width of 600 mm or more (7219), flat-rolled products of a width of less than 600 mm (7220), bars, rods and sections (7221).
- HS codes 7224 to 7228: these codes refer to primary forms (7224), flat-rolled products (7225, 7226), and bars, rods and sections (7227, 7228) of alloy steel.

9 The preceding analysis was given in Rupees, as the data source was the Department of Commerce and Industry. However, the Department of Commerce and Industry's Export Import Data Bank does not lend itself easily to large data downloads. For this section, analysing detailed products for multiple countries we use the World Integrated Trade Solution database of the World Bank. This source gives results in USD, not in Rupees. However, both the sources use the Harmonized System of sector classification, and, hence, despite the different monetary unit, trade flows are perfectly comparable using the two databases.

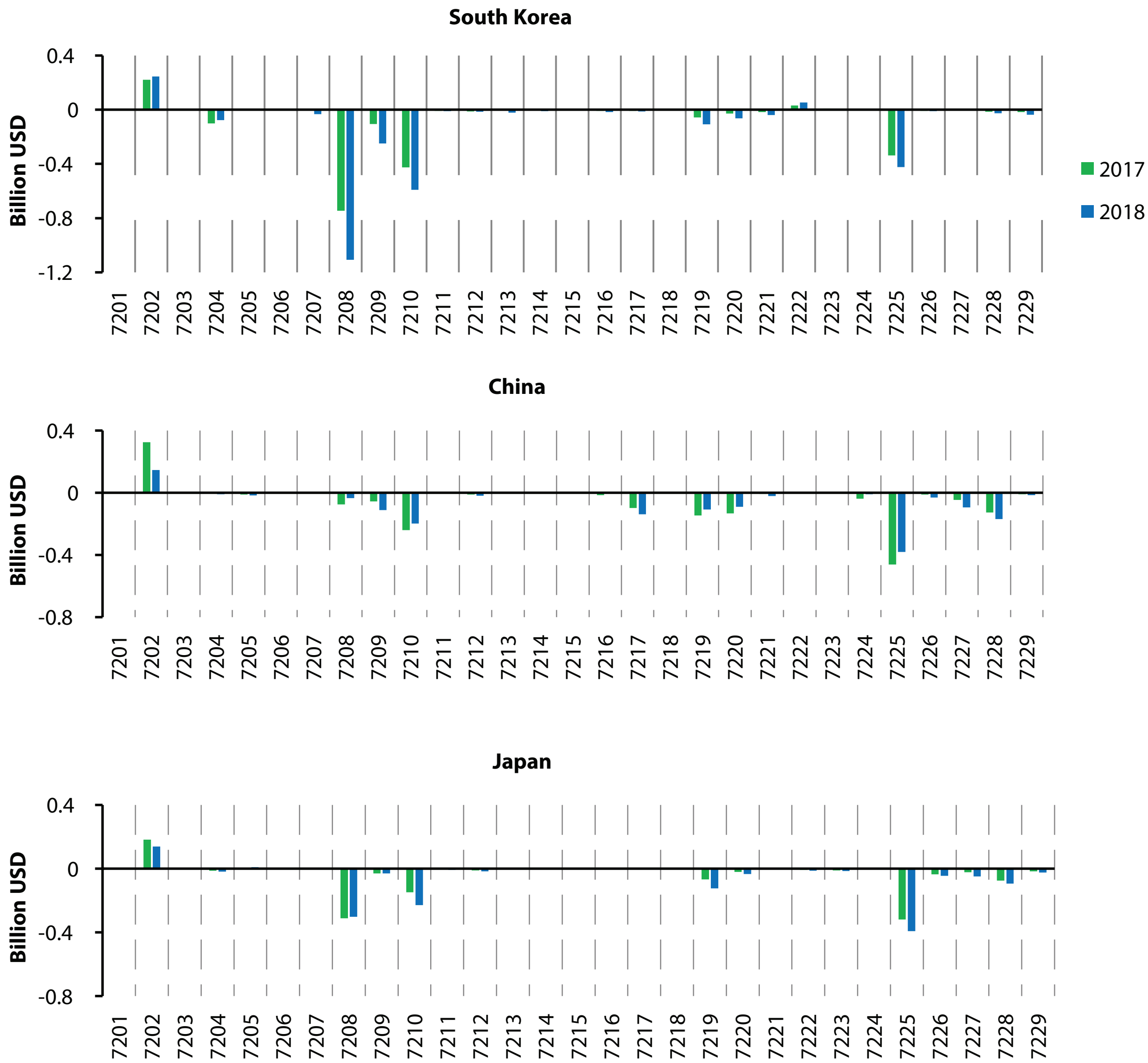


Figure 37: Net imports of iron and steel products by subsector, major trading partners

Source: TERI analysis based on the data from WITS Database (2019)

This data suggests that India is at a comparative disadvantage relative to China, Japan, and South Korea in a few areas of higher technical sophistication, including in stainless steel and alloy steel production. This is largely due to manufacturers in these countries supplying the entire global market for certain specialist products, as opposed to an inability of Indian manufacturers to produce higher quality products.

6.2.4.2 Exports

Figure 38 shows India's net trade with its three major export destinations byproduct. These are Nepal, Italy, and Belgium. India mainly exports semi-finished products of iron or non-alloy steel, and various flat-rolled products of iron or non-alloy steel, as well as small amounts of various stainless steel products.

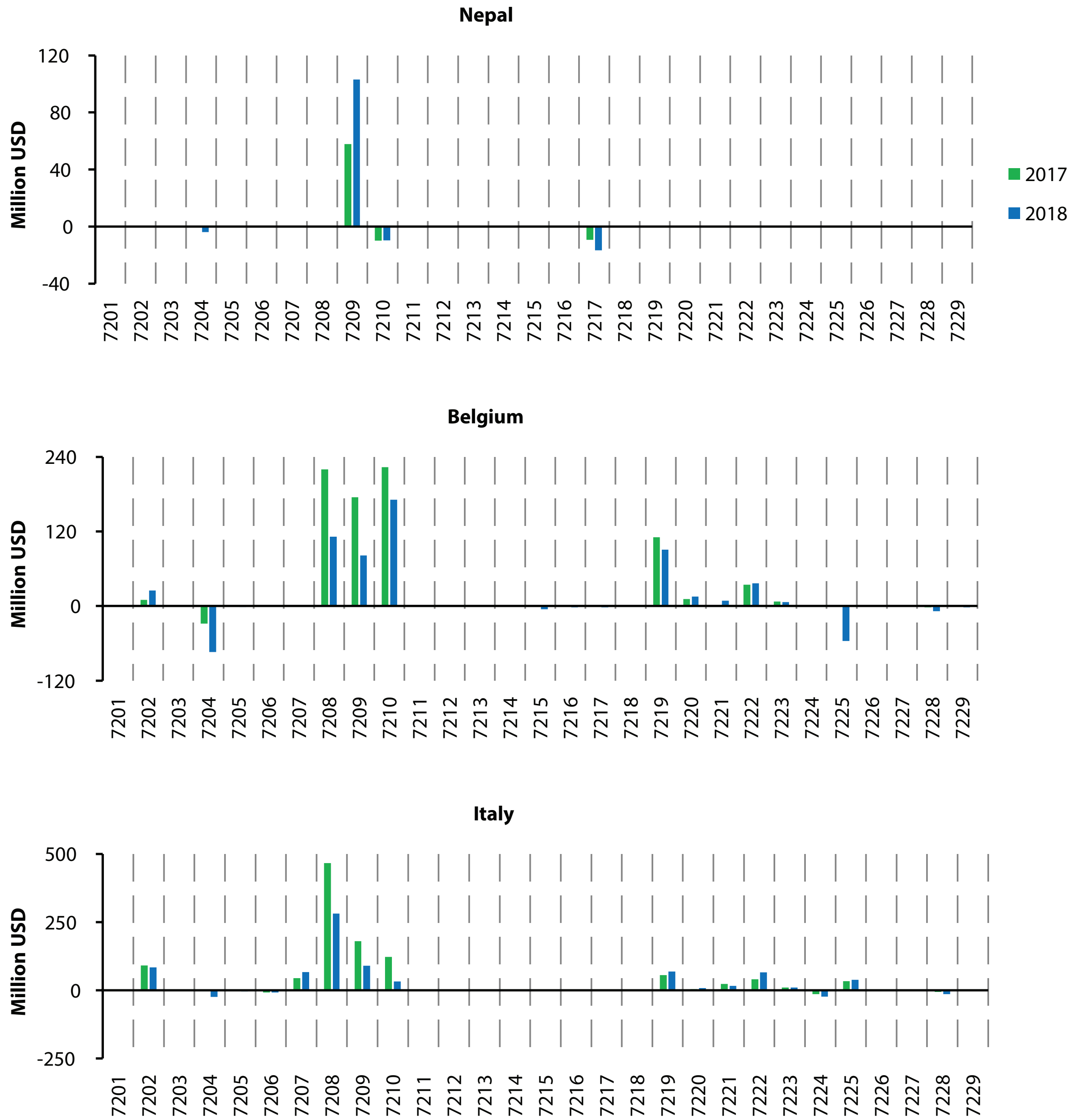


Figure 38: Net exports of iron and steel products by subsector, major trading partners

Source: TERI analysis based on the data from WITS Database (2019)

6.2.4.3 Scrap Imports

It was shown in Section 6.2 that India's export deficit in iron and steel was largely driven by net imports of scrap, notwithstanding substantial net imports of processed products from Japan, China, and South Korea. India's scrap imports come from a broad range of countries, in particular United Arab Emirates, the United States, the United Kingdom, Singapore, and the Netherlands. Figure 39 shows India's net scrap imports, in monetary terms, from the top 20 import origin countries, which cumulatively made up about 94% of India's total scrap imports.

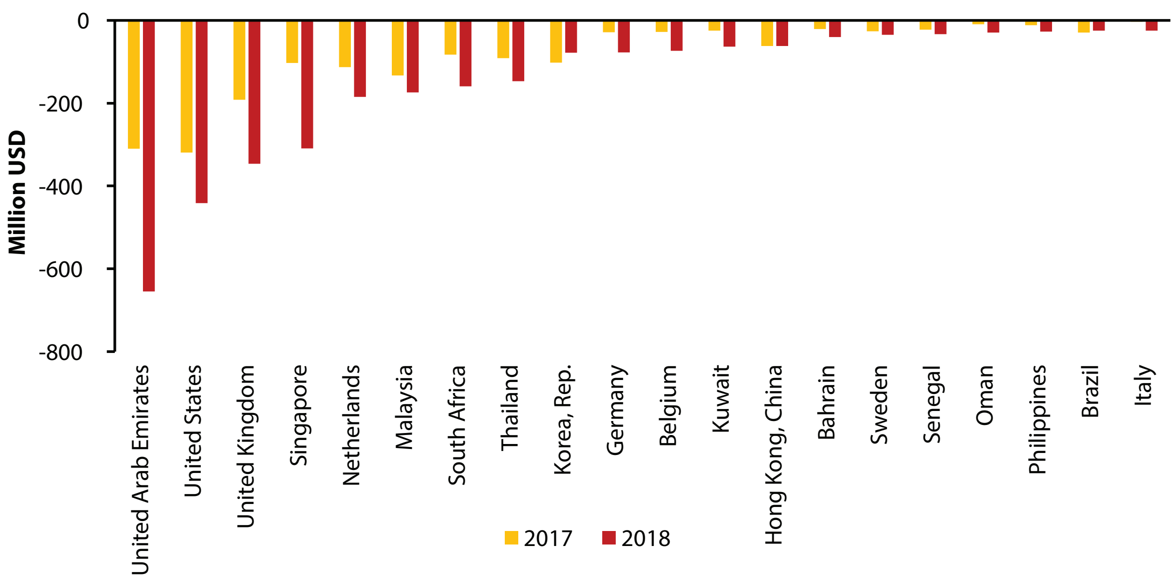


Figure 39: Net imports of scrap by country of origin

Source: Department of Commerce and Industry (2019)

6.3 Outlook for the Global Steel Market

Section 6.2 outlined how India's iron and steel trade balance had become substantially negative in 2014–15 and 2015–16, which coincided with a period of industrial slowdown in China and a glut on the global steel market. This period also coincided with a further, sharp downwards turn in the Indian iron and steel sector's financial performance on indicators such as profit margin and interest coverage ratio, although it should be noted that these indicators were on a downwards trend anyway since 2010–11. This raises the question of the prospects for the global steel market in the coming years, and the implications for the global competitive environment for the Indian iron and steel sector. We offer some reflections on these questions in this section, with a particular focus on India's three main import partners: China, Japan, and South Korea. Given China's huge size in the global steel market, at just under 50% of world crude steel production, we also provide a particular focus on China.

6.3.1 Outlook for Domestic Consumption

6.3.1.1 Steel Sector Analysis for China, Japan, and South Korea

At the outset, it is necessary to make a few definitions of terms that will structure the analysis in this section:

- *Crude steel production*: This refers to domestic production of crude steel.
- *Apparent steel consumption*: This refers to crude steel production net of exports minus imports of crude steel.
- *True steel consumption*: This refers to apparent steel consumption, net of steel embedded in the net trade of manufactured goods. It is, therefore, the closest approximation of domestic steel consumption in the national economy, as well as annual additions to the national emplaced steel stock (net of annual depreciation from the stock, of course).

A country may have a true steel consumption that is above its crude steel production, if it imports either crude steel or imports crude steel embodied in finished manufactured products. Likewise, a country's crude steel production could be above its true steel consumption if it is a net exporter of crude steel or crude steel embedded in manufactured products (or both). The focus on true steel consumption is important because it represents the closest approximation to domestic demand. In turn, it is the difference between domestic demand and domestic production capacity which will determine the export or import potential of a country. If there are large positive differences between domestic production capacity and true steel consumption, then there may be pressure on the global steel market as the excess production capacity is shifted to global markets.

Figure 40 shows crude steel production, apparent consumption, and true consumption for India's three largest import origin countries for crude steel, namely China, Japan, and South Korea. As would be expected, all three have large differences between domestic production and apparent consumption, and between apparent consumption versus true consumption. This is logical: all three are large exporters not only of crude steel but also manufactured products embedding crude steel. The scale of the cumulative delta between crude steel and true consumption is large: 272 Mt in 2016, of which China accounted for almost 70% (note that the three countries are not plotted on the same y-axis in the graph below). However, the delta between crude steel production and apparent steel consumption represents the quantum of production available for global markets (assuming that world demand for manufactured goods embedding steel remains constant). This is also large: 144 Mt in 2016, for which China again accounted for 68%. In our dataset, the cumulative delta between production and apparent consumption grew more than fourfold from 2009 to its peak in 2015. This increase was driven predominantly by China, with a small contribution also from- Korea. Japan's delta between domestic production and apparent consumption remained broadly stable (and large – Japan's delta is more than three times that of South Korea).

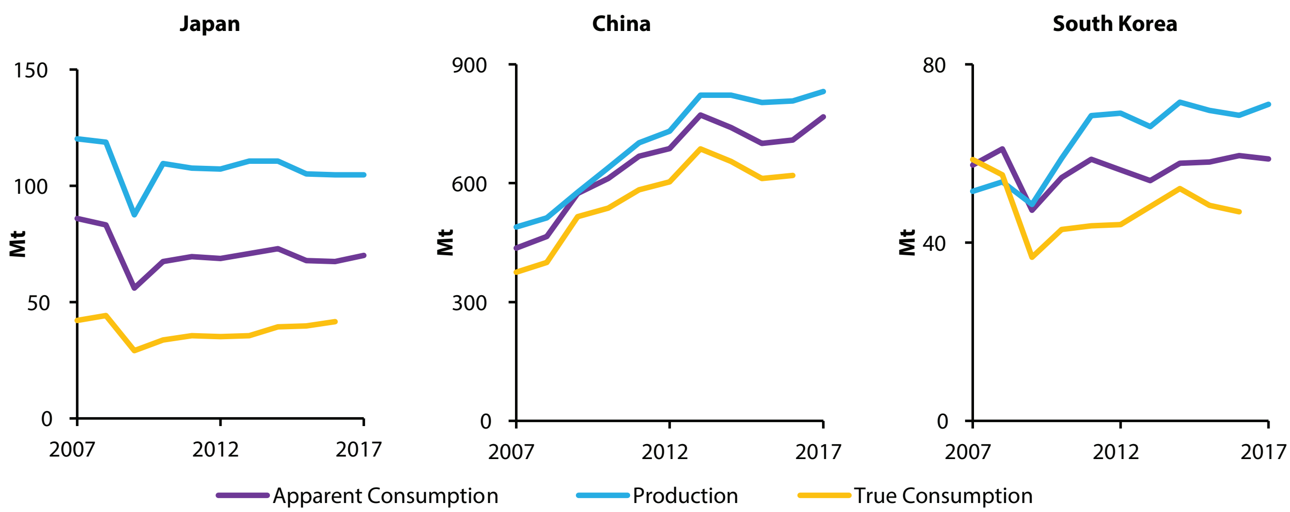


Figure 40: Production versus apparent consumption and true steel consumption: China, Japan, and South Korea (2007–17)

Source: TERI analysis based on the data from World Steel Association (2018)

What has happened to drive this change? After the Global Financial Crisis of 2008–09, countries undertook a large fiscal stimulus, focused primarily on domestic investment. This was particularly the case for China – see the huge jump in China's true steel consumption from 2008–09, and its continued growth thereafter. This increased domestic demand for steel, and large investments were made in fresh capacity. In the meantime, global trade in manufactured goods slowed down, decreasing the world demand for embedded steel. Over time, the domestic stimulus faded, and domestic demand for steel declined – see the true steel consumption decline in China and South Korea after 2013. This further increased the production capacity available for the global market.

6.3.1.2 What Is China's 'Equilibrium' Level of True Steel Consumption?

The above analysis raises the question of what China's equilibrium rate of true steel consumption should be? It is this which determines the scale of the production capacity available to the global market, assuming world demand for manufactured goods embedding steel remains constant (i.e., that the delta between apparent and true steel consumption remains constant). In order to investigate this question, we build a dataset of 70 countries for 2007–2016. The dataset covers very rich countries and very poor developing countries, and everything in between, and, therefore, provides a good overview of the development pathway. We plot real GDP per capita at constant PPP against true steel consumption per capita in kg. This allows us to investigate the relationship between domestic consumption of steel and economic development, and in so doing draw some inferences for the possible trajectory of China's true steel consumption per capita as it follows its development pathway. Figure 41 displays the results.

We plot the entire dataset in semi-transparent grey markers. Therefore, the darker the grey, the greater the concentration of data at that position on the axes. We plot China separately and also those countries which appear as outliers in terms of the true steel intensity of their GDP per capita.

From this analysis we can draw the following conclusions. First, given its level of development, China's steel intensity is completely exceptional. Only Vietnam appears to be following a comparable trajectory, albeit at an earlier stage of development. Second, there are a number of countries that appear similarly steel intensive relative to the entire dataset. These countries appear to be of several categories. First, there are those with massive export surpluses, very high degrees of urbanization, and relatively investment intensive economies, namely Taiwan and South Korea. These countries' merchandise trade surplus stood at 7.5% and 6% of GDP in 2016 (compared to 2.6% for China and 2% for Japan). While the measure of true steel consumption should net out exported steel in embedded products, maintaining this level of manufacturing production may necessitate

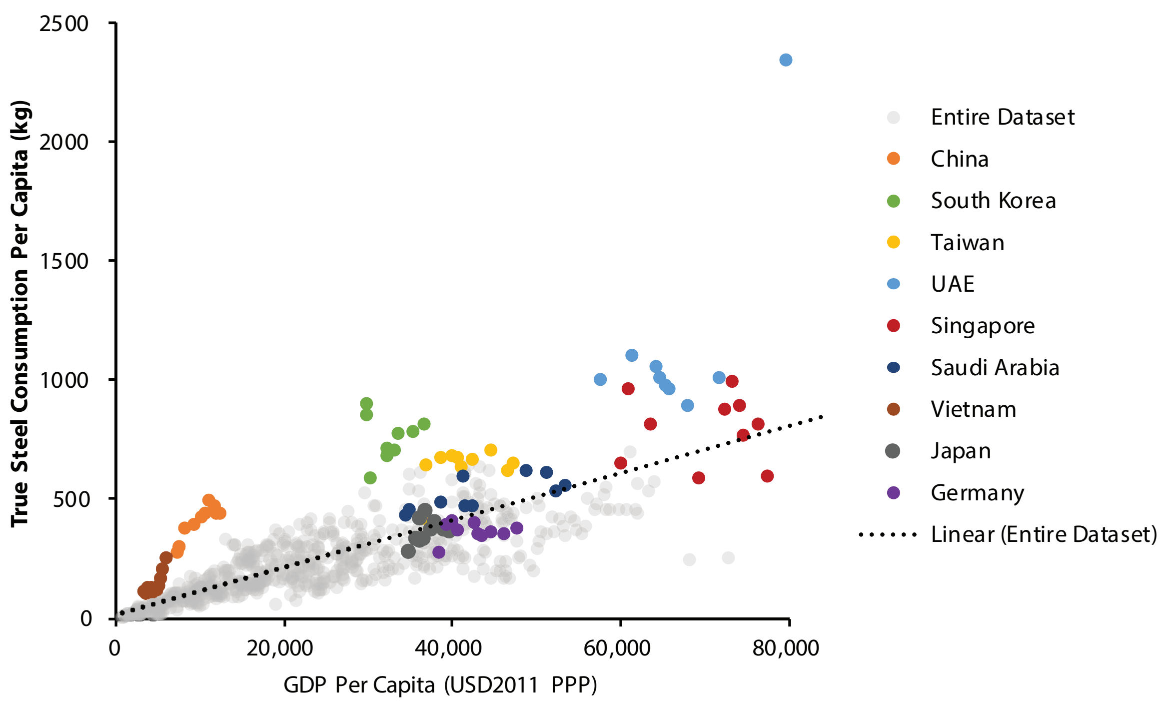


Figure 41: True steel consumption per capita versus GDP per capita

Source: TERI analysis based on the data from Penn World Table 9.1(2019) and World Steel Association (2018) large investments in steel intensive productive capacity. The second group is Middle-Eastern fossil fuel exporters, going through extremely steel intensive processes of urbanization as well as maintaining high levels of steel-intensive investment in oil and gas production capacity (UAE, Saudi Arabia). The final group is rich, essentially entirely urbanized, densely populated city-states (Singapore), whose steel intensity is driven by the steel intensity of high-rise urbanization.

It can be questioned whether China fits into any of these groups. As a continental scale economy, it is simply too large to maintain an export surplus of the scale of South Korea or Taiwan, although it will follow a similarly steel-intensive urbanization pattern. It is not an exceptionally urbanized, fossil-fuel exporting country and neither is it a city state. More appropriate benchmarks for China's equilibrium rate of true steel consumption per capita may be provided by similarly large, industrialized countries such as Germany or Japan. On the face of this evidence then, it appears that China would be already close to or indeed above its long-term equilibrium rate of true steel consumption. A rate of 500 kg of steel consumption and a population of 1.3 billion would suggest a total true steel consumption of 650 Mt, compared to an installed productive capacity in excess of 1000 Mt.

6.3.1.3 Is China's Investment Rate Sustainable?

True steel consumption is a measure of an annual flow. However, by virtue of its durability, steel is not really a consumption good but a capital good. Economies do not need an annual flow of roads and bridges, nor do households need an annual consumption of cars embedding large quantities of steel. Rather what matters is the total stock of steel in the national economy. As a country develops, this stock will be built up with large annual flows of net additions to the stock of steel. Once the total stock of steel reaches saturation levels, the annual flows of steel consumption will only be necessary to account for depreciation in the stock of steel. Saturation is generally reached at a level of about 8–16 tonnes per capita, depending on the nature of the national economy (Bleischwitz, Nechifora, Winning, *et al.* 2018).

If China's annual additions to its steel stock have been exceptionally large in recent years, then it follows that the saturation level in the steel stock would be reached concomitantly earlier (even accounting for more rapid depreciation due to a lower stock lifetime in China, for which there is some evidence). China, currently at about 7 tonnes per capita, and at 500 kg additions per year, would reach historical saturation levels by 2030–35.

Connected to this is the debate among policy makers and analysts regarding the sustainability of China's investment rate. This is connected to the discussion around the future trajectory of China's steel consumption because so much of domestic steel consumption is driven by investments in infrastructure and real estate. The debate essentially focuses on the scale and rate of build-up of leverage that has been used to fund infrastructure investment. China's total debt to GDP ratio is 259% as of Q1 2019, and has increased from 145% in Q1 2008 (Bank for International Settlements 2019). This is one of the fastest debt expansions in the history of economic development. The concern is that the returns to this investment, because it is oversupplied, will be insufficient to fund debt repayments.

Whilst this report will not provide further analysis on this issue [the annual Article IV reports of the IMF provide a running commentary (IMF 2019)], it is sufficient to say that historical experience would strongly suggest that China's investment share in GDP cannot stay at such a high level over a sustained period. We can see this when looking at the trajectory followed by its East Asian peers over the course of their economic development. Figure 42 plots the investment share in GDP versus GDP per capita for China, South Korea, Japan, and Taiwan (left panel). It also shows the same data but with GDP per capita removed from the x-axis and replaced with time (i.e., years), to provide a sense of when the various changes occurred (right panel). As we can see, China's investment rate is completely unprecedented, having been attained only once by South Korea, and that only for a brief period of time and followed by a sharp contraction. Moreover, all three countries that have preceded China

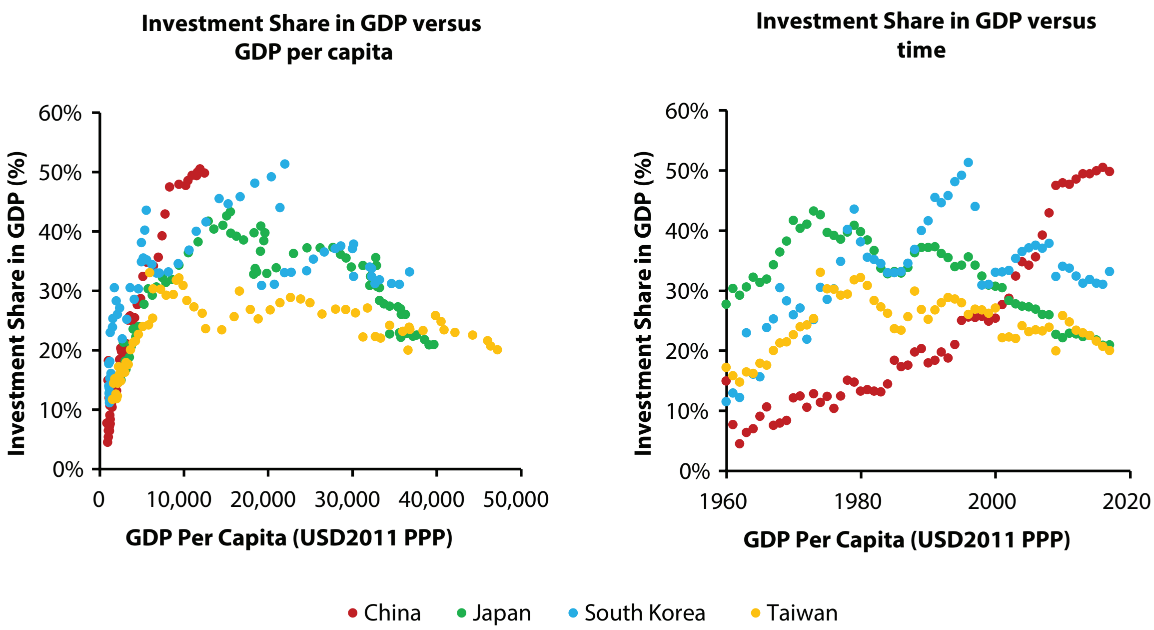


Figure 42: Investment rate in East Asian economies

Source: TERI analysis based on the data from Penn World Table 9.1 (2019)

on the path of industrialization have experienced sharp contractions in their investment rates, particular around economic shocks (oil shocks, Japanese real-estate bubble, Asian financial crisis, Global Financial Crisis). Lastly, currently China is at a level of GDP per capita at which all three predecessors started to see an inflection point and then secular decline in the rate of investment in GDP.

6.3.1.4 Has Over Capacity Been Addressed?

According to the latest monitoring report from the OECD Steel Committee, recent substantial efforts by China and other major steel producers have quite significantly affected the global production capacity/consumption gap, which stood at 425 Mt in 2018, down from a peak of about 700 Mt in 2015 (OECD 2019b). Part of this has come from significant gross capacity closures in China, amounting to about 286 Mt of production capacity in the years 2016, 2017, and 2018 (OECD 2019b). This led to a net decline in Chinese production capacity of less than 150 Mt, implying a large amount of gross capacity additions. The result is that Chinese production capacity is 1023 Mt as of 2018, 23% above Chinese production levels, and 65% above Chinese true steel consumption levels (OECD 2019b; WSA 2018c). China still has plans for further gross additions, with about 34 Mt of new capacity underway, and a further 10 Mt recently commissioned or in planning (OECD 2019b).

It is also worth noting that recent progress in closing the global (and Chinese) production–consumption gap has also been due to the increase in global production. Much of the increase in global production has been from China, whose steel production grew strongly in 2018 (and 2019), on the back of efforts to stimulate the Chinese economy. In 2018 and the first ten months of 2019, Chinese steel production grew at its fastest level since the massive stimulus of 2009–10 in the wake of the financial crisis. Thus, it seems that progress in closing the – still large – production versus consumption gap at the global level has been due to substantial net declines in Chinese steel production capacity, as well as an increase in Chinese steel production at a rate of about 10% year-on-year in 2018 and 2019. Given that Chinese manufacturing trade has been declining as a result of the ongoing US–China trade war, the increase in Chinese steel production is likely driven largely by growth in domestic consumption, which is already very high. As discussed above, there are concerns to what extent this investment-based model is sustainable.

6.4 Summary of Trade and Competitiveness

This chapter has examined the trade and competitiveness aspects of the Indian iron and steel sector, in particular as it relates to the prospects for driving a transition to a lower carbon model. Several conclusions emerge from the analysis. First, several aspects of the iron and steel sector make fashioning policies to promote decarbonization more challenging. It is a relatively trade-intensive and energy-intensive sector, implying that climate policy-driven increases in energy costs may impact on the international competitiveness of the sector. Moreover, the Indian iron and steel sector has not been experiencing particularly positive financial conditions for the last six to seven years. Profit margins are low, and the interest coverage ratio and investment rate are declining. While the steel sector's transition is a long-term endeavour, and these are short-term, cyclical indicators, the current poor financial situation raises an important longer term issue. In a cyclical, narrow margin, commodified sector, raising sufficient capital for large investments in new, risky, innovative technology may be a challenge.

Second, the analysis shows that India has a structural trade deficit in the iron and steel sector. Much of this is from the import of scrap, which compensates for India's domestic disadvantages in coking coal, iron ore, and scrap generation. However, India also has a large deficit in certain higher technology subsectors related to high-technology stainless and alloy steel. This deficit is largely due to the other world-leading manufacturers in other countries capturing the entire market for certain niche products, which it would not make economic sense for India to manufacture at a small scale. Net imports of these products come essentially from the three large industrialized East Asian countries: South Korea, Japan, and China. The question of how to raise the competitiveness of Indian steel in high-technology stainless or alloy products is, therefore, an important issue for consideration.

Finally, the global glut in steel production capacities was particularly acute in 2015–16, and had a pretty clear impact on Indian imports, particularly from China, and profit margins in the Indian iron and steel sector. Since then, substantial progress has been made to address the global production–consumption gap, which has reduced by about 30%. This has been due to large net capacity closures in China, as well as a more positive economic conjuncture in 2017 and 2018, partly due to efforts to reflate the Chinese economy with further infrastructure-led stimulus. Available evidence suggests that Chinese steel production has continued to grow strongly in 2019. However, in the mid-term China's investment and debt-led economic model is not sustainable. It seems, therefore, probable that the situation that has characterized the global steel market for the last few years continues into the foreseeable future, with a still substantial production capacity surplus and (the risk of) large export flows from major steel producers. In this context, mustering the vision, capital and risk appetite for new decarbonization technologies will be a challenge.

7
POTENTIAL FOR NEW TECHNOLOGIES

Potential for New Technologies

The previous sections have shown how even with the introduction of best available energy- efficiency technologies and ambitious resource efficiency measures, emissions in the Indian steel sector are set to grow significantly out to 2050. Moreover, the current trade and competitiveness context make investing in new, risky technologies a challenging proposition for the Indian iron and steel sector. It is, therefore, necessary to think carefully about a future transition for this sector, to ensure that India is able to maximize growth and development within the constraints of the environment.

As a result, this section will first cover the suitability of other fossil fuels for use in the iron and steel industry. These may be able to reduce emissions in the near-term, when compared with the BF-BOF and coal-based direct reduction routes, should they be cost-competitive and available. The two main fuels which will be assessed here are natural gas and SynGas from coal gasification.

Ultimately, these fossil fuels will need to be replaced by deep decarbonization technologies in the future. Section 7.2 covers a range of emerging technologies which could help India achieve deep decarbonization in the steel sector. It is also the case that these technologies can yield other significant benefits for the Indian economy, including increased energy security, promoting domestic industries and mitigating local environmental degradation.

7.1 Transition Technologies

7.1.1 Natural Gas

India has limited natural gas supplies and imports are prohibitively expensive for most sectors. In 2018–19, natural gas consumption in India was 148 MMSCMD, with just under 50% being imported (MoPNG 2019). Natural gas consumption from domestic sources is controlled by the Central Government, being designated for use in certain priority industries, including transport, fertilizers, and domestic cooking gas supply (or City Gas Distribution). Imported gas is currently very expensive at around $12/mmbtu, making coal-based DR far more competitive, despite the environmental issues associated with this route.

In our current baseline scenario, we do not assume any significant role for gas-based direct reduction as a result of these supply and price constraints. Nevertheless, it is worth testing a scenario where natural gas became more readily available at a cheaper price. With growing supplies of LNG from the US, Australia and Qatar, there is the potential that more natural gas could be made available for the steel industry in the future.

Figure 43 shows the current price premium that would be paid by gas-based direct reduction facilities in India, assuming a delivered natural gas price of $12/mmbtu. Based on these calculations, a tonne of crude steel would be around 10% more expensive than steel from the BF-BOF or coal-based DR-EAF route. Whilst this does not appear significant, the narrow profit margins in the steel industry (see Section 6.1) mean that any additional costs are avoided by plant operators. Note that these represent rough costs for a 'typical' plant and might vary substantially from costs of individual plants.

To understand how low natural gas prices would need to be to be competitive in India, we can compare costs of a tonne of crude steel from a BF-BOF plant with a gas-based DR-EAF plant, across a series of natural gas prices. As shown in Figure 44, the breakeven point where the costs of steel from these plants start to converge is when natural gas is between $6–8/mmbtu. This represents around a 40% fall in costs from today's imported price.

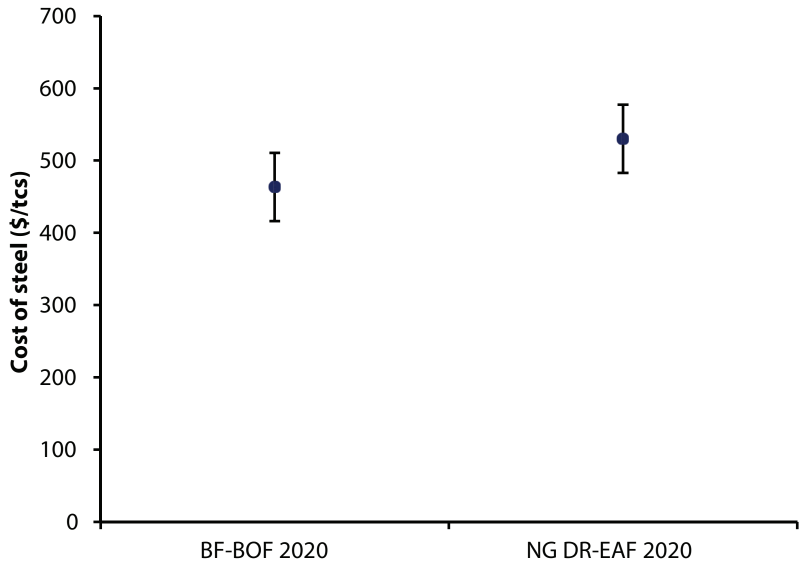


Figure 43: Costs of steel production from greenfield BF-BOF versus greenfield natural gas DR

Source: TERI analysis. Capital costs have been taken from a range of sector experts. Variable costs have been taken from CRISIL (2018); Spencer, Pachouri, Renjith, & Vohra (2018). Financing costs of 12% and loan repayment period of 20 years.

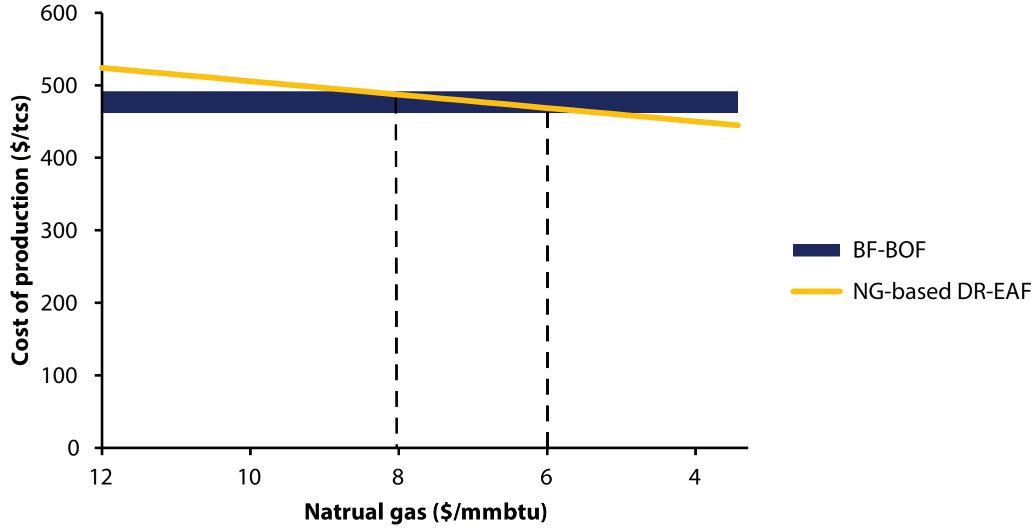


Figure 44: Costs of steel production from greenfield BF-BOF and gas-based DR-EAF plants at different natural gas prices

Source: TERI analysis. Capital costs have been taken from a range of sector experts. Variable costs have been taken from CRISIL (2018); Spencer, Pachouri, Renjith, & Vohra (2018). Financing costs of 12% and loan repayment period of 20 years.

Even if cheap shale gas was imported from the US (approx. $2.5/mmbtu), the costs of freight, regasification, taxes, and domestic transportation would result in prices of $10+/mmbtu. The only potentially cost-competitive source would be trans-boundary gas pipeline imports through the IPI or TAPI pipeline projects. These would take gas from Iran and Turkmenistan to India through Pakistan. However, these are unlikely to provide a supply in the near-term due to geopolitical tensions in the region.

Nevertheless, if we assume sufficient natural gas at a low enough price becomes available over the next decade to phase out current coal-based DR facilities, what is the impact on emissions?

In this analysis, we assume that coal-based DR facilities will be phased out by 2040, as more natural gas becomes available in India. The BF-BOF route still dominates over the time period, with the same production share assumed as in Figure 23. Natural gas-based DR can produce significantly lower emissions per tonne of crude steel versus the BF-BOF and coal-based DR routes. We assume emissions per tonne of crude steel fall from 1.1 tCO_2/tcs to 0.7 tCO_2/tcs by 2050 for the gas-based route. On a plant basis, assuming best available technologies have been deployed, this represents a 55% and 65% saving on emissions when compared with BF-BOF and DR-EAF/IF, respectively.

Figure 45 shows the emissions impact of switching from coal to natural gas in India's direct reduction facilities, compared with our *Baseline* (without significant energy efficiency measures), with our *BAT* scenario (with significant energy efficiency measures), and with *Resource efficiency* scenario (with resource efficiency measures adopted). We can see that the natural gas switch can deliver significant emissions savings, over 20% compared with the *Resource efficiency* scenario, leading to a total emissions saving of up to 50% when compared with our *Baseline*. Despite this significant reduction, further emissions savings beyond this will be limited given the still high carbon intensity of natural gas. Furthermore, there are significant emissions associated with upstream gas production and transportation, in terms of methane leakage.

There has been much discussion in the Indian steel industry around the use of natural gas. This analysis shows that prices need to be significantly lower and these are unlikely given the existing supply options. Moreover, even with a switch to natural gas, emissions are still significant and unable to reduce further beyond 2050. If natural gas does become available at a sufficiently low price, it could only ever be used as a transition fuel to a lower emission steelmaking route, many of which are discussed in the next section.

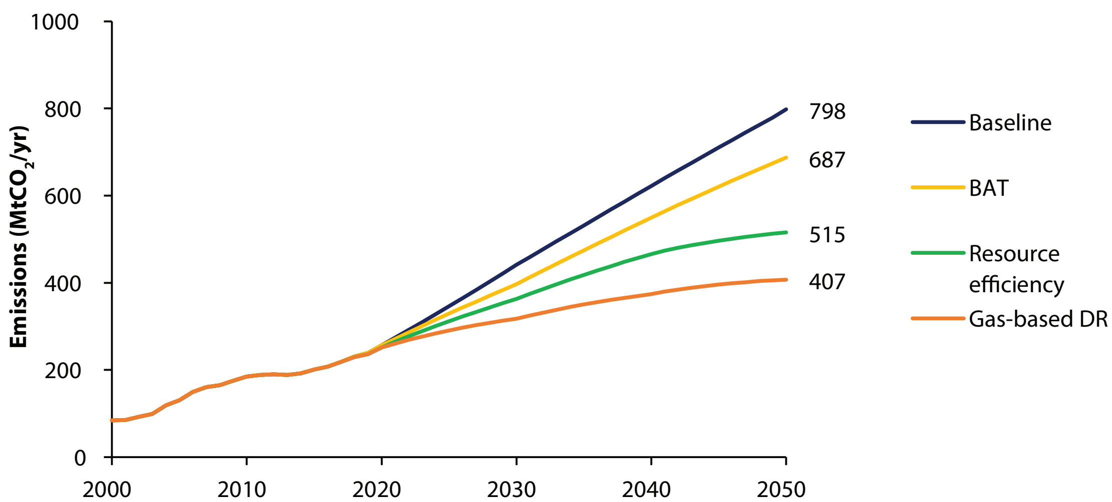


Figure 45: Emissions impact of coal to gas switch in DR facilities, 2000–50

Source: TERI analysis

7.1.2 Coal Gasification

Given the cost and availability issues with natural gas, there is an opportunity to use cheap domestic coal reserves to produce SynGas through coal gasification. As with natural gas, this could then be used in the direct reduction process to produce DRI. The Jindal Steel and Power Limited (JSPL) plant at Angul in Odisha was using this technology and was closed for sometime due to a low availability of coal after the Supreme Court revoked its coal mining licence. The plant has resumed its operation in 2020.

Further work is needed to understand the costs, raw material, energy and emission impacts of a coal gasification pathway, and how this could be used as a transition technology.

7.2 Deep Decarbonization Options

There has been substantial activity in the global steel industry to develop new technologies which can provide significant emissions savings (>80%) versus the incumbent technologies. Large R&D programmes, most notably in Europe, the US, and Japan have delivered a number of technologies which have the potential to be introduced into the Indian steel sector. Broadly, these can be split into three categories: **hydrogen**, **electrification**, and **carbon**-based routes, which cover CCUS and biomass. Analysis at the global level, under the ETC's Mission Possible work, has provided a good framework for assessing the different options, including what will be the key drivers in the trade-off of different technologies. This includes the price of electricity, the availability of CO_2 storage and the nature of the plant (brownfield or greenfield) (ETC 2018).

Figure 46 provides an overview of the large number of technologies being developed under various R&D programmes (full list with description can be found in Annex D: Emissions reduction technologies). This section will explore the applicability of these different routes to the Indian context.

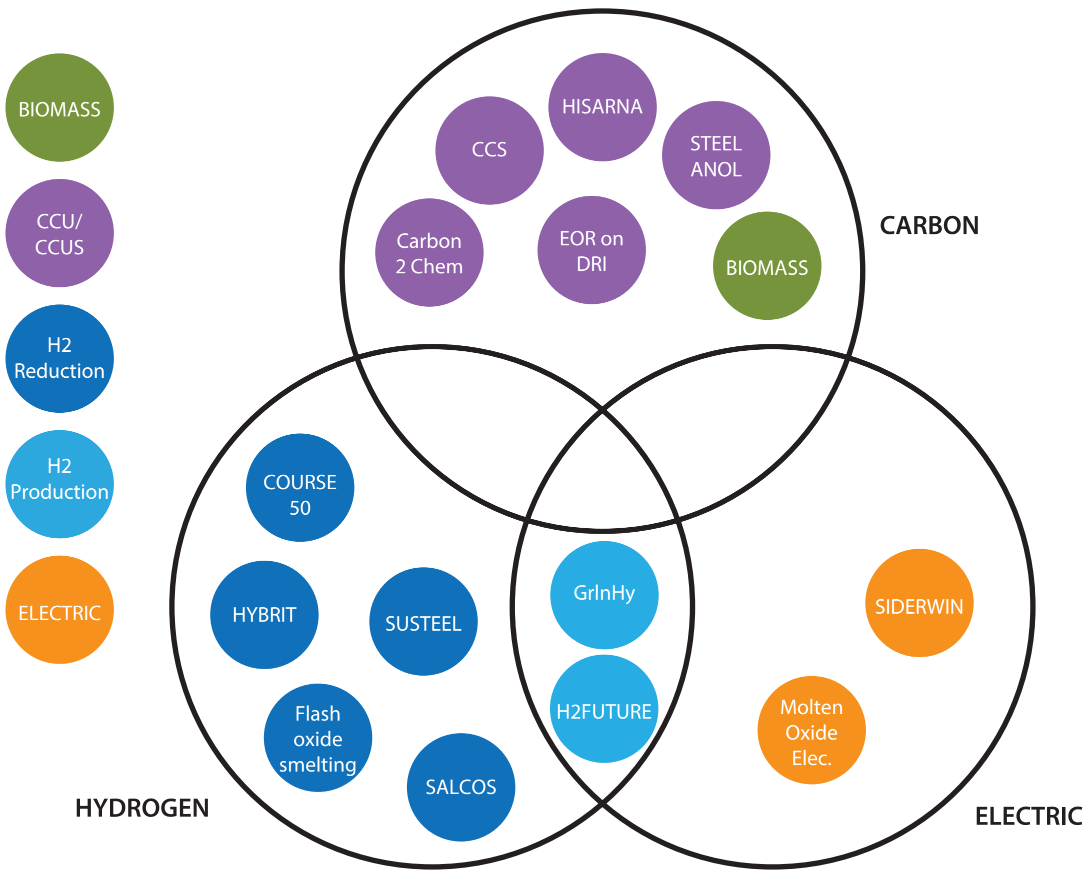


Figure 46: Overview of decarbonization technology projects for the iron and steel sector

Source: Adapted from WSA (2019b)

7.2.1 Carbon-based Routes

Most of the technologies within the carbon-based decarbonization route are based on some form of carbon capture, use and storage (CCUS) technology. CCUS technology is relatively underdeveloped in India, with only a few, small-scale projects currently underway (Gupta and Paul 2019).

Box 1: ONGC and Indian Oil CCUS pilot plant

ONGC plans to establish a pilot plant in Gujarat which would capture CO_2 from IOCL's Koyali Refinery.[10] This would then be injected into a depleted onshore crude oil reservoir at the Gandhar field, forcing more oil out of the well, in a process known as Enhanced Oil Recovery (EOR). Whilst not immediately beneficial in driving down emissions, CCUS for the purpose of EOR can help build the capability and technical know-how to develop a CCS industry for future emissions reduction.

To move forward with CCUS in India, a nationwide assessment of potential storage locations would be required, ideally undertaken by the Geological Survey of India (GSI), before its potential can be understood. Such a study would provide an understanding of the total potential and the relative costs of developing those storage resources. This is vital to understand the costs of CCUS networks, which are impacted by the length of pipelines and the number of point sources and storage locations.

Nevertheless, research studies across Europe and the US have identified that CCUS has significant potential to mitigate emissions from the iron and steel sector, should carbon storage be located nearby. A leading technology is the use of the HIsarna process, along with CO_2 capture.

The HIsarna process can reduce emissions by 20% by replacing the current sintering and pelletization processes with the powder injection of raw materials into the blast furnace (Tata Steel 2017). This allows them to be directly

[10] Details available at https://www.ongcindia.com/wps/wcm/connect/en/media/press-release/ongc-join-hands-oil-recovery

converted into liquid iron. One benefit of this process is the production of a very pure stream of CO_2, which can be captured relatively cost-effectively. Capturing CO_2 from the blast furnace in this way could reduce emissions by around 80%, when compared with a regular BF-BOF route. To reduce emissions further would require the use of biomass in the blast furnace, or higher rates of carbon capture, which is less cost-effective.

Another option within the carbon-based routes is the use of biomass. Biomass can be used in solid, gaseous, or liquid forms across the steelmaking process. Upgrading raw biomass is required before using in each process. Usually, more upgrading steps will require high operational and capital expenditures, which in turn lead to high production cost.

In addition, extra costs from harvesting, material handling, transportation, and drying mean that biomass products struggle to be economically competitive with fossil fuels like coal. For example, the current cost of coking coal is $175–200/tonnes, whereas charcoal of sufficient quality is around $225–250/tonnes, suggesting a cost premium of around 20% (Suopajarvi, Kemppainen, Haapakangas, *et al.* 2017).

The main challenge with using biomass in steelmaking in India is its availability. There is already significant competition for agricultural land for food production and climate change and population growth is set to make such land scarcer through desertification and urbanization (IPCC 2018). Moreover, there are other 'hard-to-abate' sectors which have identified biomass as one of the most cost-effective routes for emissions reduction, including aviation and feedstocks for chemicals (ETC 2018). This will further limit the availability for its use in the steel sector and likely cause increases in price.

Nevertheless, there is potential to use existing agricultural residues, without creating greater competition for agricultural land. It is estimated that there is around 234 Mt of surplus biomass available in India, equivalent to around 4.15 EJ, or 15% of India's final energy consumption (Hiloidhari, Das, and Baruah 2014). The option of using agricultural residues should be explored further, to better understand potential costs, lifecycle emissions, and availability for the steel sector, in the context of competing, cross-economy demands.

7.2.2 Hydrogen

Another option that has received growing interest is the use of low carbon hydrogen in the steelmaking process, which would replace the consumption of coal or natural gas. The natural gas-based direct reduction route currently makes up around 6% of global steel production (Midrex 2019). Whilst use of hydrogen at high quantities in the steelmaking process is relatively novel, the use of different blends of different gases, from natural gas to various SynGases, is well understood. As a result, the technology for **hydrogen-based direct reduction** of iron does not represent such a significant step for the industry. Three technology providers for gas-based direction are detailed below: Midrex, Tennova HYL, and Circored.

The Midrex Process, which is the dominant process for natural gas-based steelmaking, is already operating with hydrogen concentrations of 55–75%. This could be increased to 90% based on technology currently being developed. The balance would be made up of CO, CO_2, H_2O, and CH_4, to reduce the melting point, provide additional energy, and provide the alloying element required for steel (Midrex 2018).

ArcelorMittal in Germany plans to construct a further 0.1 Mt Midrex plant at its Hamburg site, which will be fed with the remaining hydrogen from the exhaust gas of the existing natural gas-based Midrex plant that has a capacity of 0.5 Mt. The use of hydrogen from the exhaust gas of the existing Midrex plant in this way means that production is already cost-effective today (ArcelorMittal 2019).

The HYL process is the second commercially available direct production process that has a significant share in today's gas-based DRI production. Since it does not require a gas reformer that splits the gas used into its components, it can use different gases almost simultaneously. Both the Swedish HYBRIT project and the German SALCOS project have opted for the HYL process (Tenova HYL 2018).

The HBIS group of china with Tenova has signed contract to implement Paradigm Project, a High-Tech Hydrogen Energy Development and Utilization Plant. This will be the world's first DRI production plant powered by hydrogen enriched gas. The project includes a 600,000 KTPY ENERGIRON DRI plant. This plant will use make-up gas with approximately a 70% hydrogen concentration. Due to the high amount of H_2, the HBIS plant will be the greenest DRI plant in the world by producing only 250 kg of CO_2/t-DRI. The carbon dioxide will be selectively recovered and part of it will be reutilized in downstream processes, with a final net emission of just about 125kg of CO_2/ton. Plant is expected to begin production by the end of 2021.

A third available technology, which is not in use today, is the Circored process. It is a fluidized bed reactor that uses hydrogen to produce direct reduced iron. The hydrogen can be supplied from natural gas or other sources such as water electrolysis (Outotec 2019). A plant with a capacity of 0.5 Mt of DRI was operated in Trinidad from 1999 (Millenium Steel 2006).

Pilot plants are already being established in Europe to use hydrogen in the direct reduction process, similar to existing natural gas-based direct reduction processes, which are far more common in steel industries outside of India. The HYBRIT project in Sweden aims to have a demonstration plant up and running by 2025, a full-scale plant operating in 2035, with the intention to have switched over their entire fleet by 2045 (SSAB 2019). If supplied with zero-carbon hydrogen and combined with an electric arc furnace supplied with zero-carbon electricity, this has the potential to reduce emissions by over 94% compared with conventional technologies. Residual emissions occur from the use of graphite electrodes in the EAF, as well as use of lime and natural gas. These could be brought down to zero with further research and development (Vogl and Ahman 2019).

Another option, instead of a one-time switch from natural gas or coal to hydrogen, is to start using fossil-based gas, such as natural gas or SynGas and slowly blend in higher degrees of hydrogen, to steadily decarbonize the direct reduction process. This is the approach being trialled by Salzgitter in their plant in Austria, where under the SALCOS project, they plan to use electrolytic hydrogen from wind energy to decarbonize steel production (Salzgitter 2019).

The capital costs for this route are not expected to be significantly different from existing capital costs for natural gas-based direct reduction plants and will likely reach parity after several plants are established (Vogl and Ahman 2019). The main cost element in this production route is hydrogen, which needs to be produced from low carbon electricity or use CCUS technology to be low carbon. Box 2 covers the different production routes, assessing which might be more suited to India. An assessment of the costs and their impact on steelmaking is covered in section 7.2.2.2.

Another way of using hydrogen in the steelmaking process is to produce **hydrogen plasma**, which can be used in the smelting reduction process. The Austrian steelmaker, Voestalpine are moving ahead with a trial of this technology, scaling up from 100 g to 50 kg of production under the H2FUTURE project (Sormann, Seftejani, Spreitzer, *et al.* 2018). The Indian Institute of Minerals and Materials Technology (IMMT) has also trialled this technology during their previous round of research (2010–15), at a 5–10 kg scale (IMMT, 2019). To achieve the next scale of trials (~100 kg) would reportedly require around ₹50Cr, or $7m.

Box 2: Hydrogen production technologies

One of the major challenges with using hydrogen to reduce emissions from the steel sector is producing sufficient quantities at low enough cost. Table 11 provides an overview of our assessment of the suitability of hydrogen production technologies for future, large-scale use in India. Green represents a positive score, amber is mixed, and red is negative. Technology readiness is also given a numerical value based on Technology Readiness Levels, which go from 1 (basic principles) to 9 (extensive implementation).

Table 11: Suitability of hydrogen production technologies for India in the medium term

Technology	Resource availability	Scalable	Cost	Tech readiness	Emissions	Overall suitability
Steam methane reformation				TRL 9		
Steam methane reformation+CCS				TRL 5		
Coal gasification				TRL 9		
Coal gasification +CCS				TRL 5		
Electrolysis				TRL 9		

Source: TERI analysis

Today, around the world, most hydrogen is produced through **steam methane reformation** (SMR) (IEA 2019c). In India, the fertilizer industry is a major consumer of hydrogen through this route, using hydrogen to create ammonia-based fertilizers. To reduce emissions from this production route would require CCS technology, which has its challenges in India, as discussed in the previous section. Moreover, this production requires large quantities of natural gas to be used in the reformation process. Given the existing challenges of using natural gas for direct reduction in India, primarily cost and availability (see Section 7.1.1), using natural gas through reformation would only add to these challenges as a result of the efficiency penalty of the process, which is around 70% (BEIS 2018). Therefore, the overall suitability of SMR for future, large-scale hydrogen production, with or without CCS, is limited.

Another fossil fuel-based route for hydrogen production is **coal gasification**. Coal gasification has received growing interest in China and India alike as a way to mitigate energy import shocks and make best use of domestic energy reserves. In their 14th Five-Year Plan, China is expected to target a significant ramp-up of coal to gas technologies, to be used throughout industry (China Energy Portal 2019). Recent supply-side oil shocks in India have also motivated greater interest in coal to gas, which India is particularly exposed to (Business Standard 2019). Since these events, the Government of India has announced its interest in coal gasification, likely outputting various synthetic gases (SynGas) for use in the industry, transport, and residential sectors (India Today 2019).

The low cost and sufficient availability of coal in India make this a potentially cost-effective route for hydrogen (or SynGas) production. It will nonetheless be relatively capital intensive requiring additional infrastructure for the transport and storage of coal, including railways. Moreover, the process would be highly emissions intensive without CCS. The efficiency penalty in the coal gasification process for hydrogen production is typically around 75%, resulting in emissions intensity of 500–600 gCO_2/ kWh (IEA 2019c). Again, the same issues with deploying CCS in India apply here.

Box 2: Contd...

Given India's significant potential for renewable electricity generation, through both wind and solar, **electrolysis** appears to be a promising route for hydrogen production. The electrolysis process applies an electrical charge to H_2O, splitting it into its constituent parts H_2 and O_2. It is a relatively electricity-intensive process, consuming around 1.5 kWh of electricity for every 1 kWh of hydrogen, although this is set to fall to around 1.3 kWh with further technology improvements (BEIS 2018; IEA 2019c). As a result, to produce hydrogen from electrolysis at scale will require significant expansions in renewable capacities, over and above what is already planned by the GoI.

Apart from being electricity-intensive, the electrolysis process is also very water-intensive, requiring large quantities of freshwater to avoid contaminating the catalyst. India is a water-scarce country and, therefore, facilities running electrolysers would need to maximize water recycling where possible. Furthermore, there is work being planned to assess the viability of direct seawater electrolysis, to help mitigate the impact on freshwater supplies (MNRE 2019).

The cost of electrolytic hydrogen remains a barrier, particularly when factoring in the requirement of renewable electricity to ensure hydrogen is low carbon. Currently, the high capital costs of electrolysers mean that they need to be run at high capacity utilization factors (CUF) to be cost-effective. This requires grid electricity, which is currently very carbon intensive. Nevertheless, as the emissions of grid electricity declines, this will ensure that hydrogen can be lower carbon (see Figure 47). Moreover, as the capital cost of electrolysers decline, which is expected with the future scale of deployment, the utilization factor plays a less significant role (see Figure 52).

TERI analysis suggests that by 2030, the costs of green hydrogen will fall below \$2/kg vis-a-vis \$4–6/kg at present, and will start to compete with hydrogen produced from fossil fuels (Hall, Spencer, Renjith, *et al*. 2020). Improving efficiencies of electrolysers, increasing load factors of solar plants will play an important role in driving down the costs of green hydrogen.

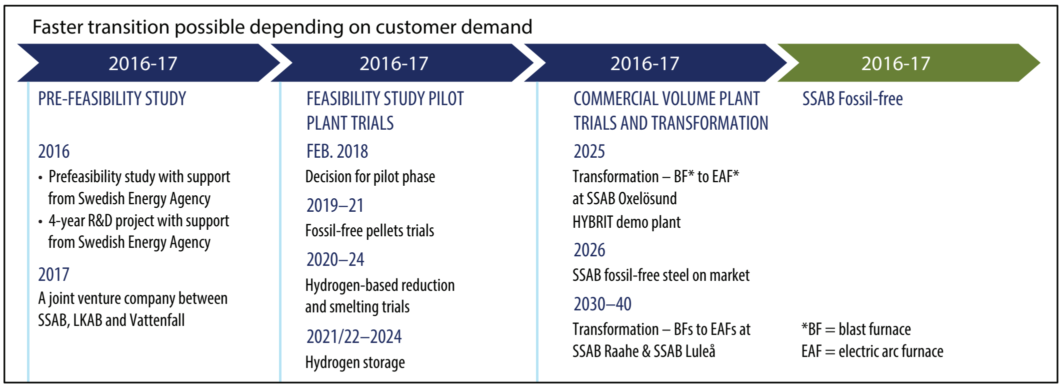
The costs of grey hydrogen produced through the methane reformation route can be achieved at around \$1.5/kg and \$2.5/kg (depending on the price of the natural gas) and could be approximately \$2-4/kg (depending on the cost of coal and the production route) for the coal gasification route, at present (Hall, Spencer, Renjith, *et al*. 2020). This is significantly higher than the costs of producing low carbon hydrogen, either green or blue.

Box 3: HYBRIT

HYBRIT (Hydrogen Breakthrough Ironmaking Technology) is a joint venture between Swedish companies, SSAB (global leader in high-strength steels), LKAB (Europe's largest iron ore producer) and Vattenfall (one of Europe's largest electricity producers), that aims to replace coal with hydrogen in steelmaking process. In this process, iron metal is produced by using hydrogen gas as the main reductant. The production route is similar to existing DR processes, except for CO_2 emissions. Hydrogen reacts with iron oxides to form water instead of carbon dioxide. In the demonstration project in Sweden, hydrogen will be produced by electrolysis of water using fossil-free electricity.

Investment: SEK 2 billion (~ US$200 Million)

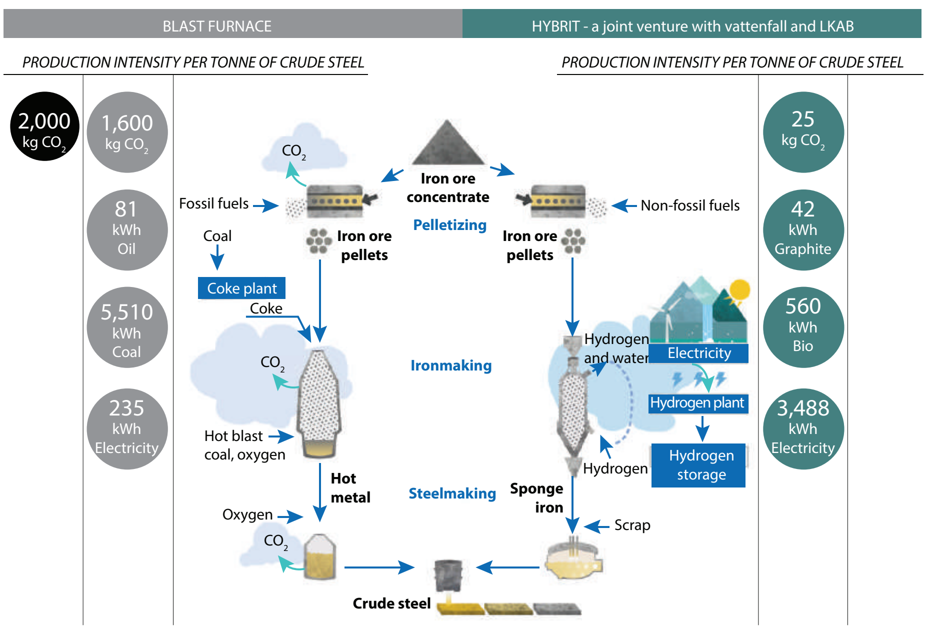
Project Phases:



Current Status:

The test production at the demonstration site in Gällivare, Sweden was completed on June 21, 2021 and around 100 tonnes of good quality DRI was produced successfully.

Traditional BF versus HYBRIT technology:



Source: SSAB (2020)

7.2.2.1 Direct Electrification

The most resource efficient way to decarbonize the iron and steel sector in the near-term is to increase the share of steel produced through an electric arc furnace. However, given EAFs can only produce finished steel from DRI and scrap, that is producing secondary steel, the main limiting factor in this route is the cost and availability of high quality scrap.[11] The rapid growth in India's demand for steel means that even with ambitious recycling policies, new primary steelmaking facilities will likely be required.

There are a couple of breakthrough technologies in the area of electricity-based reduction, which are currently at the research and development phase. In the US, Boston Metal has been awarded funding by the US Department of Energy and philanthropist, Bill Gates, to develop industrial-scale **Molten Oxide Electrolysis** (Boston Metal 2019). In Europe, the SIDERWIN project, a consortium led by ArcelorMittal with funding from the European Commission, is developing a similar technology, with additional objectives around broader electricity system integration (SIDERWIN 2018).

With the only fuel input being electricity, for electricity-based reduction to be low carbon, this will require large quantities of low carbon electricity. It is estimated that around 2.6–3.7 MWh of electricity will be required per tonne of crude steel, if used for both melting and reduction, or slightly less if only reduction (IES 2018). To illustrate the scale of electricity required, if MOE technology was to meet all of India's steel demand today (~100 Mt) it would require over 300 TWh of electricity or a quarter of India's current demand.

The electrolysis of iron ore is still at an early stage of development, in contrast to direct reduction technology, which could use hydrogen. Demonstration plants for iron electrolysis are not expected to be built before 2030, or even 2040. However, this technology uses electricity directly and could, therefore, be more energy efficient than hydrogen-based direct reduction because it does not suffer the efficiency penalty from hydrogen production. Whilst more efficient (approx. 30%), this method of hydrogen production would require approximately three times the amount of stable electricity supply versus H_2-DR, which has the potential to be more flexibly integrated into the grid (Fischedick, Marzinkowski, Winzer, *et al.* 2014).

7.2.3 Deep Decarbonization Pathway

Based on the assessment of emerging technologies in the previous section, as well as the other characteristics of the Indian steel sector, we have devised a deep decarbonization scenario. This is an illustrative scenario, showing the impact of a mix of technology solutions that we think could be well suited to the Indian context. Further analysis is required to understand the benefits of different technologies for different production routes and different plant locations.

In this scenario, we assume energy efficiency is maximized as far as possible, in line with the Best Available Technologies scenario, outlined in Section 5.2. Whilst some of these measures may be difficult to achieve, with longer payback periods, over the time 2020–50 timeframe, it will be more cost-effective and practically possible to install these measures as new plants are built.

We also assume a level of resource efficiency in line with the *Resource efficiency* scenario. This reduces steel demand by 25% versus the baseline by 2050. For a rapidly growing economy such as India, this is highly ambitious. Delivering more aggressive resource efficiency measures would require a more radical diversion from historical manufacturing and construction processes, which have not yet been observed at scale anywhere in the world.

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11 Electric Arc Furnaces can also be fed with DRI, thus producing primary steel. This concept has been described in the previous section on hydrogen.

With regards to scrap, the improved resource efficiency measures will ensure a high-level of domestic scrap availability, which will reduce the amount of primary steelmaking required. As in the *Baseline* scenario, we assume no import of scrap by 2030, which remains the case out to 2050. In a world striving to reduce emissions, mature economies will be eager to maximize use of their domestic scrap in EAFs, therefore reducing the amount available for growing economies such as India.

From 2030 onwards, we assume that new primary steelmaking facilities which would have otherwise been BF-BOF will be built with the HIsarna technology. This is reflective of the current capability around the BF-BOF route in the Indian steel sector, as well as the presence of Tata Steel, the owners of the technology. Shifting to the HIsarna process represents a slower shift to lower carbon technologies but is more likely in the 2030s versus direct electrification or hydrogen direct reduction due to the high costs of electricity and hydrogen and lack of availability of these technologies at commercial scale. From 2040 onwards, we also assume these plants are fitted with CCS technology, resulting in an 80% reduction in CO_2 emissions (Tata Steel 2017). Whilst this is uncertain, this assumption is made is to illustrate the potential of these technologies in delivering emissions reduction in the Indian iron and steel sector.

By 2040, we also assume that hydrogen reaches low enough costs so that it is nearly cost-effective with incumbent technologies. All new primary steelmaking capacity will be built using hydrogen direct reduction technologies. We also assume some blending of hydrogen into existing blast furnaces, as has been trialled in Germany (Thyssenkrupp 2019), which would reduce emissions from existing blast furnace facilities by approximately 15%.

Table 12: Deep decarbonization scenario overview

Measure	2020s	2030s	2040s	2050s
BAT energy efficiency	■	■	■	■
Moderate ambition resource efficiency	■	■	■	■
Maximize domestic scrap	■	■	■	■
Adoption of HIsarna technology		■	■	■
Addition of CCUS to HIsarna plants		■	■	■
H_2 blend in old blast furnaces		■	■	■
H_2-DR for new primary capacity		■	■	■

The scenario we present here results in over 50% lower emissions in 2050 when compared with the baseline. This scenario illustrates the potential of combining energy efficiency, resource efficiency, and emerging decarbonization technologies to reduce emissions from iron and steelmaking.

Whilst certain technologies may appear more or less favourable in different regions, in reality, a decarbonization pathway is more likely to follow this more mixed approach, with certain producers choosing CCS or electrowinning or hydrogen-based direct reduction, based on local contexts, such as the availability of carbon storage and renewable electricity. ETC India will continue to work on detailed technology assessments to better understand how different decarbonization technologies might be suited to different regions and different producers.

7.2.2.1 Emissions

To understand the emissions implications in the decarbonization scenario, we start by layering on the energy efficiency and resource efficiency measures, as described in Section 5.2. We then assume a 20% reduction in emissions from the HIsarna technology versus the BF-BOF baseline. Beyond 2040, we assume a CCS network is started to be built, resulting in an 80% reduction in emissions from these facilities by 2050.

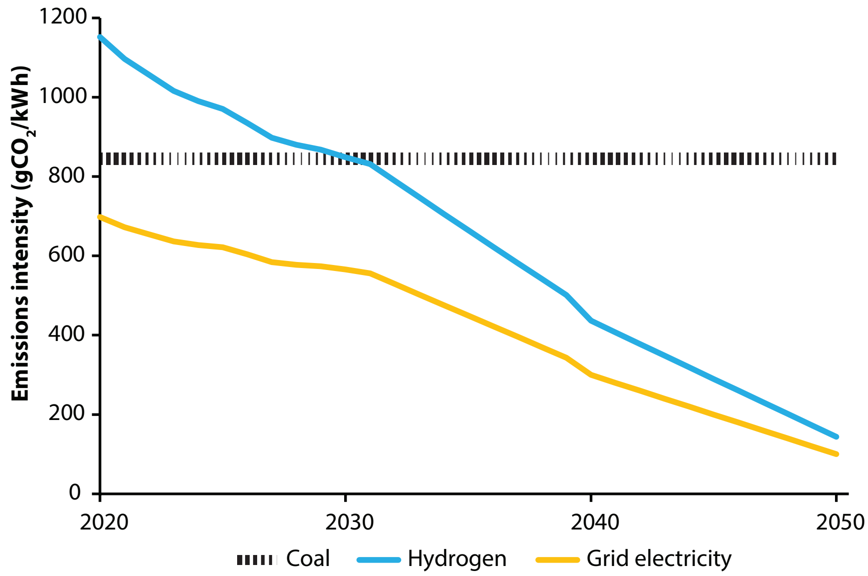


Figure 47: Emissions intensity of electricity and hydrogen, 2020–50

Source: TERI analysis

To estimate emission reduction potential from a switch to hydrogen-based primary steelmaking, we must first make assumptions around the source of electricity and its associated emissions intensity. For this analysis, we assume that 100% of the electricity comes from the grid. Whilst it might be possible to cost-effectively run an electrolyser, paired with renewables and batteries in the future, our analysis suggests that this might not be the case until around 2040. .

In Figure 47, we have plotted the decreasing emissions intensity of grid electricity from 2020 to 2050, when we assume it reaches 100 gCO_2/kWh. We can see from this chart that the emissions intensity of hydrogen remains above electricity over this time period, as a result of the efficiency loss in the electrolysis process, which requires approximately 1.5 kWh of electricity for every 1 kWh of hydrogen, falling to around 1.3 kWh by 2050 (BEIS 2018; IEA 2019c). It is also interesting to see how this compares with emissions from coal-based electricity generation. A typical thermal power plant only manages to use around 40–50% of the energy contained within coal when it is combusted for electricity generation, which results in an emissions intensity between 830 and 850 gCO_2/kWh.

Using hydrogen instead of coal in the steelmaking process tends to be more energy efficient, as with natural gas direct reduction. Therefore, whilst hydrogen will be more emissions intensive on a per unit basis versus coal today, in terms of emissions per tonne of crude steel, using hydrogen through direct reduction is less emissions intensive.

Figure 48 illustrates this relationship, showing that for the average coal-based DR plant and the average BF-BOF plant, switching to H_2-DR, using hydrogen produced from grid electricity would almost already result in a reduction in emissions. This crossover point occurs at around 650 gCO_2/kWh (the current grid emissions factor is around 700 gCO_2/kWh) (IEA 2019a). There are of course high performing facilities, with emissions around 2.1 tCO_2/tcs (including both energy-related and process emission), where the crossover point would be lower, closer to 500 gCO_2/kWh. The declining emissions intensity of the BF-BOF and DR-EAF routes are due to the assumptions made around the deployment of best available energy-efficiency technologies.

Nevertheless, by the point at which hydrogen-based direct reduction facilities could be deployed at scale, which we assume to be in the 2040s, emissions from grid electricity will be low enough to make the H_2-DR steelmaking substantially less emissions intensive.

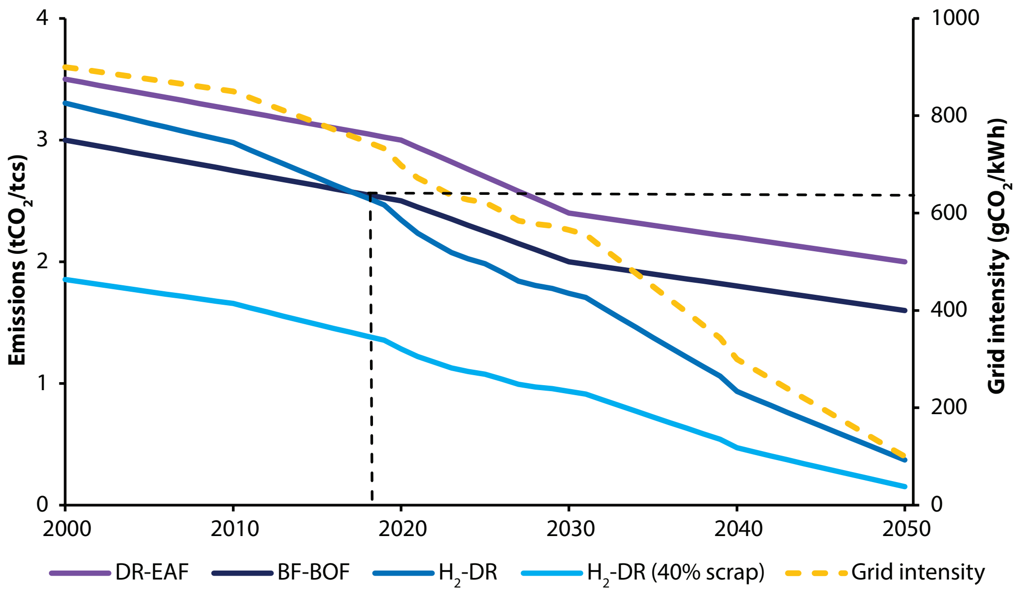


Figure 48: Emissions of different steelmaking routes

Source: TERI analysis. DR-EAF here refers to coal-based direct reduction

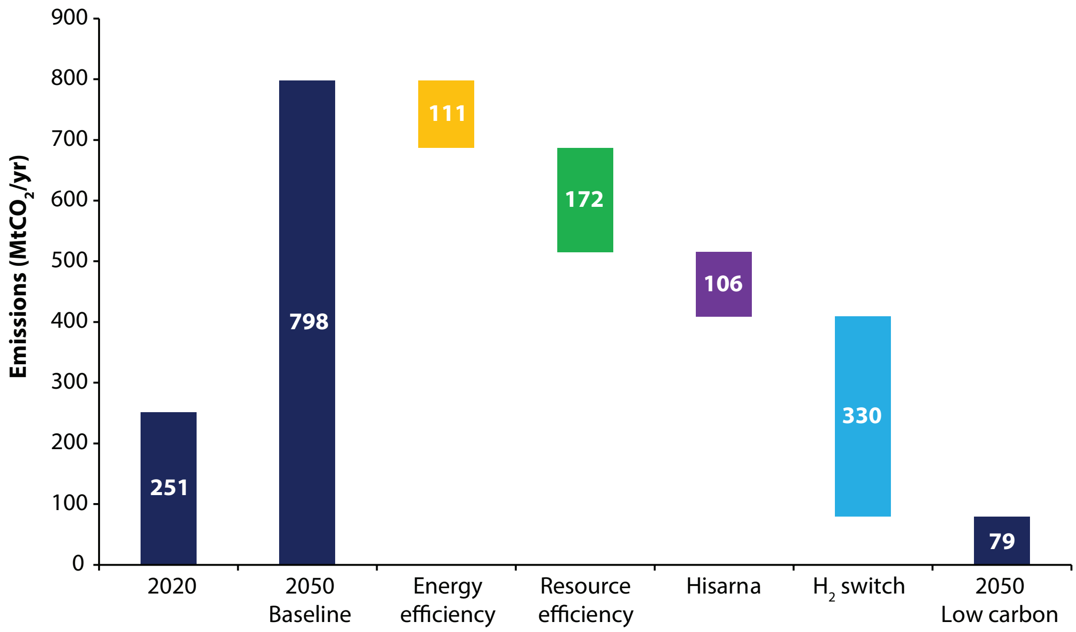


Figure 49: Emissions reduction potential for the Indian iron and steel sector

Source: TERI analysis

For the H_2-DR emission intensity, we are assuming a direct reduction facility feeding an EAF with 100% DRI. This is rarely the case in India, where the average split between DRI and scrap in the EAF is around 60/40. If we assume this split in a H_2-DR facility, emissions would be substantially lower and competitive with all incumbent technologies on an emissions-intensity basis at far higher grid intensities.

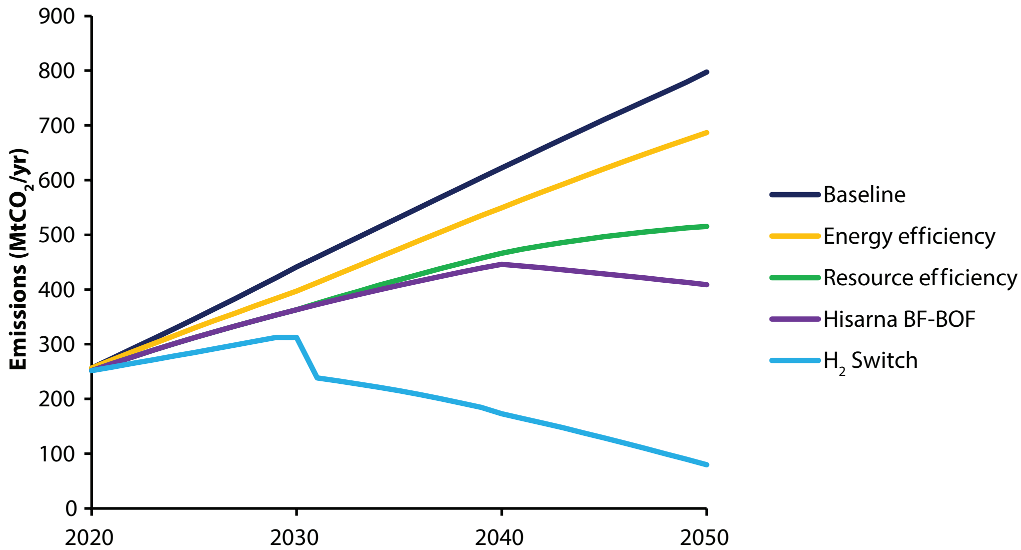


Figure 50: Deep decarbonization pathway for the iron and steel sector

Source: TERI analysis

In a scenario where we assume the deployment of HIsarna technology instead of the conventional blast furnace from 2030, all new primary steelmaking facilities switch to hydrogen direct reduction post-2040, along with the deployment of best available energy-efficiency technologies and advanced resource efficiency measures, emissions could be reduced by 50% versus the baseline. This represents a more than 60% decrease in the emissions intensity of steel production, which falls from around 2.5tCO_2/tcs today, to just below 1tCO_2/tcs by 2050.

Whilst this scenario represents a significant reduction in emissions, we believe that it is plausible for the Indian context. The majority of the emissions reductions are achieved through the deployment of cost-effective energy and resource efficiency measures that are available today, or in the near future. Some of these will take time to adopt as the stock of steelmaking facilities changes over time but will nonetheless be possible to implement before 2050.

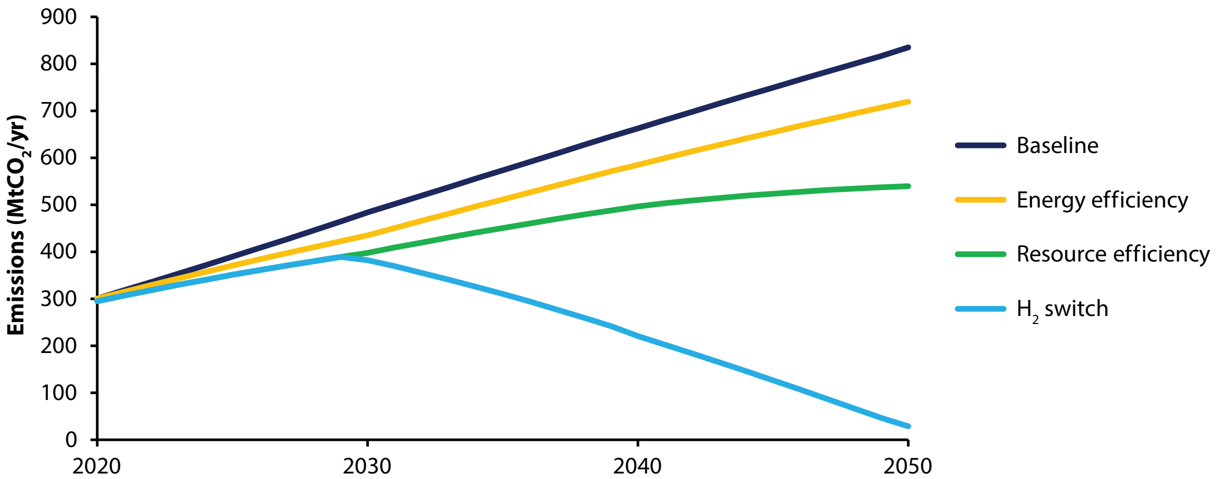
The greatest areas of uncertainty in this scenario are the cost and availability of breakthrough technologies, including HIsarna (and CCUS) and hydrogen direct reduction. HIsarna is more advanced than hydrogen-based steelmaking and has the support of a major Indian player, Tata Steel. Nevertheless, to achieve deep emissions reduction, CCS infrastructure will be required, which is underexplored in India.

On hydrogen direct reduction, the technology should be fully tested and available at this point in time, with multiple pilots to be completed in the 2020s. The greater uncertainty is in the cost of hydrogen, which is heavily dependent on the costs of electricity inputs and the capital costs of electrolysers. Assuming sufficient additional cost reductions in these areas, driven by an increase in global hydrogen demand over this period, hydrogen should become cost-competitive at some point before 2050.

Beyond 2050, we expect that emissions from the iron and steel sector can further reduce as emissions from the electricity system decrease and older, high GHG stock is retired. Further work would be required to understand how this fits into a broader long-term strategy for India's emission reduction pathway, where the economy reaches net-zero emissions.

Box 4: Optimistic hydrogen future

Whilst the above decarbonisation pathway represents a plausible scenario of how low carbon technologies might be introduced into the Indian iron and steel sector, we know that technology developments can change rapidly. Arguably, there is a possible scenario where rapid developments in hydrogen production technologies and in the hydrogen direct reduction production process could result in an earlier introduction of a low carbon alternative in India. We present an alternative high ambition hydrogen scenario, which reflects this.



Source: TERI analysis

Such a scenario would put the steel sector on a trajectory towards net zero by 2050 but would clearly be extremely challenging to achieve. In order for this to be a reality, at low or zero additional cost, one would need to assume (i) the availability and deployment of H_2-DR technology in India by 2030 (ii) the deployment of electrolysers at $400/kW or below by 2030 (iii) electricity prices below $30/MWh by 2030 (iv) either fully decarbonised grid electricity or sufficient off-grid renewables and (v) additional available electricity supply of over 700TWh. Taken in combination, these assumptions help to illustrate the difficulty in reaching a net zero target for the Indian steel sector by 2050.

In particular, the additional electricity that would be required is a significant challenge. Electricity demand in India is still likely to be growing at around 4% a year in 2030; adding additional load from the electricity required to produce hydrogen for the steel sector would put even greater strain on the expanding network. This is before considering how the other heavy industry sectors that might also need to electrify. There are very few, if any, economies which have been able to rapidly decarbonise their electricity whilst also increasing electricity demand, highlighting the challenge this poses.

7.2.2.2 Costs

This section will cover the additional costs of the main decarbonization technologies, including hydrogen-based direct reduction and HIsarna, or the smelting reduction process.

One of the main components for the costs of decarbonizing steel production through the use of hydrogen direct reduction is the cost of hydrogen. In this example, we assume that all hydrogen is produced via electrolysis, using electricity as an input. Therefore, the cost of electricity is also important. Figure 51 illustrates the impact of different electricity prices and capital costs on the cost of hydrogen production. The costs of hydrogen produced from SMR and coal gasification, given Indian coal and gas prices, are also represented, to identify where electrolytic hydrogen might become cost-competitive.

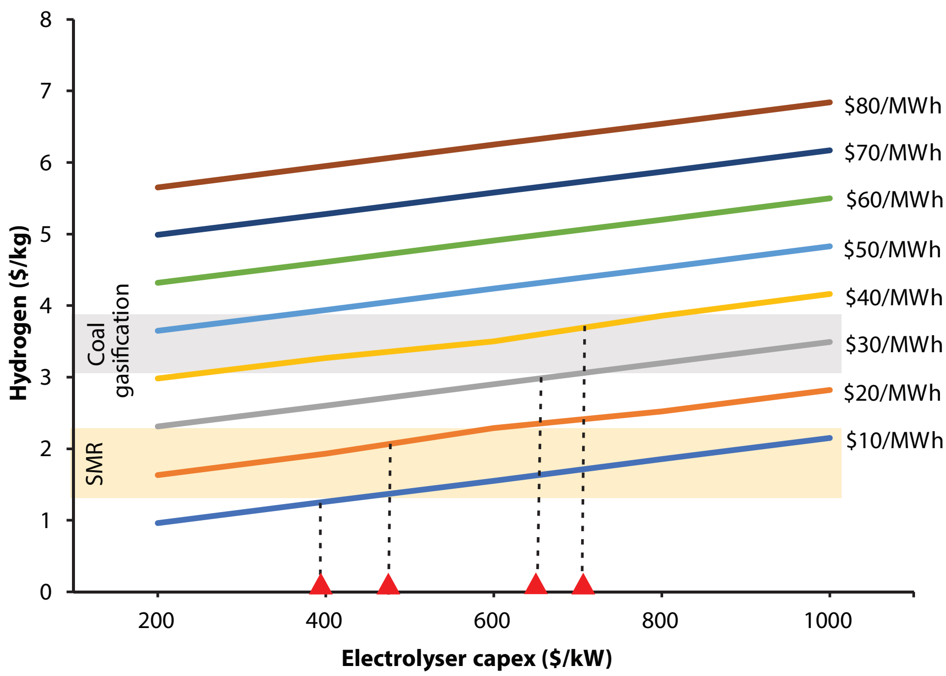


Figure 51: Costs of hydrogen from electrolysis

Source: TERI analysis using data from BEIS (2018) and IEA (2019c)

Note: The costs of hydrogen produced from SMR and coal gasification are exclusive of the costs of CCS .

Current industrial electricity prices are around $80/MWh, the result of high connection costs and the cross-subsidization of agricultural and residential electricity prices. Grid electricity prices for other consumers are closer to $60/MWh. Hydrogen produced from electrolysis could become competitive with hydrogen produced from SMR if electricity prices fall between $10–20/MWh. With further cost reductions in renewables and storage, we expect the cost of grid electricity to reduce further out to 2050, as they start to displace more expensive fossil-based electricity generation. To be competitive with hydrogen produced from coal gasification, electricity prices would need to be between $30–40/MWh and capital costs of electrolysers below $400/kW. This level of cost reduction for electrolysers is entirely plausible by 2050, particularly at the scales of deployment that are expected around the world to satisfy global, low carbon hydrogen demand.

Whilst it appears that low carbon hydrogen could one day be competitive with fossil-based equivalents, we are assuming here that the electrolyser operates at a 90% utilization factor. With growing shares of renewables in the power system, it might be necessary to operate the electrolyser more flexibly to follow supply. In Figure 52, we can see that at higher capital costs, lower utilization factors have a significant impact on the cost of hydrogen, making it uncompetitive with fossil-based equivalent technology. However, as capital costs decline, the utilization factor of the electrolyser becomes less and less important. Even operating at 30% utilization factor, which could be supplied via solar panels and battery storage, electrolysers could be competitive with SMR and coal gasification.

For the costs of hydrogen supplied to direct reduction facilities, we have taken a range falling from $8/kg today to $2/kg by 2050. Whilst we could reasonably expect costs of hydrogen production from electrolysis to fall to around $2/kg by 2050 (BNEF 2019), additional costs are added for buffer storage, compression, and some pipeline transportation. We are assuming that most hydrogen production would occur on-site, i.e. at the steel plant, so these costs are minimized.

Based on these cost assumptions, we have compared the cost of steel production from BF-BOF with H_2-DR out to 2050. We assume that the capital costs of the H_2-DR facility are equivalent to those of a natural gas-based facility

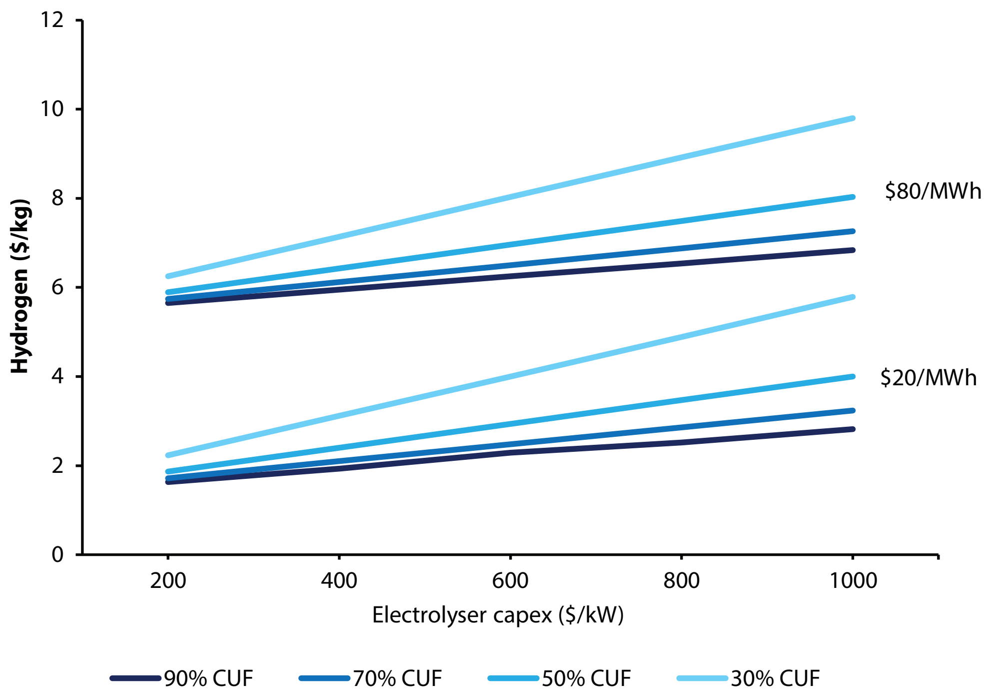


Figure 52: Impact of varying capacity utilization factors on cost of hydrogen

Source: TERI analysis using data from BEIS (2018) and IEA (2019c)

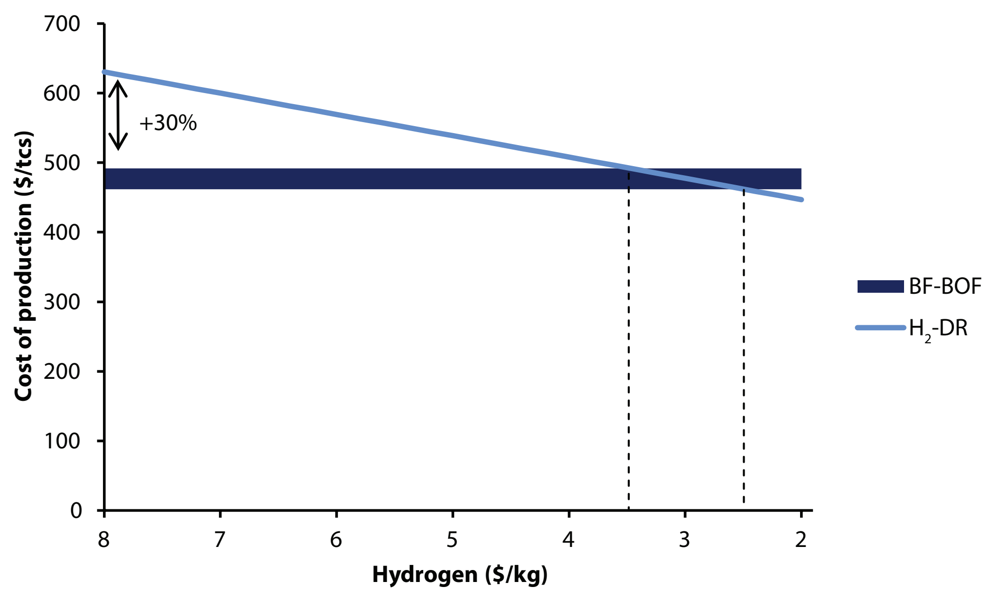


Figure 53: Cost of H_2-DR versus BF-BOF for greenfield sites

Source: TERI analysis. Capital costs have been taken from a range of sector experts. Variable costs have been taken from CRISIL (2018); Spencer, Pachouri, Renjith, et al. (2018); Vogl and Ahman (2019). Financing costs of 12% and loan repayment period of 20 years.

(Vogl and Ahman 2019). The main area of uncertainty is in the energy input assumptions over the 2050 time horizon; the costs of electricity and coal. The costs of coal are likely to steadily increase over time, with the base price of coal increasing by 4.5% in nominal terms per year between 2010 and 2017 (Spencer, Pachouri, Renjith, *et al.* 2018).

Based on this analysis, the delivered costs of hydrogen would need to be between $2.5–3.5/kg to be competitive with a greenfield BF-BOF plant, depending on the efficiency of the BF-BOF facility and the price of coking and non-coking coal. Costs of steel production from existing BF-BOF facilities (brownfield) will be much lower, particularly if the capital costs are fully depreciated.

These costs could be managed further by the using the steel plant and associated electrolysers and hydrogen production to help balance the electricity system. Analysis by the Climate Policy Initiative identified balancing requirements up to six times what they are today by 2030, which would increase even further out to 2050 (Udetanshu, Pierpont, Khurana, *et al.* 2019). A hydrogen-based steel facility could add flexibility to the system in several ways, either through

- frequency response from varying the operation of the electrolyser, which can be useful for the second-to-second balancing of the grid;
- stored hydrogen used for on-site power generation, similar to existing captive generation. This could be cost-effective hour-to-hour or even day-to-day; and
- use of hot iron briquettes to store thermal energy, which can then be used to run a generator.

For the smelting reduction process, or HIsarna, the capital costs tend to be 10–15% lower than a conventional BF-BOF due to the removal of the sinter plant and coke oven (IEA 2019c). This means that this process can be cost-competitive with conventional production routes from today. The additional costs of CCUS infrastructure are more uncertain but likely to result in costs of production equivalent to or greater than those faced by the conventional BF-BOF route today. Further work is required to understand the costs and potential of CCUS infrastructure for India.

Whilst the cost impacts today are relatively significant, where they could be as high as 30%, falling to around 15% by 2030, the cost impacts on end-user products are relatively minimal. We have undertaken some analysis to show the impact of raised steel prices on three typical products which use steel: a car, a house, and an air conditioning unit. These are based on Indian product and steel intensity data.


Steel
+0.3-0.8%
0
100
200
300
400
Cost of average air conditioning unit ($)
Steel
+1-2%
0
2,000
4,000
6,000
8,000
10,000
12,000
Cost of average 4-wheeler ($)
Steel
+2-4%
0
10,000
20,000
30,000
40,000
Cost of metro apartment ($)

8. ANNEXES

8.1 Annex A: Large Steel Plants in India

Name, address & state	Steelmaking technology	Capacity (Mtpa)
Tata Steel Limited, Bistupur, Jamshedpur, Jharkhand	BOF	10
SAIL Rourkela Steel Plant, Rourkela, Odisha	BOF	4
Jindal Steel & Power Ltd Chhendipada Road, SH - 63, At/ Po - Jindal Nagar, Angul, Odisha	BOF & EAF	6
Essar Steel Ltd., 27 KM, Surat- Hazira Road, Hazira, Gujarat	EAF	10
JSW Steel Ltd , Vijayanagar Works, Toranagallu, Bellary, Karnataka	BOF & EAF	12
Rashtriya Ispat Nigam Ltd (RINL) Vizag, Andra Pradesh	BOF & EAF	7.3
SAIL, Durgapur Steel Plant, Durgapur, Burdwan, West Bengal	BOF	1.8
Bhushan Steel Limited Narendrapur, Meramandali, Kusupanga, Dhenkanal, Odisha. (Tata Steel limited)	BOF & EAF	5.6
JSW Steel ltd., Gitapuram, Dis-Raigad, Maharashtra	EAF	5
SAIL, Bokaro Steel Plant, Ispat Bhawan, Bokaro steel city, Jharkhand	BOF	4.5
Jindal Steel & Power Limited, (JSPL) Post Box No. 16, Kharsia Road, Raigarh, Chhattisgarh	EAF	3.6
SAIL, IISCO Steel Plant, Burdwan, Near Asansol, Dist- Burdwan, West Bengal	BOF	2.5
Bhilai Steel Ltd, Bhilai, Chhattisgarh	BOF	7.5
Bhushan Power & Steel Limited Village Thelkoloi and Dhubenchappar, Tehsil Rengali, Lapanga, Sambalpur, Odisha	EAF	2.3
Monnet Ispat & Energy Limited Naharpali, Raigarh, Chhattisgarh	EAF	1.5
Tata Steel Limited, Kalinga Nagar Industrial Complex, Duburi, Jajpur, Odisha, 755026	BOF	3
Monnet ISPAT & Energy Ltd./JSW Steel Ltd, Monnet Marg Mandir, Hasoud, Raipur, Chhattisgarh	EIF	1.5
Electrosteel steels limited (Bokaro)	BOF	2.5
Usha Martin (Jamshedpur)	EAF	1

8.2 Annex B: Countries used in regression analysis

1	Algeria	13	Germany	25	Poland
2	Argentina	14	Greece	26	Portugal
3	Austria	15	Hungary	27	Romania
4	Bangladesh	16	India	28	Russia
5	Brazil	17	Indonesia	29	South Africa
6	Chile	18	Iran	30	Spain
7	China	19	Italy	31	Sweden
8	Colombia	20	Kazakhstan	32	Thailand
9	Czech Republic	21	Malaysia	33	Turkey
10	Egypt	22	Mexico	34	United Kingdom
11	Finland	23	Pakistan	35	Vietnam
12	France	24	Philippines		

8.3 Annex C: Energy Efficiency Technologies

List of energy efficiency technologies by technology route, process and level of adoption, where A is widespread adoption, B is adopted by sector leaders and C is not yet adopted. Compiled from a range of reports and verified by sector experts (WSP, Parsons Brinckerhoff & DNV GL (2015); JISF (2014); CII (2013); Morrow, Hasanbeigi, Sathaye, & Xu 2014; BEE (2018).

BF-BOF		Process	Level of adoption	Energy savings (GCal/t-product)
1	Waste heat recovery	Sintering	B	0.08
2	High Efficiency Coke Oven Gas Burner in Ignition Furnace	Sintering	B	0.20
3	Increasing sinter bed depth	Sintering	B	0.00
4	Improvement in segregated charging of sintering material	Sintering	A	0.04
5	Coke Dry Quenching (CDQ)	Cokemaking	B	0.224
6	Coal Moisture Control (CMC)	Cokemaking	B	0.056
7	Automated Combustion Control of Coke Oven	Cokemaking	B	0.0432
8	Partial fuel substitution in coking plant	Cokemaking	C	0.00
9	Top pressure recovery turbine (TRT)	Ironmaking	B	0.04
10	Preheating through WHR from Hot Stoves of Blast furnace	Ironmaking	B	0.33
11	Pulverised coal injection (PCI)	Ironmaking	B	0.0825
12	Injection of coke oven gas	Ironmaking	C	0.016

13	Recovery of blast furnace gas	Ironmaking	A	0.0096
14	Stove flue gas recycling	Ironmaking	C	0.00
15	Use of iron ore pellets in DRI kiln/ BF	Ironmaking	A	0.344
16	Converter gas heat recovery device	Steelmaking	B	0.03
17	Converter gas recovery device	Steelmaking	A	0.201
18	Heat recovery from steelmaking slag	Steelmaking	C	0.0183
19	Increased use of recycled steel scrap	Steelmaking	C	0.00
20	Oxygen burners system for ladle preheating	Casting and Refining	B	0.146
21	Regenerative burners in reheating furnace	Rolling	B	0.045
22	Rotary Hearth Furnace (RHF) Dust Recycling System	Others	C	0.05
DR-EAF/EIF		Process	Level of adoption	Energy savings (GCal/t-product)
23	Use of iron ore pellets in DRI kiln/ BF	Ironmaking	A	0.344
24	Waste Heat Recovery from Sponge Iron kiln	Ironmaking	A	0.00
25	Charge or scrap preheating	Steelmaking	C	0.0525
26	Scrap densification or shredding	Steelmaking	C	0.07125
27	Coherent Jet Gas Injection Technology	Steelmaking	B	0.00
28	Improved process control	Steelmaking	B	0.0258
29	Ultra high power transformers	Steelmaking	B	0.001
30	Waste heat recovery from EAF	Steelmaking	C	0.08
31	Ecological and Economical Arc Furnace	Steelmaking	C	0.13
32	Oxy-fuel burners or lancing	Steelmaking	B	0.0335
33	Slag Foaming, Exchangeable Furnace and Injection Technology	Steelmaking	B	0.06
34	Hot Charging DRI	Steelmaking	B	0.12
35	Increased use of recycled steel scrap	Steelmaking	A	0.00
Common technologies		Process	Level of adoption	Energy savings (GCal/t-product)
36	Near net shape casting	Casting and Refining	B	0.7125
37	Direct rolling	Rolling	C	0.18
38	Hot charging of slab	Rolling	C	0.00
39	Installing VVVF drives to electrical motors	Others	B	0.01
40	Cogeneration (including Gas Turbine Combined Cycle)	Others	B	0.3

8.4 Annex D: Emissions Reduction Technologies

	Technology / Project	Description	Link
1	SALCOS	The SALCOS technology uses hydrogen-based DRI-EAF steelmaking. Project linked to the GrInHy project, for production of green hydrogen.	https://salcos.salzgitter-ag.com/en/index.html?no_cache=1
2	SUSTEEL	Based on hydrogen-based DRI-EAF steelmaking (Hydrogen Plasma Smelting Reduction: HPSR process). Project linked to the H2 future hydrogen technology	https://www.voestalpine.com/blog/en/innovation-en/the-three-pillars-of-decarbonization/
3	HYBRIT	Direct reduction of iron into steel using hydrogen and renewable energy, which generates water as a byproduct instead of carbon dioxide.	http://www.hybritdevelopment.com/
4	COURSE 50	This involves reforming coke oven gas with the use of catalysts and utilizing unused heat in order to increase its hydrogen content (from 55% to 67%). This hydrogen enriched gas is then to be used for the reduction of iron ore in the blast furnace.	https://www.jisf.or.jp/course50/outline/index_en.html
5	Flash Oxide Smelting	The process would use inexpensive, abundant natural gas (or hydrogen) to both heat the ore in the furnace and to remove oxygen, converting the ore into iron metal.	https://www.energy.gov/sites/prod/files/2016/12/f34/fcto_h2atscale_workshop_sohn.pdf
6	GrInHy	Salzgitter, along with partners Sunfire GmbH, Paul Wurth S.A., Tenova SpA, French research center CEA and Salzgitter Mannesmann Forschung GmbH, are building the world's most powerful Steam Electrolyser (StE) for the energy efficient production of hydrogen.	https://www.green-industrial-hydrogen.com/
7	H2FUTURE	Under the coordination of the utility VERBUND, the steel manufacturer Voestalpine and Siemens, a large-scale 6 MW PEM electrolysis system will be installed and operated at the voestalpine Linz steel plant in Austria.	https://www.h2future-project.eu/
8	Steelanol	Steelanol is making industrial waste gases into liquid fuels, through biotech solutions for transformation of carbon monoxide to ethanol.	http://www.steelanol.eu/en
9	Carbon2Chem	Based on utilization of industrial waste gases, aiming to use smelting gases for chemicals production (e.g., methanol)	https://cec.mpg.de/en/projects/carbon2chem-reg/

10	Hisarna	HIsarna is a new type of furnace in which iron ore is directly injected and liquefied in a high-temperature cyclone so that it drips to the bottom of the reactor where powder coal is injected. The two react into liquid iron.	https://www.tatasteeleurope.com/en/innovation/hisarna/about-hisarna
11	EOR on DRI	Using the waste stream of CO_2 from the direct reduction process to enhance oil recovery.	
12	CCUS	Using carbon capture, utilsation and storage technology to capture CO_2 emissions from the blast furnace to reduce emissions.	
13	Biomass	Using biomass derived char as substitute of coke and coal	
14	Siderwin	Based on CO_2-free steelmaking through electrolysis, transforming iron oxide (e.g. hematite) into a steel plate (at the cathode) and oxygen (anode).	https://www.siderwin-spire.eu/
15	Molten Oxide Electrolysis	Boston Metal is a leading company using this technology.	https://www.bostonmetal.com/

8.5 Annex E: Iron and Steel Subsector Technological Intensity Classification

Subsector codes and descriptions taken from Department of Commerce and Industry. Technological intensity classification assigned by authors.

Code	Description	Technological intensity
7204_sector	FERROUS WASTE AND SCRAP; REMELTING SCRAP INGOTS	low_tech
7225_sector	FLT-RLLD PRDCTS OF OTHR ALLOY STL OF WDTH 600 MM OR MORE	high_tech
7228_sector	OTHR BARS,RODS,ANGLS,SHPS,SCTNS OF OTHR ALLOY STL,HOLLOW DRILL BARS AND RODS OF ALLOY OR NON-ALLOY STL	high_tech
7227_sector	BARS AND RODS, HOT-ROLLED, IN IRREGULARLY WOUND COILS, OF OTHER ALLOY STEEL	high_tech
7208_sector	FLAT-ROLLED PRODUCTS OF IRON OR NON-ALLOY STEEL, OF A WIDTH OF 600 MM OR MORE, HOT- ROLLED, NOT CLAD, PLATED OR COATED	medium_tech
7209_sector	FLT RLLD PRDCTS OF WDTH>= 600MM,COLD-RLLD (COLD-REDUCED),NOT CLAD,PLTD/COATD	low_tech
7219_sector	FLT-RLLD PRDCTS OF STAINLESS STL OF WDTH>=600 MM	high_tech
7217_sector	WIRE OF IRON OR NON-ALLOY STEEL	low_tech
7220_sector	FLAT-ROLLED PRODUCTS OF STAINLESS STEEL, OF A WIDTH OF LESS THAN 600 MM	high_tech
7226_sector	FLT-RLD PRDCTS OF A WIDTH OF <600 MM	low_tech

7229_sector	WIRE OF OTHER ALLOY STEEL	high_tech
7205_sector	GRNL AND PWDR,OF PIG IRON,SPGLSN,IRON/STEEL	low_tech
7224_sector	OTHER ALLOY STEEL IN INGOTS OR OTHER PRIMARY FORMS; SEMI-FINISHED PRODUCTS OF OTHER ALLOY STEEL	high_tech
7212_sector	FLT-RLLD PRDCTS OF IRON/NON-ALOY STEEL OF A WDTH<600 MM,CLAD,PLTD/COATD	low_tech
7203_sector	FERUS PRDCTS FROM DIRECT REDUCTN OF IRON ORE AND OTHR SPNGY FERS PRDCTS IN LMPS,PLLTSETC; >=99.94% PURE IRON BY WT IN L	low_tech
7206_sector	IRON AND NON-ALLOY STEEL IN INGOTS OR OTHER PRIMARY FORMS (EXCLUDING IRON OF HEADING 7203)	low_tech
7218_sector	STAINLESS STEEL IN INGOTS OR OTHER PRIMARY FORMS; SEMI-FINISHED PRODUCTS OF STAINLESS STEEL	high_tech
7216_sector	ANGLS,SHAPES AND SCTNS OF IRON/NON-ALLOY STL	medium_tech
7211_sector	FLT-RLLD PRDCTS OF IRON/NON-ALOY STL OF WDTH<600 MM,NT CLD,PLTD/COATD	medium_tech
7215_sector	OTHER BARS AND RODS OF IRON OR NON-ALLOY STEEL	medium_tech
7214_sector	OTHER BARS AND RODS OF IRON OR NON-ALLOY STEEL, NOT FURTHER WORKED THAN FORGED, HOT-ROLLED, HOT-DRAWN	medium_tech
7213_sector	BARS AND RODS, HOT-ROLLED, IN IRREGULARLY WOUND COILS, OF IRON OR NON-ALLOY STEEL	medium_tech
7221_sector	BARS AND RODS, HOT-ROLLED, IN IRREGULARLY WOUND COILS, OF STAINLESS STEEL	high tech
7201_sector	PIG IRON AND SPIEGELEISEN IN PIGS, BLOCKS OR OTHER PRIMARY FORMS	low_tech
7223_sector	WIRE OF STAINLESS STEEL	high tech
7207_sector	SEMI-FINISHED PRODUCTS OF IRON OR NON- ALLOY STEEL	low_tech
7210_sector	FLT-RLLD PRDCTS OF IRON/NON-ALOY STEEL OF WDTH >=600 MM,CLAD,PLATD/COATD	low_tech
7222_sector	OTHER BARS AND RODS OF STAINLESS STEEL; ANGLES, SHAPES AND SECTIONS OF STAINLESS STEEL	high tech
7202_sector	FERRO-ALLOYS	low_tech

9. BIBLIOGRAPHY

Accenture. (2017). *Steel Demand Beyond 2030.* Retrieved July 2019, from https://www.oecd.org/industry/ind/Item_4b_Accenture_Timothy_van_Audenaerde.pdf

ArcelorMittal. (2019). *ArcelorMittal commissions Midrex to design demonstration plant for hydrogen steel production in Hamburg.* Retrieved from ArcelorMittal: https://corporate.arcelormittal.com/news-and-media/news/2019/sep/16-09-2019

Bank for International Settlements. (2019). *Total Credit to the Non-Financial Sector*. Retrieved 22 11, 2019, from https://www.bis.org/statistics/totcredit.htm

BEE. (2018). *Improving Energy Efficiency in Iron & Steel Sector.* Retrieved from https://www.keralaenergy.gov.in/files/Resources/Iron__Steel_Sector_Report_2018.pdf

BEE. (2019). *PAT- Notifications.* Retrieved from https://beeindia.gov.in/content/pat-notifications

BEE. (2019). *Perform, Achieve and Trade.* Retrieved from https://beenet.gov.in/UI_Forms/General/Login.aspx?AspxAutoDetectCookieSupport=1

BEIS. (2018). *Hydrogen supply chain: evidence base.* Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/760479/H2_supply_chain_evidence_-_publication_version.pdf

BHP Billiton. (2018). *Indian steel demand may double to 170 mt by 2025: BHP Billiton* . Retrieved July 2019, from Economic Times: https://economictimes.indiatimes.com/industry/indl-goods/svs/steel/indian-steel-demand-may-double-to-170-mt-by-2025-bhp-billiton/articleshow/64863427.cms?from=mdr

Bleischwitz, R., Nechifora, V., Winning, M., Huang, B., & Geng, Y. (2018). Extrapolation or saturation – Revisiting growth patterns, development stages and decoupling. *Global Environmental Change, 48*, 86-96.

BNEF. (2019). *Cost of hydrogen from renewables to plummet next decade.* Retrieved from: https://www.bloomberg.com/news/articles/2019-08-21/cost-of-hydrogen-from-renewables-to-plummet-next-decade-bnef

Boston Metal. (2019). *Boston Metal*. Retrieved from https://www.bostonmetal.com/

Bryan, M., & Jenkins, S. (2013). Regression Analysis of Country Effects Using Multilevel Data. *Institute for Labour Studies*.

Business Standard. (2019). *India vulnerable to oil price, capital inflow shocks.* Retrieved from https://www.business-standard.com/article/pti-stories/india-vulnerable-to-oil-price-and-capital-inflow-shocks-119111900937_1.html

CBRI Roorkee. (2019). Interview with Dr Ajay Chourasia, Senior Scientist.

CEA. (2017). *General Review 2017.* New Delhi: Central Electricity Authority.

China Energy Portal. (2019). *14th Five-Year Plan.* Retrieved from https://chinaenergyportal.org/wp-content/uploads/2019/09/GIZ_14th-Five-Year-Plan-and-energy-sector-expert-commentary-Special-Infographic.pdf

CII. (2013). *Technology Compendium on Energy Saving Opportunities.* Retrieved from http://www.indiaenvironmentportal.org.in/files/file/iron_steel.pdf

CIL. (2018). *Coal Vision 2030: Stakeholder's consultation.* Retrieved from https://www.coalindia.in/DesktopModules/DocumentList/documents/Coal_Vision_2030_document_for_Coal_Sector_Stakeholders_Consultation_27012018.pdf

CRISIL. (2018). *Coal imports to remain hot.*

Cullen, J., Allwood, J., & Bambach, M. (2012). Mapping the global flow of steel: from steelmaking to end-use goods. *Environmental Science & Technology* .

Department of Commerce and Industry . (2019). *Export Import Data Bank.* Retrieved 11 17, 2019, from https://commerce-app.gov.in/eidb/default.asp

Eom, J., Le, K., Pl, C., & Sh Kim, P. (2012). *China's Building Energy Use: A Long-Term Perspective based on a Detailed Assessment.* US Department of Energy.

ETC. (2018). *Mission Possible.* Retrieved from http://www.energy-transitions.org/sites/default/files/ETC_MissionPossible_FullReport.pdf

Eurostat. (2019). *Structural Business Statistics*. Retrieved 11 15, 2019, from https://ec.europa.eu/eurostat/data/database

Firoz, A. (2014). *Long Term Perspective for Indian Steel Industry.*

Fischedick, M., Marzinkowski, J., Winzer, P., & Weigel, M. (2014). *Techno-economic evaluation of innovative steel production technologies.* Retrieved from https://doi.org/10.1016/j.jclepro.2014.05.063

GoI. (2018). *Second Biennial Update Report to the United Nations Framework Convention on Climate Change.*

Gupta, A., & Paul, A. (2019). Carbon capture and sequestration potential in India: A comprehensive review. *Energy Procedia*, 848-855.

Hiloidhari, M., Das, D., & Baruah, D. (2014). Bioenergy potential from crop residue biomass in India. *Renewable and Sustainable Energy Reviews*.

IBM. (2018). *Indian Mineral Yearbook 2018*. Retrieved from http://ibm.nic.in/index.php?c=pages&m=index&id=1363

IEA. (2018). *Energy Balances of Non-OECD Countries*. Retrieved from https://www.iea.org/statistics/relateddatabases/energybalancesofnon-oecdcountries/

IEA. (2019a). *Emissions Factors*. Retrieved from http://data.iea.org/payment/products/122-emissions-factors-2017-edition.aspx

IEA. (2019b). *IEA Technology Roadmap: The global iron and steel sector*. Retrieved July 2019, from http://www.oecd.org/sti/ind/86th%20Steel%20Committee%20meeting%20%20Presentation%20by%20IEA,%20IEA%20Technology%20Roadmap.pdf

IEA. (2019c). *The Future of Hydrogen*. Retrieved from https://www.iea.org/reports/the-future-of-hydrogen

IEA. (2019d). *World Energy Outlook*.

IES. (2018). *Overview of breakthrough low-CO2 iron and steel production technologies*. Retrieved from https://www.ies.be/files/ANNEX_Technology_Database_13072018.pdf

IMF. (2019). *IMF ARTICLE IV STAFF REPORTS*. Retrieved from https://www.imf.org/en/Publications/SPROLLS/Article-iv-staff-reports#sort=%40imfdate%20descending

IMMT. (2019). *Ongoing Projects*. Retrieved from http://www.immt.res.in/ProjectsSE.aspx?Did=16

India Today. (2019). *India looking at technology in coal gasification to get clean energy*. Retrieved from https://www.indiatoday.in/india/story/india-looking-technology-coal-gasification-get-clean-energy-pm-modi-global-business-forum-1603222-2019-09-26

IPCC. (2018). *Global Warming of 1.5C*. Retrieved from Chapter 3: Impacts of 1.5°C of Global Warming on Natural and Human Systems: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Chapter3_Low_Res.pdf

IRG. (2010). *Total Commercial Floor Space Estimatesfor India*. USAID.

ITA. (2019). *Steel Exports Report: India* . Retrieved from https://www.trade.gov/steel/countries/pdfs/exports-India.pdf

JISF. (2014). *Technologies Customized List & Technologies One By One Sheets*. Retrieved from http://www.jisf.or.jp/business/ondanka/eco/docs/IndiaTechnologiesCustomizedListv2.pdf

JPC. (2020). *The Indian iron and steel database 2019-20*.

Material Economics. (2018). *The Circular Economy, a powerful force for future climate mitigation*.

MDPI. (2020). Hydrogen Ironmaking: How It Works. *Challenges and Prospects of Steelmaking Towards the Year 2050*. doi:https://doi.org/10.3390/met10070922

Midrex. (2018). *Hydrogen uses in ironmaking*. Retrieved from US Department of Energy: https://www.energy.gov/sites/prod/files/2018/08/f54/fcto-h2-scale-kickoff-2018-8-chevrier.pdf

Midrex. (2019). *World Direct Reduction Statistics*. Retrieved from http://www.midrex.com/wp-content/uploads/Midrex_STATSbookprint_2018Final-1.pdf

Millenium Steel. (2006). *Circored fine ore direct reduction*. Retrieved from http://millennium-steel.com/wp-content/uploads/articles/pdf/2006/pp37-40%20MS06.pdf

MNRE. (2019). *Solar driven seawater hydrogen production and producing methane by sequestering - Invitation for Proposals*. Retrieved from https://mnre.gov.in/sites/default/files/webform/notices/Invitationofproposals.pdf

MoEFCC. (2019). *Reference Report for "National Resource Efficiency Policy" for India*. Retrieved from https://www.teriin.org/sites/default/files/2019-04/National-Policy-Report.pdf

MoPNG. (2019). *Natural Gas Scenario in India*. Retrieved from http://petroleum.nic.in/natural-gas/about-natural-gas

Morrow, W., Hasanbeigi, A., Sathaye, J., & Xu, T. (2014). Assessment of energy efficiency improvement and CO2 emission reduction potential in India's cement and iron & steel industries. *Journal of Cleaner Production*, 131-141.

MoS. (2017). *National Steel Policy*.

MoS. (2018). *Make in Steel, Make in India*.

MoS. (2019). *Annual Report 2018-19*. Retrieved from https://steel.gov.in/sites/default/files/MoS%20AR%20Eng.pdf

MoS. (2020). Steel: A strategic partner in rural India's growth story.

MoS. (2021). *Annual Report 2021*.

MOSPI. (2017a). *Annual Survey of Industries: Volume 1*. Kolkata: Government of India, Ministry of Statistics and Programme Implementation (MOSPI).

MoSPI. (2017b). *MOTOR VEHICLES - Statistical Year Book India 2017*. Retrieved July 2019, from Ministry of Statistics & Programme Implementation: http://mospi.nic.in/statistical-year-book-india/2017/189

MoSPI. (2018). *HOUSING - Statistical Yearbook 2018*. Retrieved July 2019, from Ministry of Statistics & Programme Implementation: http://mospi.nic.in/statistical-year-book-india/2018/197

MoSPI. (2019a). *Energy Statistics*. Retrieved from http://www.mospi. gov.in/sites/default/files/publication_reports/Energy%20 Statistics%202019-finall.pdf

MOSPI. (2019b). *National Accounts Statistics 2018*. Retrieved 11 18, 2019, from http://mospi.nic.in/publication/national-accounts-statistics-2018

Nippon Steel. (2015). *Ultra High Strength Steel for Sustainable Building Structures*. Retrieved from https://pdfs.semanticscholar.org/60e0/37cb7e03cc92e32ff8562cf0365e38042ed8.pdf

NITI Aayog. (2018). *Moving Forward Together: Enabling Shared Mobility in India*. Retrieved from https://niti.gov.in/writereaddata/files/document_publication/Shared-mobility.pdf

Odysee-Mure. (2017). *Key Indicators*. Retrieved July 2019, from Odysee-Mure: http://www.indicators.odyssee-mure.eu/online-indicators.html

OECD. (2016). *Historical population data and projections (1950-2050)*. Retrieved July 2019, from OECD.Stat: https://stats.oecd.org/Index.aspx?DataSetCode=POP_PROJ

OECD. (2018a). *Economic Outlook No 103 - July 2018 - Long-term baseline projections*. Retrieved July 2019, from OECD.Stat: https://stats.oecd.org/Index.aspx?DataSetCode=EO103_LTB

OECD. (2018b). *GDP long-term forecast (indicator)*. Retrieved June 28, 2019, from OECD data: https://data.oecd.org/gdp/gdp-long-term-forecast.htm

OECD. (2019a). *Latest developments in steelmaking capacity*. Retrieved from http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=DSTI/SC(2019)3/FINAL&docLanguage=En

OECD. (2019b). *Recent Developments in Steelmaking Capacity*. Paris: OECD.

Outotec. (2019). *Outotec Circored Hydrogen-based Reduction*. Retrieved from https://www.outotec.com/products/direct-and-smelting-reduction/circored-hydrogen-based-reduction/

Penn World Table 9.1. (2019). *Penn World Table*. Retrieved 11 22, 2019, from https://www.rug.nl/ggdc/productivity/pwt/

POSCO. (2018). *A comprehenisve survey of steel demand forecasting methodologies*.

Rue du Can, S., Khandekar, A., Abhyankar, N., Zheng, N., Fridley, D., Zhou, N., & Phadke, A. (2019). Modeling India's energy future using a bottom-up approach. *Applied Energy*, 1108-1125.

Salzgitter. (2019). *STIL*. Retrieved from https://www.salzgitter-ag.com/fileadmin/footage/MEDIA/SZAG_microsites/salcos/STIL-02-19-SpecialPrint-Salcos-Hydrogen-en.pdf

Samajdar, C. (2012). Reduction in Specific Energy Consumption in Steel Industry - with special reference to Indian steel industry. *Energy and Environmental Engineering Journal*.

Sandbag. (2019). *EUA Price*. Retrieved from https://sandbag.org.uk/carbon-price-viewer/

SBT. (2018). *Companies taking action*. Retrieved from Science Based Targets: https://sciencebasedtargets.org/companies-taking-action/

Siddiqui, K. (2015). Challenges for Industrialisation in India: State versus Market Policies. *Research in World Economy*.

SIDERWIN. (2018). *Objectives*. Retrieved from SIDERWIN: https://www.siderwin-spire.eu/content/objectives

Sormann, A., Seftejani, M., Spreitzer, D., & Zarl, M. (2018). *The way to a carbon free steelmaking*. Retrieved from https://www.researchgate.net/publication/328075380_The_way_to_a_carbon_free_steelmaking

Spencer, T., Pachouri, R., Renjith, G., & Vohra, S. (2018). *Coal Transition in India*. Retrieved from https://www.teriin.org/sites/default/files/2018-12/Coal-Transition-in-India.pdf

SSAB. (2019). *SSAB, LKAB and Vattenfall ready to step up work to achieve fossil-free steel production*. Retrieved September 2019, from SSAB: https://www.ssab.com/company/newsroom/media-archive/2019/09/13/10/21/ssab-lkab-and-vattenfall

SSAB. (2020). *Fossil-free steel production*. Retrieved from https://www.businessfinland.fi/49cde1/globalassets/finnish-customers/02-build-your-network/bioeconomy--cleantech/alykas-energia/jarmo-lilja.pdf

SteelConstruction.info. (2016). *Cost of structural steelwork*. Retrieved July 2019, from SteelConstruction.info: https://www.steelconstruction.info/Cost_of_structural_steelwork

Suopajarvi, H., Kemppainen, A., Haapakangas, J., & Fabritius, T. (2017). Extensive review of the opportunities to use biomass-based fuels in iron and steelmaking processes. *Journal of Cleaner Production*, 709-734.

Tata Steel. (2017). *HIsarna: Game Changer in the Steel Industry*. Retrieved from https://www.tatasteeleurope.com/static_files/Downloads/Corporate/About%20us/hisarna%20factsheet.pdf

Tenova HYL. (2018). *HYL News*. Retrieved from https://www.tenova.com/fileadmin/user_upload/HYL_News_-_December_2018.pdf

TERI. (2018). *TERI Energy & Environment Data Diary and Yearbook (TEDDY) 2017/18*. Retrieved from https://www.teriin.org/projects/teddy/index.html

The Hindu. (2019). *Steel, cement sectors pin hopes on housing and road spends*. Retrieved from https://www.thehindubusinessline.com/economy/budget/steel-cement-sectors-pin-hopes-on-housing-and-road-spends/article28297591.ece#

Thiruvengadam, V., Wason, J., & Gayathri, L. (2004). Cost Modeling of Reinforced Concrete Buildings. *13th World Conference on Earthquake Engineering*. Vancouver: https://www.iitk.ac.in/nicee/wcee/article/13_1956.pdf.

Thyssenkrupp . (2019). *World first in Duisburg as NRW economics minister Pinkwart launches tests at thyssenkrupp into blast furnace use of hydrogen*. Retrieved from https://www.thyssenkrupp.com/en/newsroom/press-releases/world-first-in-duisburg-as-nrw-economics-minister-pinkwart-launches-tests-at-thyssenkrupp-into-blast-furnace-use-of-hydrogen-17280.html

Times of India. (2008). *33% of Indians live in less space than US prisoners*. Retrieved July 2019, from Times of India: https://timesofindia.indiatimes.com/india/33-of-Indians-live-in-less-space-than-US-prisoners/articleshow/3753189.cms

ToI. (2018). *Govt caps life of commercial vehicles at 20 years*. Retrieved from Times of India: https://timesofindia.indiatimes.com/india/commercial-vehicles-older-than-20-years-cannot-ply-from-april-2020/articleshow/63337343.cms

Udetanshu, Pierpont, B., Khurana, S., & Nelson, D. (2019). *Developing a roadmap to a flexible, low-carbon Indian electricity system: interim findings*. Retrieved from CPI: https://climatepolicyinitiative.org/wp-content/uploads/2019/02/CPI-India-Flexibility-WEB.pdf

US Census Bureau. (2017). *Annual Survey of Manufactuerers*. Retrieved 11 16, 2019, from https://www.census.gov/programs-surveys/asm/data/tables.html

US Department of Transportation. (2019). *State Motor-Vehicle Registrations - 2017*. Retrieved October 2019, from Office of Highway Policy Information: https://www.fhwa.dot.gov/policyinformation/statistics/2017/mv1.cfm

Vogl, V., & Ahman, M. (2019). What is green steel? Towards a strategic decision tool for decarbonising EU steel. *ESTAD proceedings*.

WITS Database. (2019). *World Integrated Trade Solution*. Retrieved 11 20, 2019, from https://wits.worldbank.org/

World Bank. (2017). *World Development Indicators*.

WSA. (2018a). *World Steel Statistics*. World Steel Association.

WSA. (2018b). *Steel in Automotive*. Retrieved from World Steel Association: https://www.worldsteel.org/steel-by-topic/steel-markets/automotive.html

WSA. (2018c). *Steel Statistical Yearbook 2018*.

WSA. (2019a). *Steel and raw materials*. Retrieved from https://www.worldsteel.org/en/dam/jcr:16ad9bcd-dbf5-449f-b42c-b220952767bf/fact_raw%2520materials_2019.pdf

WSA. (2019b). *Towards a net-zero emissions steel industry*. Retrieved from IETS: https://iea-industry.org/app/uploads/5-Ekdahl-Towrds-a-net-zero-emissions-steel-industry.pdf

WSA. (2020). *Steel Statistical Yearbook 2020 Concise Version*.

WSP, Parsons Brinckerhoff & DNV GL. (2015). *Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050*.