Perspective from **Franklin Templeton Emerging Markets Equity**

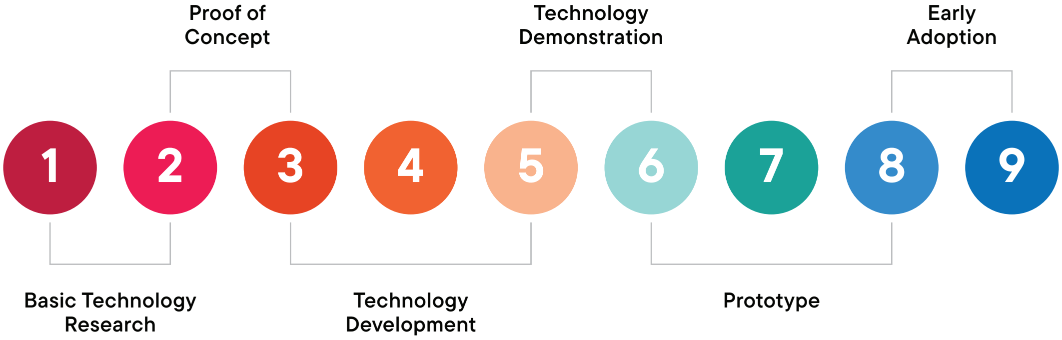
# Green steel

June 2023

The steel industry is one of the largest contributors to global carbon emissions, accounting for 7% of total emissions in 2019.[1] Left unchecked, emissions are forecast to rise by 44% by 2050.[2] However, there is another option wherein emissions could fall by 54% by 2050: green steel from zero-emissions hydrogen. The challenge for investors and the industry is cost. Producing green steel from zero-emissions hydrogen is estimated to require an investment of US$2.8 trillion.[3] This report focuses on the process to produce green steel, breaking down the costs and technology used in each step in the process.

There are other options for the decarbonization of the steel industry, including carbon capture and storage (CCS), bioenergy and direct electrification. The technology readiness level (TRL) is one approach to assess the feasibility of each of these processes.[4] Zero-emission hydrogen is classed as demonstration on the TRL, CCS is proof of concept, bioenergy is early adoption and direct electrification is prototype.

Exhibit 1: Technology Readiness Level



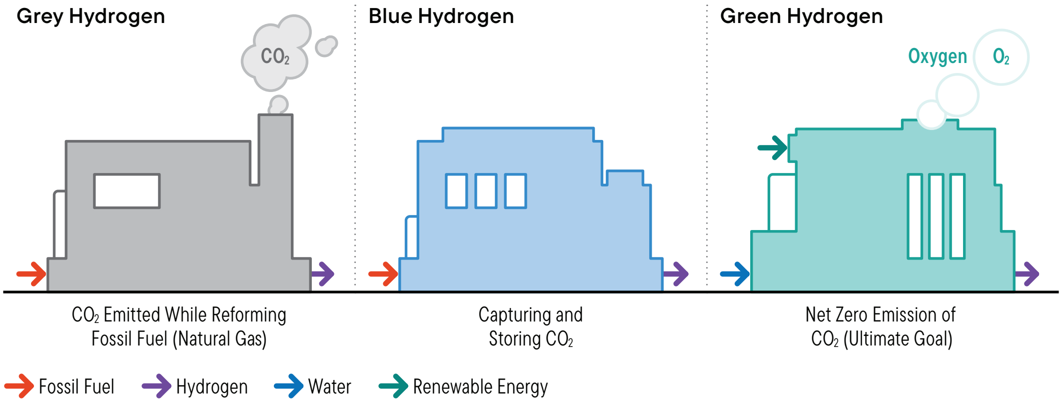
Source: John C Mankins / NASA. For Illustrative Purposes Only.

We acknowledge that steel is a highly polluting industry. We believe that divesting is not the right approach to addressing the challenges the industry faces. Our focus is on engaging with companies that recognize the impact steelmaking has on the environment, and working with them as they embark on the journey toward net zero. Companies we engage with are at different stages of the decarbonization journey, ranging from acknowledgment, to planning, to testing new technologies. We assess the sustainability policies of individual companies via our evaluation of their environmental, social and governance (ESG) policies.

## The path to lowering emissions in the steel industry

Scientists have prefixed hydrogen with color labels to denote the different methods of production, as hydrogen can be a clean or dirty source of power. Hydrogen is a clean source of power when it is created using renewable energy, which is labeled green hydrogen. It is a dirty source of power when it is created using coal or natural gas, labeled grey or blue hydrogen.

Exhibit 2: Not All Hydrogen Is Created Equal: Grey, Blue, Green Hydrogen



Source: Frackcheck. For Illustrative Purposes Only.

Zero-carbon hydrogen can act as catalyst for accelerating the decarbonization of other industries including fertilizer, transportation/shipping, ceramics and glassmaking. Hydrogen also has the potential for use in energy storage based on renewables. Using hydrogen as a heat source is not new—what has changed is the dramatic decline in cost of renewable energy and expectations that economies of scale will drive down the cost of electrolyzers needed to produce hydrogen.

### Obstacles to producing green steel

Green steel plants are under construction or at the advanced planning stage in Sweden, China, Germany and Spain. However, there are several obstacles to be overcome before the technology can be widely adopted. These include:

1. The supply of high-grade iron ore.
2. Access to new renewable energy sources.
3. Electrolyzer supply.
4. Sunk costs of blast furnaces and the US$2.8 trillion cost of decarbonizing the steel industry.[5]

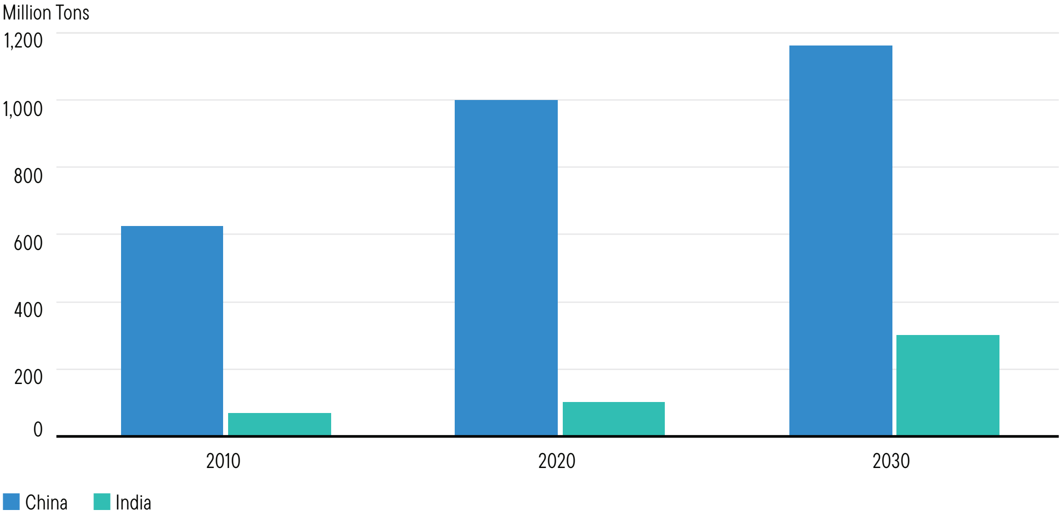
### The global steel market

Global steel demand in 2022 was estimated to be 1.8 billion tons (b/t), broken down as 1.35b/t from new steel and 0.45 b/t from scrap.[6] Steel demand is forecast to grow to 2.5–2.8 b/t by 2050 based on assumptions for steel consumption per capita as economies develop and mature.[7] Global per-capita stock of steel is estimated to be 4.5 tons, 12 tons in the United States, and 7.5 tons in China.[8] Given the industrialization needs of India and the MENA region, the demand assumptions are unlikely to disappoint, in our view.

### Steel production in India to rise by 2.5x

India stands out as one of the primary drivers of increased steel demand as the economy industrializes and steel consumption increases from current low level of 80 kilograms (kg) per capita to an estimated 160 kg per capita by 2050.[9] Relative to production of 111 million tons in 2020,[10] production is forecast to rise to 300 million tons by 2030.[11] While this is a rapid pace of growth, it is less than half the one billion tons of steel China produces annually.

Exhibit 3: India and China Steel Output (2010–2030)



Source: World Steel Association. China Metallurgical Industry Planning and Research Institute. 2021. There is no assurance any forecast, projection or estimate will be realized.

Forecasts for an additional one billion tons of steel demand globally by 2050 are plausible once the global economy continues to expand and more economies industrialize. As such, the primary lever for the steel industry to decarbonize is unlikely to come from lower demand; rather, the industry will have to adopt new production processes, including producing steel from zero-emission hydrogen. This is of global relevance as without the decarbonization of the steel industry (along with transport, and energy) countries will fail to achieve their net-zero commitments.

### Carbon emissions from steelmaking

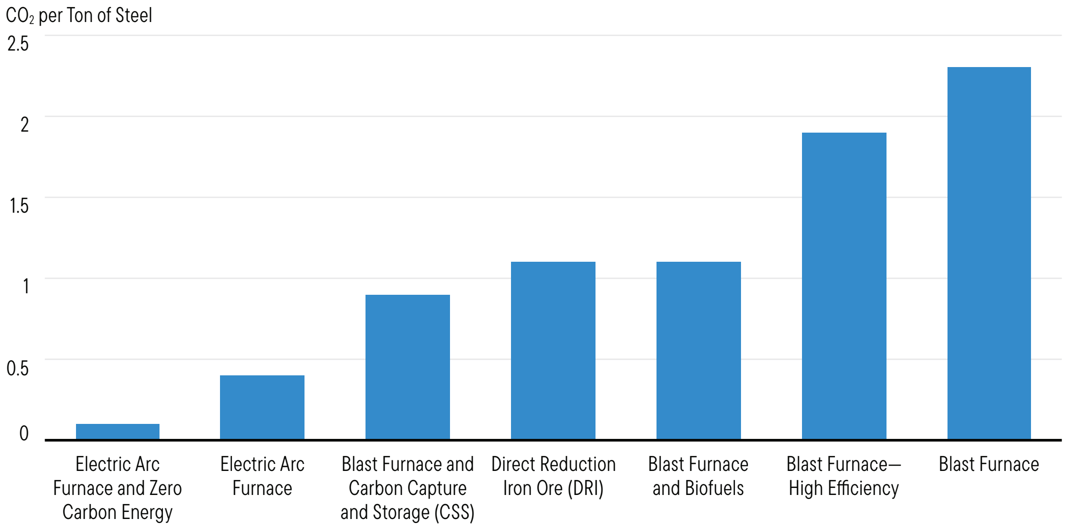
For every ton of steel produced, the global average of carbon emissions is 1.85 tons.[12]

As economies mature, the raw material used in production of steel changes, and with it, the carbon intensity. In the developed world, where the steel capital stock is high, scrap steel is the primary raw material for steel production in an electric arc furnace (EAF). The carbon intensity of steel produced via EAF is 0.4 tons of carbon dioxide ($CO_2$) per ton of steel. In emerging markets where the capital stock of steel is low and there is a greater reliance on using iron ore and coal in a blast furnace, the emission intensity is 2.3 tons of $CO_2$ per ton of steel produced. This contrasts with steel produced from direct reduced iron (DRI) using green hydrogen, which emits a mere 0.1 ton of indirect $CO_2$ emissions.[13]

### Green steel plans by country

Europe is currently at the forefront of producing green steel, thanks to low renewable energy costs in selected countries and supportive government policies. Its carbon emissions from steel are already below the global average, at 1.1 tons of $CO_2$ per ton of steel.[14] This is due to its large stock of steel per capita and high use of scrap (50%) in steel production.

## Exhibit 4: $CO_2$ Intensity of Steel Production



Source: Energy Transitions Commission. 2022.

### Green steel plans by country

The European Commission has approved state aid valued at 50% of the cost to upgrade the European steel industry. The subsidies reflect its strategic importance in meeting Europe's net-zero commitment as well as the role that the industry can play in innovation.

ArcelorMittal[15] recently received approval for a €515 million state aid for a planned €1 billion DRI plant in Spain and €55 million to construct an EAF using DRI in Germany. The US Inflation Reduction Act also has incentives to produce hydrogen; however, given the supply and low cost of shale gas, not all the hydrogen produced will be zero carbon. China does not have a national policy on steel decarbonization, but individual companies are pursuing their own plans to align with investor expectations.

In contrast, India is one of the most carbon-intensive steel producers globally, at 2.8 tons of $CO_2$ per ton of steel.[16] The country produces less than 1% of global steel output, but accounts for 17% of global steel carbon emissions. This reflects its use of coal as a reductant and a heat source for the blast furnace.

India plans to reach its net-zero commitment by 2070, 20 years later than that required to limit the pace of global warming to below 1.5°–2°C. Clearly, some form of technology transfer to India will be required to facilitate the decarbonization of its steel industry, and potentially an improvement on its net-zero commitments.

Our assessment of the outlook for steel production in India is that companies have a greater focus on increasing blast furnace capacity as opposed to focusing on lower-carbon production methods. This reflects India's stage of development and limited availability of scrap steel, which can be used in more efficient electric arc furnaces. We are engaging with local steel companies on their decarbonization journey, but acknowledge that more developed emerging markets, including South Korea, are more advanced in theirs.

Analysis of steel company expansion plans in India between 2022–2025 highlights a 20% capacity increase to 177 million tons. This compares with a 5% increase in the prior three years. All of this capacity increase is via blast furnaces, which are more energy-intensive and emit more carbon than energy-efficient electric arc furnaces.

China is the world's largest steel producer, with annual production of one billion tons a year. The elevated production reflects China's industrialization policies and its focus on infrastructure development. China is responsible for 54% of global carbon emissions from the steel industry, reflecting is dominance in production.

China's plan to reach net zero by 2060 will require significant investment in renewable energy and in carbon-intensive industries, including steel. Companies we have engaged with have highlighted detailed plans, but we acknowledge that without government support and technology transfer, progress may be slower than corporate plans suggest.

## Case Study: Baosteel

Baosteel[17] is a China-based steel producer; its parent company Baowu Steel Group is the world's second-largest steel company.[18] Baosteel reports its 2022 steel output was 52 million tons.

### Decarbonization plans

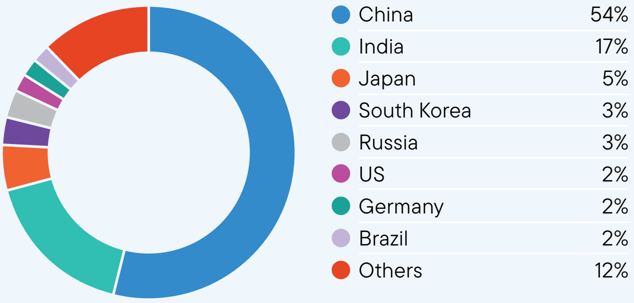
Baosteel is working with an Italian company, Tenova, to build DRI capacity using its Energiron direct-reduction technology process. The company is planning a 30% reduction in carbon emissions by 2030, targeting US$1.5 billion capital expenditure to achieve this goal, which is centered around six decarbonization targets:

1. Hydrogen production of 1 million tons (m/t) in 2023, 1.8 m/t in 2024.
2. Using hydrogen to produce DRI and build a new electric arc furnace.
3. Signing renewable energy takeoff agreements and exploring tapping nuclear power from the new Zhanjing nuclear power plant scheduled to open in 2028.
4. Optimizing energy efficiency.
5. Sourcing scrap steel from auto manufacturers as an input.
6. Conducting a feasibility study on carbon capture and storage.

### Green steel

The company plans to produce steel from grey hydrogen utilizing natural gas in the near term, with the feasibility study in CCS enabling a transition to blue hydrogen over time. Baosteel is transitioning from coal to natural gas to hydrogen to produce DRI between 2023–28 and eventually aims to use 100% renewable power for steel production in its furnaces.

Exhibit 5: Global Carbon Emissions by Country



Source: Global Efficiency Intelligence. 2022.

The company's transition to zero-emission hydrogen to produce DRI and green steel is an ambitious one. Baosteel will have to master two production processes and source sufficient renewable energy to enable this. The construction of a nuclear power plant close to its iron works may resolve the latter challenge. CCS studies are likely to have some government support given their broad applicability. Our view of the company's plans is to welcome the intent but we note that progress has been limited thus far.

### Constraints

Baosteel has identified a shortage of scrap steel in China as a constraint, but is approaching auto manufacturers to address this. Subsidies from the government are limited, which could slow the company's decarbonization efforts given the costs involved. Baosteel is relying heavily on CCS to offset its use of natural gas as the reductant agent, and this technology remains unproven at scale. Despite these constraints, if Chinese policymakers pivot to more aggressively support the decarbonization of the industry, Baosteel could be a beneficiary.

***Note: Baosteel is used as an example in this paper because it is the largest Chinese steel company. Franklin Templeton does not recommend or endorse Baosteel.***

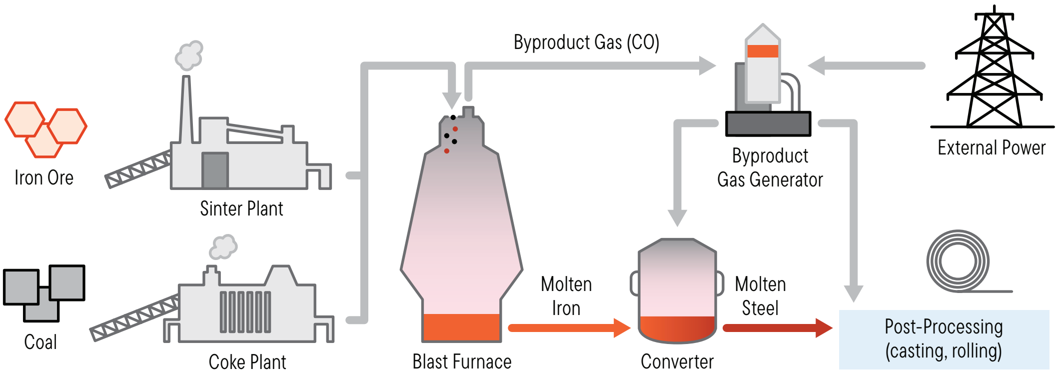
### Sources of carbon in steelmaking

Coal is the primary source of carbon emissions in the steelmaking process. This can be divided between direct and indirect emissions. As illustrated in Exhibit 6, the direct release of emissions happens when coal is added to iron ore in a blast furnace and heated to 3,000°F. Heating coal releases carbon monoxide gas, the reductant agent, which then triggers a chemical reaction separating or reducing the oxygen in the iron ore. Molten iron is produced with the released oxygen combining with carbon to create carbon dioxide.

Exhibit 6: Blast Furnace Steelmaking Process

**Blast Furnace Operation**

**Blast Furnace**



Source: POSCO. 2018. For Illustrative Purposes Only.

The indirect source of emissions is the process of burning fossil fuels to create the necessary heat for the chemical reaction to occur in the blast furnace. This can be coal, gas or other fossil fuels.

When producing steel from green hydrogen, the blast furnace is replaced with a fluidized reduction furnace. Hydrogen acts as the reducing agent when it is added to the iron ore, and triggers a chemical reaction separating or reducing the oxygen in the iron ore. Iron pellets are produced when released oxygen combines with hydrogen to create water. The iron pellets are known as DRI.

There are no direct sources of carbon produced in this process as green hydrogen is carbon-free. In the fluidized reduction furnace, the iron ore and hydrogen mix does not melt; rather, it is formed into DRI. When the DRI is added with scrap metal in the EAF, there are no indirect sources of emissions—assuming the electricity is produced from renewable energy.

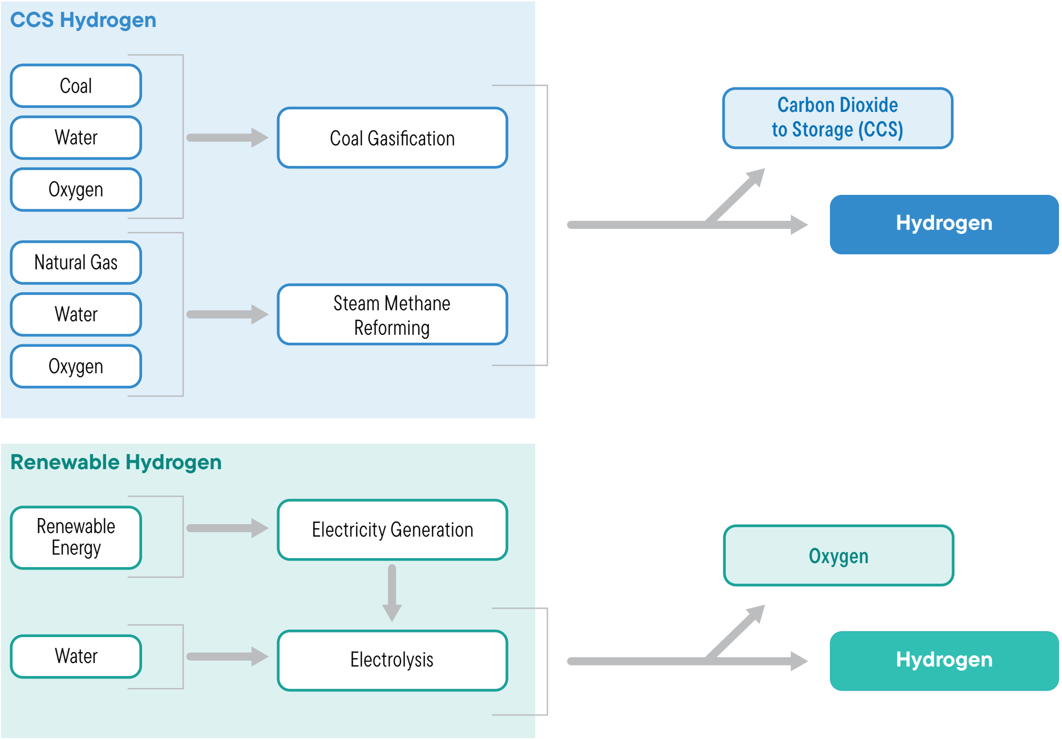
Emerging market steel companies tend to have high direct and indirect emissions, as most use coal as the reductant and heat source. POSCO[19] in South Korea does have well-developed plans to transition from coal to hydrogen as a reductant and heat source. South Korea is likely to be an importer of green hydrogen, which will raise the cost of green steel production relative to peers using renewable energy to produce green hydrogen.

Chinese steel companies also have decarbonization plans, but they are not as advanced as those in South Korea and rely on blue hydrogen as a transition fuel. We remain in discussion with these companies as to whether investing in unproven technology such as carbon capture and storage to produce blue hydrogen is the best use of scarce capital.

### Carbon capture and storage

Carbon capture and storage (CCS) is an alternative method to reduce emissions in steel production. Steel companies propose using CCS with hydrogen produced from coal gasification or the steam methane reforming process. As highlighted in Exhibit 7, the primary difference between these two processes and zero-emission hydrogen is the former use coal or natural gas as the heat source to separate water into hydrogen with carbon dioxide as a by-product, whereas the latter uses renewable energy with oxygen as a by-product. CCS technology remains in its infancy and is untested at scale, as reflected in its classification on the technology readiness scale as proof of concept.

Exhibit 7: Hydrogen Production Processes



Source: Hydrogen for Australia's future, Commonwealth of Australia. 2018. For Illustrative Purposes Only.

Capturing the carbon released in coal gasification or steam methane reforming process is in principle an effective way to reduce emissions. It has been widely researched as a valid technology to contribute to the achievement of net-zero emissions. As the name suggests, carbon is captured—or more specifically the flue gas—from the burning of fossil fuels, which is pumped through ducts as opposed to being vented into the air.

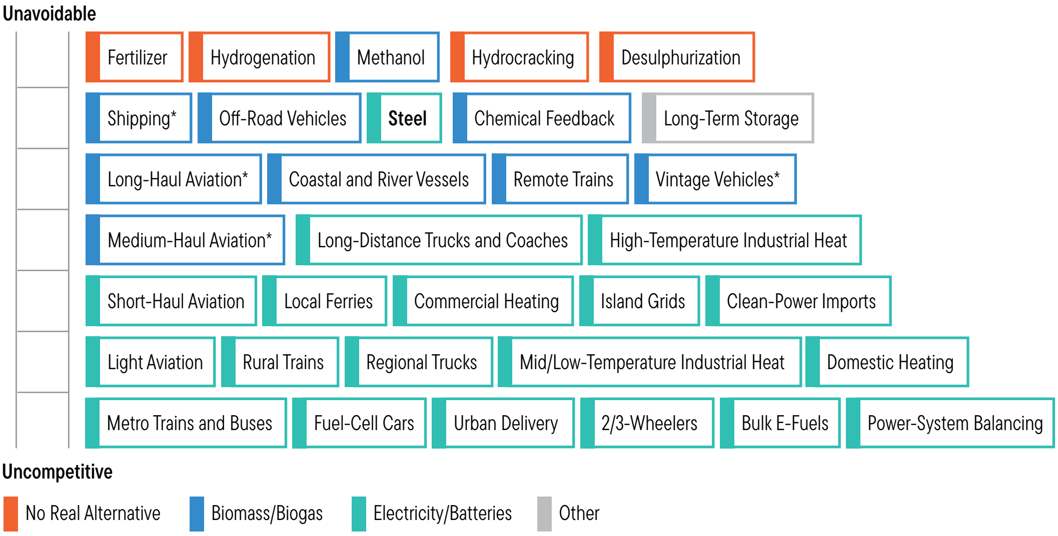
There are a number of challenges with CCS—the most significant is the absence of a large-scale plant. The largest proof of concept is in Iceland, but its capacity is a mere 4,000 tons of carbon dioxide per annum, the equivalent annual emissions for 250 people.[20] The plant captures carbon dioxide from the air—as opposed to flue emissions from the burning of fossil fuels—implying the technology is not transferable to the decarbonization of steel.

Reflecting the challenge the proof of concept plant faces in scaling up, the original goal of the Icelandic plant was the removal of 300 million tons of carbon dioxide from the air by 2025. This goal has since been scaled back to 500,000 tons by 2030. The concern for investors is steel producers' large-scale CCS plans will have to be scaled back, missing their decarbonization targets.

## Hydrogen as an energy source

Hydrogen can be used as a replacement for fossil fuels in transportation, petrochemicals, electricity generation, heating, cooling and steel. However, it may not be appropriate to use hydrogen as a replacement fuel source for all these applications. Aside from petrochemicals, the others can utilize electricity generated from renewable sources or batteries. This is particularly relevant for transportation that has already been electrified or uses batteries. Michael Liebreich[21] created the Hydrogen ladder to summarize the fuel's relative competitiveness using the European Union's A to H energy-efficiency scale.

Exhibit 8: Hydrogen Ladder



Source: Liebreich Associates. 2021. For Illustrative Purposes Only. *Via ammonia or e-fuel rather than H2 gas or liquid.

## Hydrogen supply

Global hydrogen supply must increase dramatically if it is to be a practical fuel source in steel production. The International Energy Administration (IEA) estimates total global production in 2022 was 94 m/t and forecasts this needs to rise to 530 m/t by 2050 based on the needs of industry (including steel) transportation and power. Given the assumption that a ton of green steel requires 90kg of hydrogen, if the industry switched to hydrogen-based green steel today, it would require 122 m/t of hydrogen or 130% of total current supply, based on existing output of new steel. However, most hydrogen produced today is from coal or natural gas.

The technology to create hydrogen from water is well-established, nevertheless, there are two practical challenges to increasing green hydrogen supply to the IEA's 530 m/t forecast. The first is the supply of renewable electricity, used as the heat source, and the second is the supply of electrolyzers, which is the process system that uses electricity to convert water into hydrogen and oxygen.

Low current supplies of green hydrogen represent an obstacle we have identified to increasing green steel output in both emerging and developed markets. Currently, green hydrogen is only produced in demonstration quantities of a few million tons per year. Nevertheless, we view current output as a snapshot before major investment in the sector begins. As the cost of inputs to generate renewable energy continues to decline, we expect investment plans for green hydrogen to accelerate.

### Renewable energy

Creating a ton of steel is estimated to require 4.3 megawatt hours of electricity to produce the required amount of hydrogen.[22] Converting current global steel output to green steel from green hydrogen would require 5,700 terra watt hours (TWh) of electricity. This represents over twice the current installed capacity of renewable electricity globally.[23]

Analyzing steel company reporting of Scope 1/2 emissions[24] for FY2022, we focus on steel carbon intensity. Steel companies in Asia have higher carbon intensity compared to those in Europe and the US. While this is not the sole factor we use in our assessment of companies, we use the data in our engagement with company management on their plans to improve carbon efficiency.

## The green hydrogen production process

An electrolyzer is a system that uses electricity to convert water into hydrogen and oxygen gas via electrolysis. Hydrogen gas can be stored as a compressed gas or liquid. This gas/liquid has many purposes. It can be used as the reductant agent to create DRI, and can also be used as a fuel to generate energy for transportation or a heat source to produce molten steel from DRI. The oxygen created via electrolysis can be released into the atmosphere or captured to supply other industrial or medical processes.

Electrolyzer technologies that separate water into hydrogen and oxygen include proton exchange membrane (PEM), alkaline, solid oxide, and ion exchange membrane electrolyzers. Due to their lower cost, alkaline electrolyzers are the most popular, but this could change if the cost of precious metals used in PEM electrolyzers comes down.

The central challenge in the production of hydrogen using electrolyzers is their supply and cost. Economies of scale matter. Based on the forecast demand of 500 m/t of hydrogen per year by 2040 (rounded down from 530 m/t by 2050), the world will need 4,000 GW of electrolyzer capacity, which implies a compound annual growth rate of 25% per annum from the estimate installed capacity of 38 GW of electrolyzers in 2025.[25]

### The steelmaking process

There are three commercialized processes for making steel:

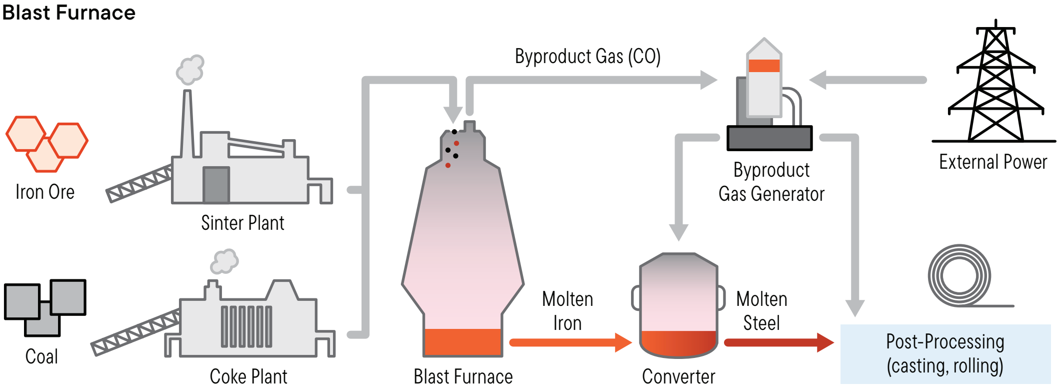
1. Blast furnace operation.
2. Fluidized reduction furnace using a mix of fuels.
3. Fluidized reduction furnace using hydrogen.

The traditional blast furnace method, the most widely used steelmaking process globally, utilizes fossil fuels as a heat source to raise the temperature in the blast furnace to 3,000°F, when coal and iron ore are added to create molten iron. This is then processed in a converter to produce molten steel.

## Exhibit 9: Steelmaking Process

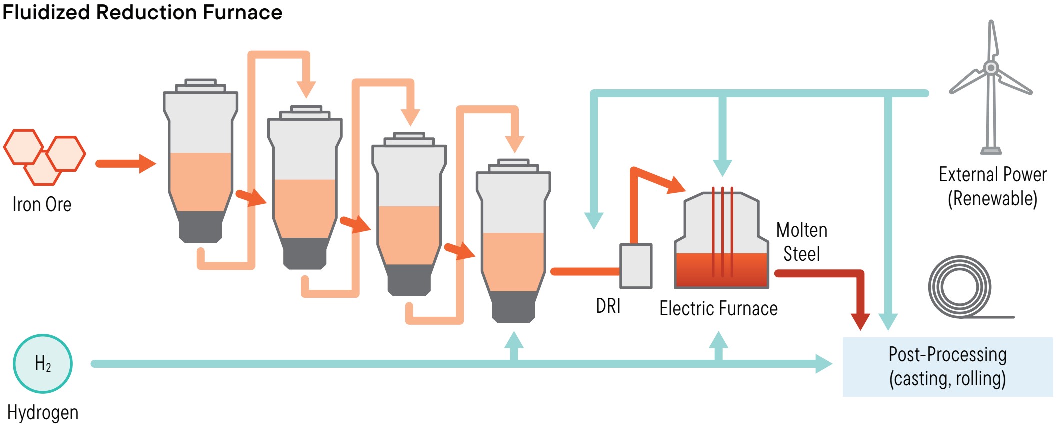
**Blast Furnace Operation**

**Blast Furnace**



**Hydrogen Based Steelmaking (HYREX)**

**Fluidized Reduction Furnace**



Source: POSCO. 2018. For Illustrative Purposes Only.

The fluidized reduction furnace process dispenses with the blast furnace and processes the iron ore with coal and hydrogen to create DRI, which is then processed into molten steel. The zero-emissions version of the fluidized reduction furnace uses green hydrogen and processes the DRI in a EAF to produce molten steel.

The hybrid version of a fluidized reduction furnace uses a mix of fuels: hydrogen and iron ore to make DRI, and coal in the melter gasifier to produce molten iron. This is then processed into steel.

Steel companies can be fully integrated and produce the DRI as well as molten steel in the EAF, or they can focus on only one part of the processes. The production of ultra-low emissions DRI is the most energy-intensive part of the process and requires a reliable source of renewable energy to produce the hydrogen to act as the reductant agent. This has implications for the geography of where DRI can be produced, as some regions globally are more endowed with renewable energy resources than others, which we discuss in the constraints section.

The key difference between a blast furnace and fluidized reduction furnace is the reductant agent. Raw iron ore needs to have the oxygen it contains “reduced” to produce molten iron. This can be done by the addition of carbon such as coal or gas, which combines with the oxygen in the super-heated iron ore to release carbon dioxide as one of the byproducts. Or, it can be done by the addition of hydrogen, which also combines with oxygen, but the byproduct is water.

## Case Study: SSAB/LKAB/Vattenfall HYBRIT project

### Fossil-fuel-free steel

Three Swedish companies—steel manufacturer SSAB, mining company LKAB and the energy company Vattenfall[26]—aim to create the world's first zero-carbon steelmaking process from mine to finished product. Its location in Sweden reflects the availability of low-cost renewable energy and high-grade iron ore. The consortium calls their process Hydrogen Breakthrough Ironmaking Technology or HYBRIT.

### Abundant natural resources

Sweden has a long history in steelmaking based on its abundant renewable energy resources and high-grade iron ore mines. In the 18th century, Sweden dominated global steel production, accounting for an estimated 35% of production.[27] That began to change when lower-cost coal replaced charcoal as the reductant in the steelmaking process. However, its reserves of high-grade iron ore remain, and an abundance of renewable power has once again placed it at the center of the global steel industry, albeit not by volume.

### Green steel timeline

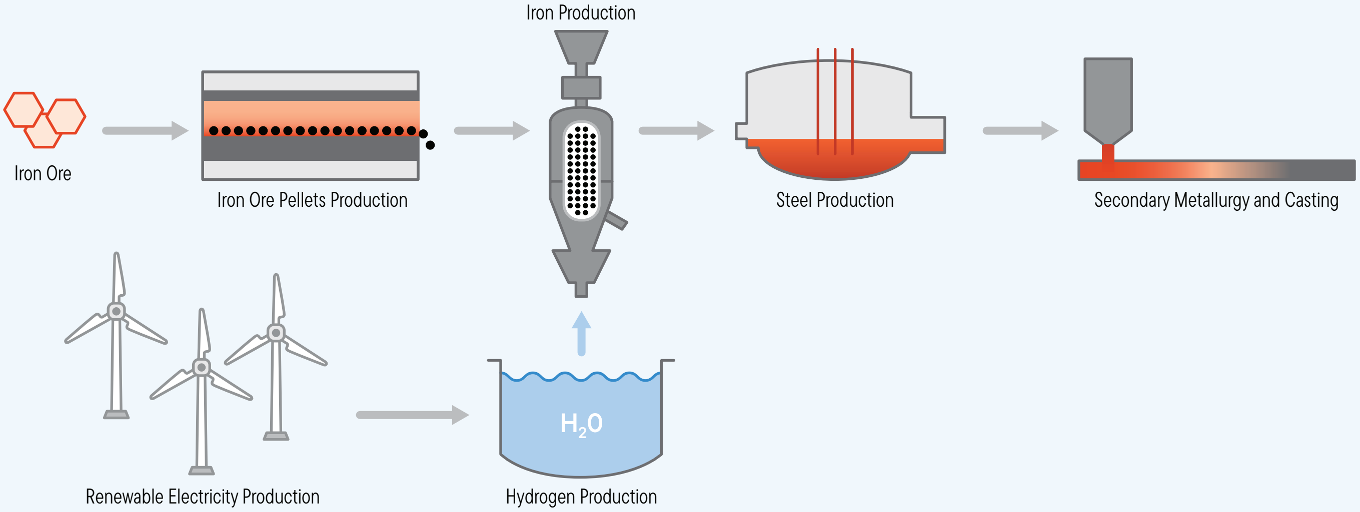
The process of creating fossil-fuel-free steel in Sweden started in 2016, when the Swedish energy agency funded a feasibility study on the process. This led to a joint venture between SSAB/LKAB/Vattenfall. Fossil-fuel-free DRI was produced in 2018 at a demonstration plant. The next phase of development, for which the European Commission has been granted US$100 million in funding, is a plant expected to produce 1.3 m/t of DRI by 2026 and 2.7 m/t by 2030.[28] SSAB already uses DRI in its blast furnaces, but plans to spend US$4.3 billion on new infrastructure including a renewable-energy-fueled electric arc furnace to reduce carbon emissions to zero.[29]

### The Swedish cost advantage

The cost difference per ton of steel produced in a blast furnace using natural gas and in an electric arc furnace using renewable energy and DRI produced from hydrogen is estimated to be a 17% cost advantage for green steel.[30] However, this is highly dependent on fossil fuel, power and iron ore costs. One of the reasons why the HYBRIT project was launched in Sweden is the ability of the three firms SSAB/LKAB/Vattenfall, which each specialize in individual parts of the steelmaking process, to come together and agree on long-term investments and long-term input prices to reduce the financial risks of the project. Companies in other countries will need to secure similar long-term supply agreements to unlock the investment required for projects with a life span of 30–50 years.

***Note: SSAB/LKAB/Vattenfall is used as an example in this paper because it is the only consortium developing integrated DRI, steel and using renewable power. Franklin Templeton does not recommend or endorse SSAB/LKAB/Vattenfall.***

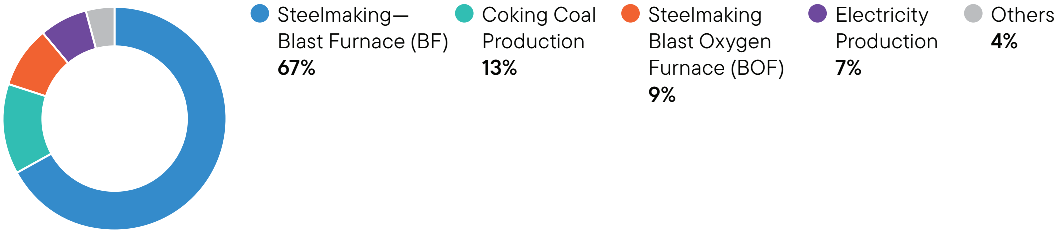
Exhibit 10: SSAB's HYBRIT Process



Source: SSAB. 2020. For Illustrative Purposes Only.

Switching to hydrogen-based steelmaking removes an estimated 90% of the carbon released compared to traditional blast furnace. If the electricity used to power the electric arc furnace is renewable, emissions can be further reduced, but not eliminated as some carbon is still required in the steelmaking process.

Exhibit 11: Carbon Emissions in Traditional Steelmaking Process



Source: International Energy Agency.

### Combined expertise to demonstrate green steel production

Producing ultra-low emissions DRI in a fluidized reduction furnace is classed as a demonstration technology on the technology readiness scale. A consortium of companies with expertise in renewable energy, steel and iron-ore mining are currently testing the most advanced prototype in Sweden. Sweden is uniquely well-positioned to produce ultra-low emission DRI and green steel, as it has high-quality iron ore required for producing DRI and ample renewable energy available for producing green hydrogen.

Emerging market companies are closely watching developments in Sweden for the potential commercialization of this technology. South Korea's POSCO is accelerating its own plans for producing ultra-low emission DRI independent of Sweden's prototype, but we note that full hydrogen-based steelmaking remains in the planning as opposed to prototype stage.

## Constraints on green steel production

To scale up green steel production using hydrogen as the heat source and reductant agent, there are supply related and financial issues that must be resolved. These include:

1. High-grade iron ore availability.
2. Access to new renewable energy sources.
3. Electrolyzer capacity.
4. Sunk costs of blast furnaces and the US$2.8 trillion cost of decarbonizing the steel industry.[31]

### High-grade iron ore availability

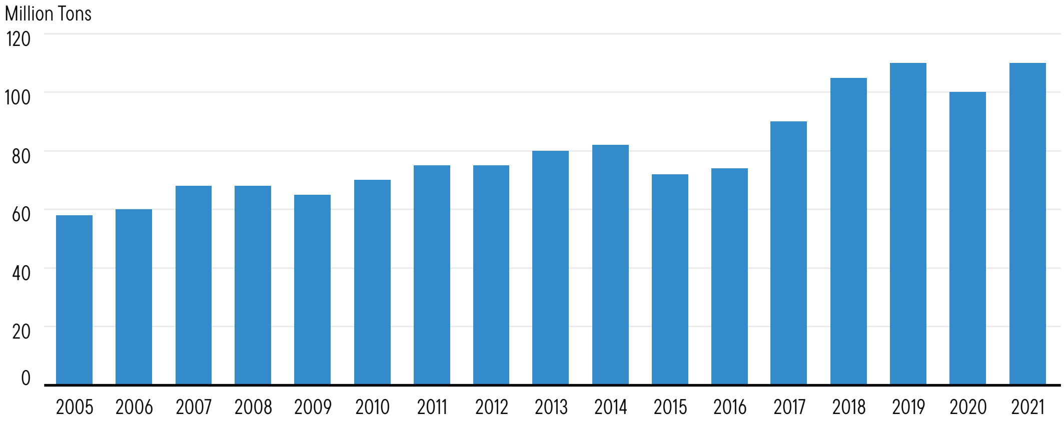
The production of DRI in a fluidized reduction furnace requires higher-grade iron ore, or 72% magnetite, produced mostly in Brazil, Canada and South Australia. Blast furnaces use 67% hematite, which is produced mostly in Western Australia, China and Brazil. In 2021, global production of 67% hematite was 2.5 billion tons,[32] higher-grade production is estimated to be 115 m/t.[33]

Planned fluidized reduction furnaces imply demand for higher-grade iron ore will increase to 150 m/t by 2030.[34] As higher-purity iron ore grades trade at an average 20% premium to lower grade,[35] there is an incentive for producers to invest in production. The leading producer in Brazil has announced plans for 72 m/t of DR agglomerates, which includes higher-grade iron ore by 2030. Brazil is expected to be the largest supplier of high-grade iron ore globally.

Exhibit 12: World's Largest Iron-Ore-Producing Countries

Source: BHP. 2020. There is no assurance any forecast, projection or estimate will be realized.

Exhibit 13: Global Direct Reduction Iron Ore (DRI) Production



Source: Worldsteel. 2022.

Current plans to increase higher-grade iron ore production take us through to 2030. Supply between 2030–2050 will have to increase dramatically if plans for the decarbonization of steel production are to be fulfilled. Reasons why there are few plans beyond 2030 relate to a lack of clarity of the role that carbon capture and storage will play in decarbonization plans as well as the regulatory stance on alternative fuels, including biomass and biogas.

### Access to new renewable energy sources

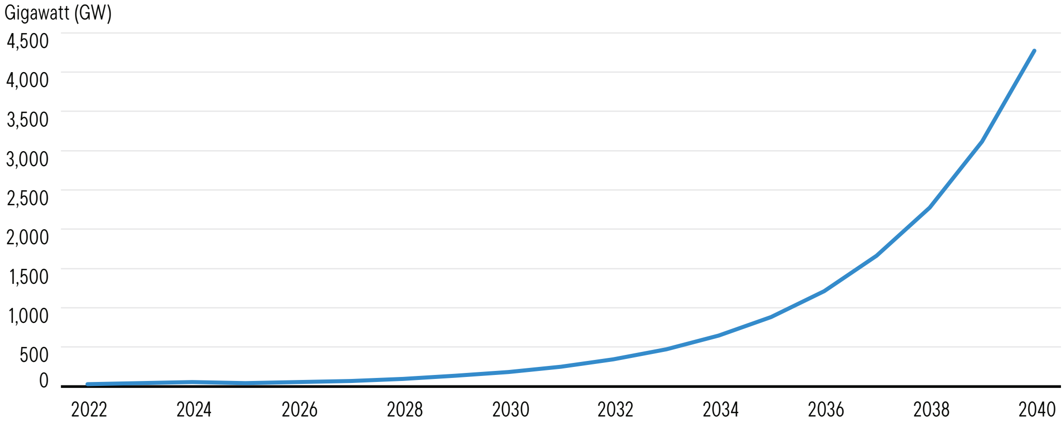
While the label "green hydrogen from renewable resources" may appear uncontroversial, the challenge relates to the principle of additionality. In Europe, the European Commission is keen to ensure that green hydrogen is produced from additional renewable energy sources as opposed to displacing existing capacity. The concern is electricity produced from fossil fuels would be needed to replace the renewable electricity used for hydrogen production, and thus push up total carbon emissions. As the European Commission established the principle and rules governing additionality in the first quarter of 2023, producers now have the clarity they need to push ahead with investment plans.

Access to renewable energy is a key factor for steel producers to consider when establishing new steel plants based on fluidized reduction furnaces. Scandinavia benefits from abundant renewable energy from hydro and wind sources. This is reflected in Europe's first DRI plant and first large-scale battery plant locating in Sweden. Southern Europe benefits from solar electricity, with DRI and battery plants also planned for the region. The United States has access to renewable energy, but the low cost of shale gas implies that this is the preferred energy source for producing hydrogen used in producing steel. Australia and the Middle East also benefit from abundant sources of renewable energy and are likely to be sources of green hydrogen. Asia stands out as having limited surplus renewable energy and may be an importer of hydrogen used in producing green steel.

### Electrolyzer capacity

Electrolyzer capacity is clearly a constraint on hydrogen production. Current global electrolyzer capacity is estimated to be 5 GW,[36] which is forecast to rise to 38 GW in 2025, and to 4,000 GW if forecast demand of 500 m/t of green hydrogen per year by 2040 is to be achieved.[37] This implies a compound annual growth rate of 37% per from the estimate installed capacity of electrolyzers in 2025.

Exhibit 14: Installed Base of Electrolyzers



Source: Carbon Commentary. 2022. There is no assurance any forecast, projection or estimate will be realized.

While this pace of growth in electrolyzer capacity is dramatic, companies such as NEL[38] of Norway is looking to ramp up production capacity to deliver on the needs of the industry. The IEA forecasts electrolyzer capacity will accelerate dramatically in the coming years as new production in Australia, Europe and the United States comes on stream. Supporting the production of this equipment is the premium that users of green steel have indicated they are prepared to pay to access the supply.

### Sunk costs of blast furnaces and cost of steel industry transformation

The current installed capacity of blast furnaces, which can cost billions to build and have a life span of 30–50 years, represents a constraint on the transformation of the steel industry. Given the age profile of blast furnaces globally, it appears that the switch to fluidized reduction furnaces will occur first in Europe and South Korea. Emerging markets including China will make the switch at a later date, but still intend to build demonstration plants in the near term to master the technology.

South Korean POSCO's oldest blast furnace first started production in 1973 in Pohang (according to company records) and is still in operation. The company is planning to switch to hybrid fluidized reduction furnaces that use a combination of hydrogen and coal. The development of fully hydrogen-based steelmaking in a fluidized reduction furnace is also in the planning stages. The company notes obstacles it needs to overcome including a reliable supply of renewable hydrogen, which must be imported due to the high cost of energy in South Korea compared to Northern Europe and the Middle East.

The primary challenge for the transformation of the steel industry is cost. Producing steel from zero-carbon green hydrogen is estimated to require an investment of US$2.8 trillion.[39] This is broken down as US$800 billion for the conversion of steel plants, based on estimated costs and capacity of Arcelor Mittal as well as electrolyzer costs of US$500 billion based on the sale prices from NEL and up to US$1.5 trillion in renewable electricity investment.[40]

## Case Study: POSCO

POSCO is a South Korean-based steel producer which is ranked the fifth largest globally,[41] with capacity of 42 million tons of steel in 2022.[42]

### Decarbonization plans

The company is committed to becoming carbon neutral by 2050. Between now and 2030, POSCO is focused on refining the technology required to produce green steel from hydrogen. Its 2030 target is for a 10% reduction in carbon emissions, which is a modest goal. However, the transition to net zero is not linear, with technology advances accelerating as each step in the decarbonization process is mastered.

### Green steel

In 2022, the company announced plans to invest US$14 billion in replacing blast furnaces in Gwangyang and Pohang. These are transitional technologies utilizing a hybrid fluidized reduction process called FINEX. This uses a reductant made up of 75% coal and 25% hydrogen to produce DRI, which is then processed in a converter to produce molten steel. As the company successfully implements the FINEX process, it will then pursue 100% hydrogen-based steel in a fluidized reduction furnace.

POSCO estimates that the complete transition to hybrid fluidized reduction process to produce green steel will require 3.7 million tons of hydrogen and 4 GW of renewable power annually. The government will partially meet the cost of developing the infrastructure required to meet this capacity.

As the technology matures, POSCO plans to transfer the technology to expand its plant in Indonesia and build a new plant in India to tap into the forecast growth in steel demand.

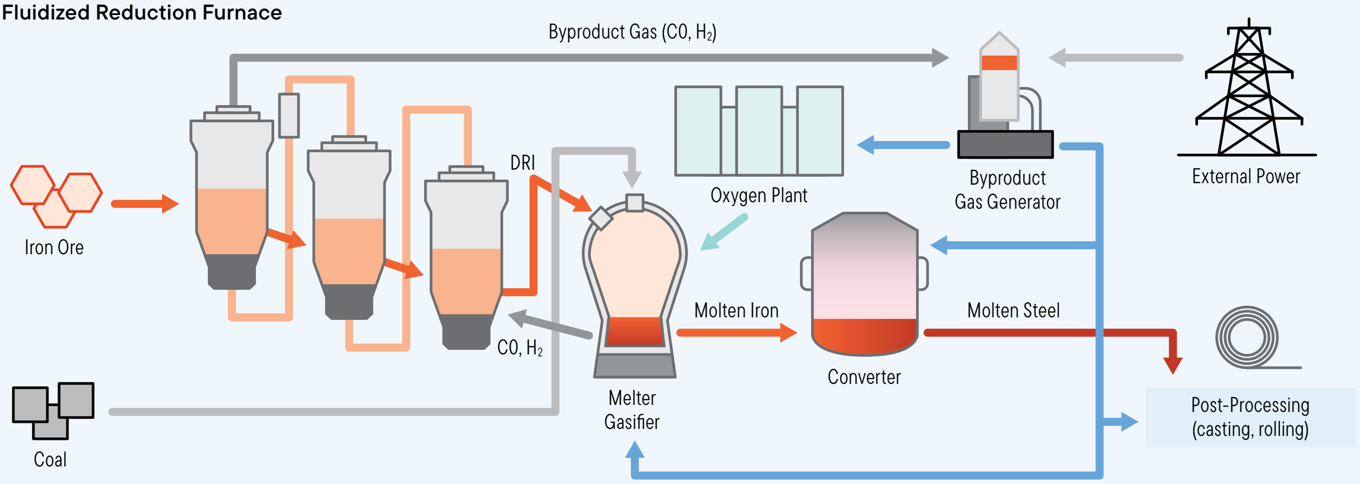
### Planning versus producing

Among the emerging market companies we have engaged with, POSCO is ahead of peers in its green steel production plans. However, its goal of a 10% reduction in carbon emissions by 2030 is modest. Its FINEX production process still uses 75% coal as a reductant, and it is unclear if the 25% hydrogen it will use is green or grey. We continue to engage with management on the detail behind the plans, and whether the company can be more ambitious in its carbon reduction goals.

***Note: POSCO is used as an example in this paper because it isthe largest steel company in emerging markets ex-China. Franklin Templeton does not recommend or endorse POSCO.***

Exhibit 15: POSCO FINEX Production Process

**Fluidized Reduction Furnace**



Source: POSCO. 2018.

This is the cumulative cost by 2050, implying an annual investment of slightly under US$100 billion per annum from 2020, which is the start date of Arcelor Mittal's investment forecasts. While the numbers are large, so is the industry. The global iron ore market is valued at US$130 billion in 2022, based on global production of 2.6 billion tons and an average contracted price of US$50 per ton.

## Conclusion

The steel industry is one of the largest contributors to global carbon emissions, accounting for 7% of total emissions in 2019. Emissions are forecast to rise by 44% by 2050. However, the successful decarbonization of the industry could change this increase in emissions to a significant decline via a switch to green steel produced with green hydrogen, as opposed to fossil fuels. There is also hope that carbon capture and storage could help reduce emissions; however, this technology remains unproven at scale.

A switch to green steel produced utilizing green hydrogen as a raw material will require an investment of up to US$2.8 trillion. The switch is already underway in Europe with a demonstration plant in Sweden, and Chinese steel companies are also planning to demonstrate the feasibility of the technology at scale. China's decarbonization plans will be important to watch given it is the world's largest steel producer. India will likely see the biggest increase in steel production in the coming decades. The country continues to focus on fossil fuels to produce steel and has ambitious plans for building blast furnaces, which are carbon-intensive.

We are optimistic that the switch to green steel using hydrogen as the reductant and heat source will occur in developed markets. However, as the drivers of the forecasted one billion tons' increase in steel demand by 2050 will be concentrated in emerging markets, these countries will need support and technology transfer if the challenge of decarbonization in the global steel industry is to be successful.

Our focus is on engaging with all companies. From a carbon perspective, this includes those with a high carbon footprint with a view to lowering it, as well as those with a low carbon footprint with a view to sharing best practice of what can be achieved with higher-emitting companies. We believe companies we engage with are at different stages of the transition to a lower carbon future. Our on-the-ground presence and cross-sector research collaboration helps to navigate the expectations and practicality of this transition.

1. Source: Energy Transitions Commission.
2. Source: Energy Transitions Commission. There is no assurance that any estimate, forecast or projection will be realized.
3. Source: Carbon Commentary. Note: green hydrogen is produced via renewable energy. There is no assurance that any estimate, forecast or projection will be realized.
4. Source: Mankins.
5. Source: Carbon Commentary. There is no assurance that any estimate, forecast or projection will be realized.
6. Source: World Steel.
7. Source: MDPI. There is no assurance any estimate, forecast or projection will be realized.
8. Source: International Energy Administration.
9. Source: India National Steel Policy. There is no assurance that any estimate, forecast or projection will be realized.
10. Source: World Steel Association.
11. Source: India National Steel Policy. There is no assurance that any estimate, forecast or projection will be realized.
12. Source: Energy Transitions Commission
13. Source: Energy Transitions Commission.
14. Source: European Commission
15. Arcelor Mittal is used as an example in this paper as it one of the 1st companies to receive state aid for a new DRI plant and furnace, and it also has the most detailed breakdown of capex forecasts. Franklin Templeton does not recommend or endorse Arcelor Mittal.
16. Ibid.
17. Baosteel is used as an example in this paper because it is the largest Chinese steel company. Franklin Templeton does not recommend or endorse Baosteel.
18. Source: World Steel Association.
19. POSCO is used as an example in this paper because it isthe largest steel company in emerging markets ex-China. Franklin Templeton does not recommend or endorse POSCO.
20. Source: Bloomberg New Energy.
21. Michael Liebreich is a leading global expert on clean energy and transportation, smart infrastructure, technology, climate finance and sustainable development. Franklin Templeton does not recommend or endorse Michael Liebreich.
22. Source: Carbon Commentary.
23. Ibid.
24. Scope 1, emissions are defined as greenhouse gasses that are produced directly at the source of the industrial activity of a company. Scope 2 covers the indirect emissions from purchased energy sources, such as a company's consumed electricity or cooling.
25. Carbon Commentary. There is no assurance that any estimate, forecast or projection will be realized.
26. SSAB/LKAB/Vattenfall is used as an example in this paper because it is the only consortium developing integrated DRI, steel and using renewable power. Franklin Templeton does not recommend or endorse SSAB/LKAB/Vattenfall.
27. Source: Metals Journal.
28. Source: SSAB.
29. Ibid.
30. Source: UBS.
31. Source: Carbon Commentary. There is no assurance that any estimate, forecast or projection will be realized.
32. Source: US Geological Survey.
33. Source: Green Steel Tracker.
34. Ibid.
35. Source: Platts.
36. Source: Carbon Commentary.
37. Source: Carbon Commentary. There is no assurance that any estimate, forecast or projection will be realized.
38. NEL is used as an example in this paper because it is the leading producer of electrolyte equipment. Franklin Templeton does not recommend or endorse NEL.
39. Source: Carbon Commentary. There is no assurance that any estimate, forecast or projection will be realized.Source: POSCO.
40. Ibid.
41. Source: World Steel Association.
42. Ibid.

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