Energy
Transitions
Commission

Pursuing Zero-Carbon Steel in China

A Critical Pillar to Reach Carbon Neutrality

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Authors & Acknowledgments

Authors

Ji Chen, Shuyi Li, Xiangyi Li, Ye (Agnes) Li

Authors listed alphabetically. All authors from RMI unless otherwise noted.

Other Contributors

Ting Li

Adair Turner (Energy Transitions Commission)

Contact

Shuyi Li, sli@rmi.org

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About Us

ABOUT RMI

RMI is an independent nonprofit founded in 1982 that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We awork in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing.

ABOUT ENERGY TRANSITIONS COMMISSION

The Energy Transitions Commission (ETC) is a coalition of global leaders from across the energy landscape: energy producers, energy-intensive industries, equipment providers, finance players, and environmental NGOs. Our mission is to work out how to build a global economy that can both enable developing countries to attain developed world standards of living and ensure that the world limits global warming to well below 2°C and as close as possible to 1.5°C. For this objective to be reached, the world needs to achieve net-zero greenhouse gas emissions by around mid-century.

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Preface

On September 22, 2020, President Xi Jinping proposed the strategic goal of peaking carbon emissions by 2030 and achieving carbon neutrality by 2060 (the Dual-Carbon Goals). This provides clear and strong political impetus for China to fully carry out decarbonization. Reducing the emissions from the steel industry is going to be a large part of that.

China produces and consumes more than half of the world's steel, accounting for about 17% of the country's carbon emissions. This makes the steel industry the country's second largest carbon emissions sector. Since the declaration of China's Dual-Carbon Goals, the steel industry has responded positively: Relevant departments of the central government have stepped up efforts to formulate action plans for the steel industry to peak emissions and industry associations and research institutions carried out research on paths for emissions peaking and carbon neutrality. Furthermore, leading enterprises such as Baowu Group and HBIS Group announced their targets to achieve carbon neutrality by 2050, along with schedules and formulated action plans for emissions peaking and carbon neutrality.

RMI and the Energy Transitions Commission's 2019 report China 2050: A Fully Developed Rich Zero-Carbon Economy (hereinafter referred to as the China 2050 Report) provides a comprehensive vision of a zero-carbon scenario for China's entire economy. The report makes a preliminary analysis of the energy consumption structure of China's steel industry after complete decarbonization.

This report aims to build on the China 2050 Report and further analyzes the specific path of China's steel industry to achieve the above zero-carbon scenario by 2050. We believe that under the 2050 zero-carbon scenario, China's steel demand will accelerate to peak and decline rapidly, and the product structure, energy consumption structure, and production process will undergo great changes:

- Secondary steel will replace primary steel to become the main force of China's steel production capacity.
- Fossil fuel and raw materials will largely withdraw from the steel production process.
- Hydrogen-based steelmaking will play an important role in primary steel production.
- Carbon capture and storage (CCS) technology will provide end-of-pipe treatment for decarbonization of carbon emissions associated with the remaining blast furnace-basic oxygen furnace (BF-BOF) steelmaking, which is often called “long process steelmaking” in China.

We chose the 2050 target for zero-carbon steel because we believe that China's steel industry is capable of and should decarbonize completely earlier than the country as a whole. This will allow it to make an important contribution to China's goal of achieving carbon neutrality by 2060.

Chapter 1:
Paving China's Path to Zero-Carbon Steel: Challenges and Opportunities

Under China's goal of reaching carbon peaking by 2030 and carbon neutrality by 2060, the steel industry—a pillar industry and a large energy consumer—must take action. Although China's steel industry faces many challenges to transition to zero carbon, it also has many advantages to leverage.

At the starting point of the zero-carbon transition, China's steel sector is facing both challenges and opportunities. The major challenges include cheap coal resources as the major feedstock, BF-BOF-dominating steel production, and the young age of steel capacity. But China also has many opportunities to leverage: the steel demand is going to peak and decline with a growing supply of scrap, China's steel companies have strong capability to develop and scale up new technology, and the country has a national zero-carbon target.

China is the world's largest producer and consumer of steel

China is the world's largest producer and consumer of steel. Even under the impact of the global pandemic in 2020, China's steel production reached a new high. In 2020, China produced more than 1 billion tons of crude steel, accounting for 56.4% of the world's total.[1] A total of 995 million steel products were consumed in China, accounting for 56.2% of the world's total. On the consumption side, 58.3% of steel was used in the building sector, 16.4% in machinery manufacturing, and 5.4% in automobile manufacturing (Exhibit 1).[2] China exports 51.4 million tons of steel and imports 37.9 million tons, a net export of 13.5 million tons.[3] China's steel products are mainly used to support industrialization and urbanization.

China's steel sector emitted more than 1.5 billion tons of CO_2 in 2017.[4] This accounts for 17% of the national total, making it the second largest emitter after the power sector (Exhibit 2).[5] Reducing emissions in the steel industry is crucial to achieving China's goal of carbon neutrality.

Exhibit 1: China steel production and consumption in 2020

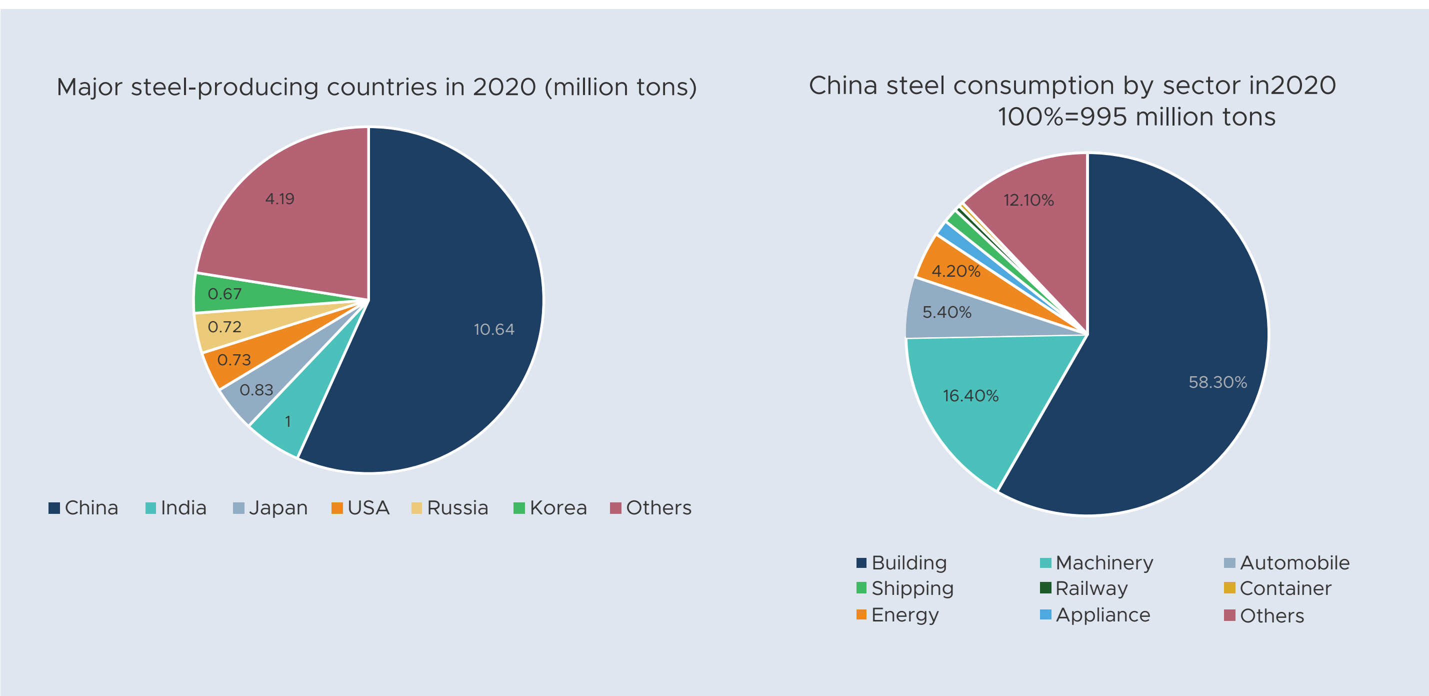
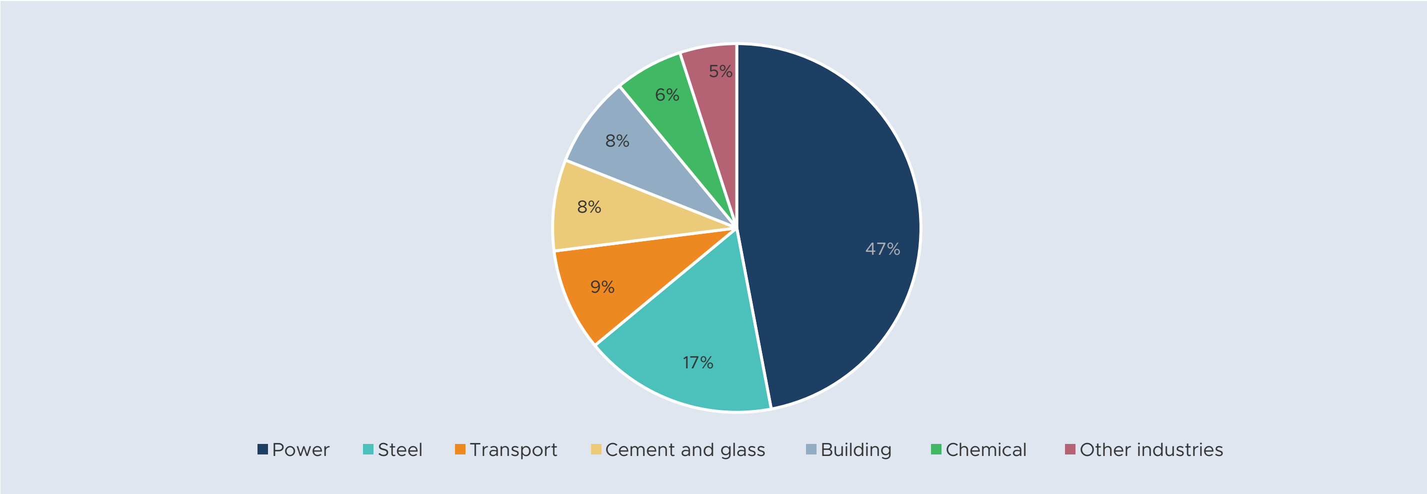


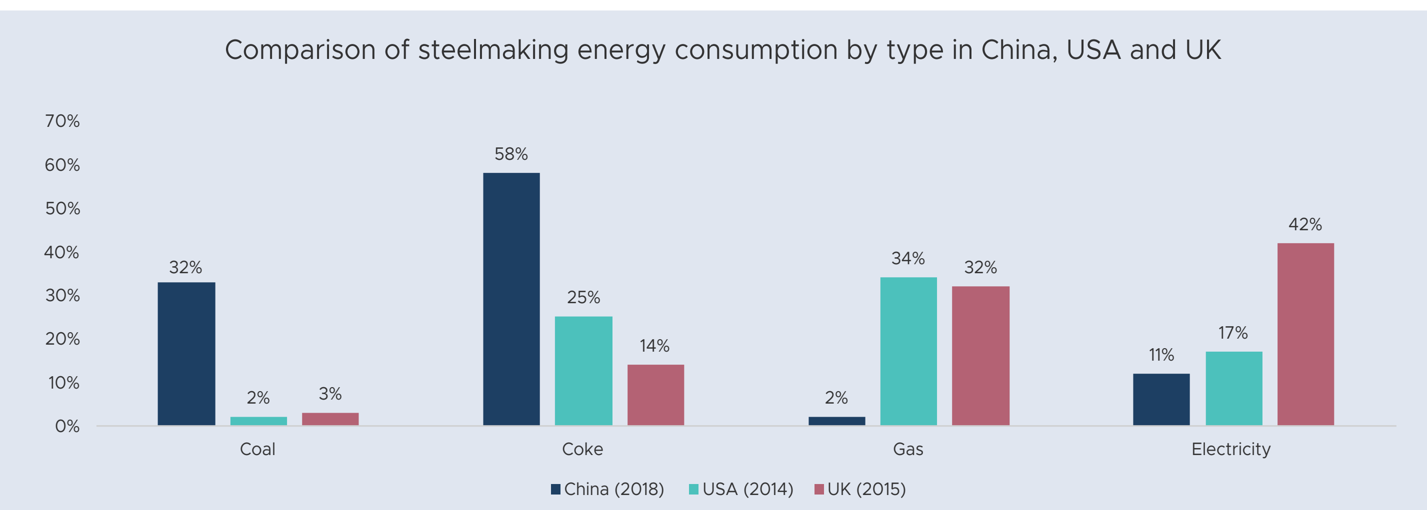
Exhibit 2: China's carbon emissions by sectors in 2019



Challenges for China's transition to a zero-carbon steel industry

China has abundant and cheap coal resources, making coal the dominant fuel for steelmaking, and coal has the highest carbon emissions compared with other metallurgical energy sources at the same calorific value. China's coal consumption and coke consumption account for a much higher proportion of energy use in steelmaking compared with developed countries such as Europe and the United States. As shown in Exhibit 3, in the case of the United States and the UK, without considering electricity consumption (which is related to electric arc furnace steel production), the energy type with the highest share of steelmaking in both countries is natural gas. For the same calorific value, coal combustion produces more than twice as much CO_2. Decarbonization of the Chinese steel industry is therefore a greater challenge.

Exhibit 3: Comparison of steelmaking energy consumption by fuel type in China, USA and UK



Sources: China Metallurgical Planning and Research Institute, China Statistic Book, Global Efficiency Intelligence (2017), Statista

China's steel production predominantly uses BF-BOF, of which the carbon emissions intensity is more than twice that of the EAF route. The BF-BOF route accounts for 90% of China's steel production, while EAF-based secondary steelmaking accounts for only 10%. In contrast, the global average share of the BF-BOF route is 73%, and only about 30% in the United States, far lower than the level of China. Coal is the main energy source and reduction agent of the BF-BOF route. The comprehensive energy consumption per ton of steel is about 550 kg of coal equivalent (kgce), emitting about 2 tons of CO_2. EAF-based steelmaking, with electricity as its main energy source, consumes about 500 kilowatt-hour (kWh) of electricity and emits about 0.6 tons of CO_2 per ton of steel (calculated based on average grid carbon intensity[i]).

The China steel sector has a larger share of young facilities, and the fast transition could take a higher stranded asset cost. Currently, the average age of China's blast furnace fleet is about 13 years, less than one-third of the typical lifetime of these plants. Compared with other countries, the stranded high-carbon asset of the steel sector would be larger for China. Therefore, it is crucial to answer the question of how to handle the existing assets.

Advantages of the zero-carbon transition of China's steel industry

China's steel industry is entering a stage of declining demand. Maturing industrialization and urbanization is gradually slowing down the speed of infrastructure construction in China, and the demand for basic materials such as steel will gradually peak and begin to decline. China's steel consumption has reached more than 700 kg per person, higher than the peak level in Europe and the United States. This is expected to peak in the short term and begin to continuously decline according to analysis, [6] with the total crude steel output soon entering a stage of decline.

The growth of total steel stock and the increasing supply of scrap are enabling the development of secondary steel in China. The increasing steel stock per capita in China also increases the stock of scrap resources. The early used steel products gradually reach their useful life, releasing more and more available scrap resources, which enables the accelerating development of secondary steelmaking with scrap as raw material.

China's steel industry needs to seize this opportunity to expand scrap output and utilization, expand secondary steelmaking capacity, and reduce the overall average carbon intensity of steel production.

China's steel industry has the experience and ability to promote innovation and the scale-up and industrialization of new technologies. China's steel industry has gone from purchasing foreign second-hand metallurgical equipment to manufacturing, integrating, and reinventing the equipment. China's steel smelting equipment manufacturing ability and technology reached an advanced level on a global scale with an independent supply rate of 95%. [7] These advances have improved production efficiency and energy efficiency as well.

Since 2000, China's comprehensive energy consumption per ton of steel has dropped by nearly 40%, and the energy consumption level and waste emissions level of many processes have reached the international advanced level. Facing the new carbon-neutrality target, Chinese steel companies have started planning on new technologies. Baowu, HBIS, Jiuquan Iron and Steel, Jianlong Steel, and other companies have begun to cooperate with domestic and foreign technology partners in areas such as hydrogen steelmaking and smelting reduction. China's steel industry can make full use of its strong innovation capability to play a key role in the rapid industrialization and scale-up of new technologies, and contribute to the decarbonization of China and the global steel industry.

i: Assumed grid carbon intensity is 0.9 tons CO_2/MWh. Reference: China National Center for Climate Change Strategy and International Cooperation, 2019. Baseline Emission Factor of China Regional Grid for Emission Reduction Projects.

The Chinese steel industry, led by the state-owned enterprises (SOEs), has the motivation and stability to implement national strategies and policies. In 2020, the top 10 steelmakers in China accounted for 39% of output. There is still a gap between the industry concentration and the 60% target proposed by the Ministry of Industry and Information Technology. However, the development trend and policy direction show that future production capacity will be concentrated in the head enterprises, and the mergers and acquisitions toward SOEs will be stronger. In general, SOEs have a stronger and more stable implementation of national policies and a leading role for the whole industry. For example, after China announced its carbon-neutrality target, SOEs such as Baowu Group, HBIS Group, and Ansteel Group announced their carbon-peaking and carbon-neutrality plans.

This report conducts an in-depth study of the zero-carbon roadmap for China's steel industry. The report covers the following:

- Chapter 2: A forecast of future demand and production of steel under the zero-carbon scenario.
- Chapter 3: Analysis of economic and market feasibilities of scrap utilization and the development of secondary steelmaking.
- Chapter 4: Analysis of transitional and breakthrough technologies of zero-carbon primary steelmaking and their future cost-competitiveness.
- Chapter 5: An integrated picture of the zero-carbon roadmap of China's steel industry from the perspectives of timeline and regional distribution.
- Chapter 6: A summary of the key public policies and industry developments required to drive progress toward a zero-carbon steel industry.

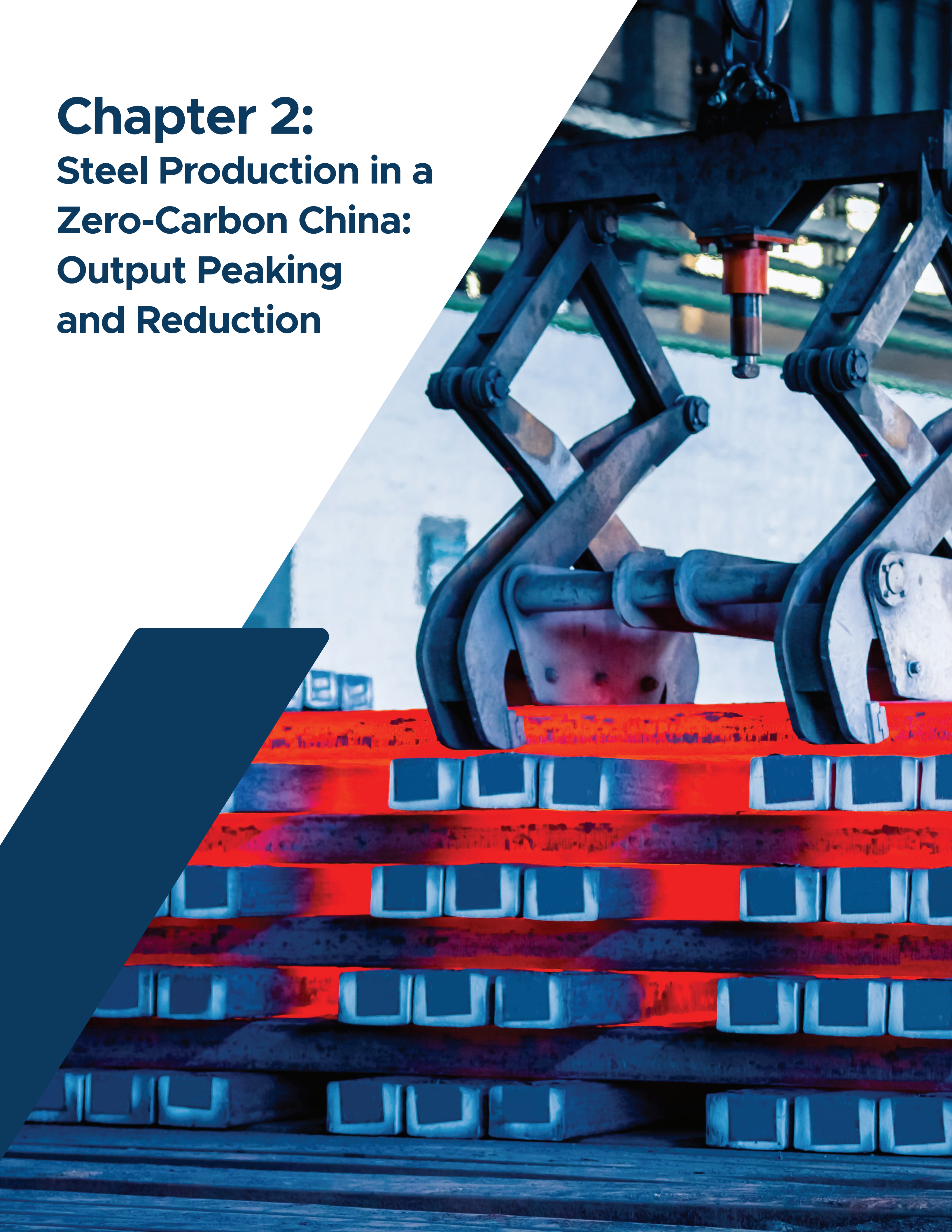
Exhibit 4: The top 10 China steel companies' production and state-owned enterprise (SOE) ratio in 2020

	Corporate	Production (million tons)	Type
1	Baowu Steel *	115.29	Central SOE
2	HBIS *	43.76	Regional SOE
3	Shagang (Shasteel)	41.59	Private
4	Angang (Ansteel) *	38.19	Central SOE
5	Jianlong	36.47	Private
6	Shougang (Shousteel)	34	Regional SOE
7	Shangang (Shansteel)	31.11	Regional SOE
8	Delong	28.26	Private
9	Valin	26.78	Private
10	Fangda	19.6	Private
	Total	415.05	
	State-owned enterprise (SOE) total	262.35	
	State-owned enterprise (SOE) ratio	63%	

Source: World Steel Association

*Note: Baowu Steel, HBIS, and Ansteel had announced carbon-peaking and carbon-neutrality targets by June 2021.

Chapter 2:
Steel Production in a Zero-Carbon China: Output Peaking and Reduction



The first step to achieve a zero-carbon steel industry is to reduce the production of crude steel, because carbon emissions are related to production, and carbon peaking is dependent on production peaking. Crude steel production is significantly related to the demand of the downstream industries and is usually affected by the import and export volumes and upstream raw material prices. In China, crude steel production is mainly driven by domestic demand. In 2020, domestic steel consumption accounted for more than 95% of total crude steel production, and steel exports accounted for less than 5% of that.

According to RMI's projections, in a zero-carbon development scenario, domestic steel demand in downstream industries will continue to be the key influencing factor to steel production in the future. This is true even though the imports and exports are highly uncertain, and their proportion is likely to increase as domestic consumption decreases. Therefore, this chapter will focus on the analysis of China's future steel demand, and explore the factors affecting future import and export, to get the outlook of China's crude steel production under the zero-carbon scenario.

Steel Demand in a Zero Carbon China

Even without a zero-carbon transition target, steel demand in China will peak and then rapidly fall with the completion of industrialization and urbanization. Now that the low-carbon target is released and added to this sector as a constraint, steel demand peaking and reduction processes will be accelerated.

The new development stages of industrialization and urbanization in China are the two main reasons that drive down steel demand domestically. Industrialization is one key factor that drives up steel demand in general. As most Chinese provinces and cities have entered the later stage of industrialization or even the post-industrialization stage,[8] the proportion of manufacturing industry has decreased overall, leading to the high-quality development stage of China's industrialization process. Under this new normal, demand for steel-intensive products is decreasing, manufacturing companies are enhancing product quality, and the overall demand for crude steel is much lower than before.[9]

The urbanization rate in China has skyrocketed to over 60% in past decades, about 20% less than that of an average developed country. In the next few decades, the growth rate of urbanization in China will slow down. Building livable, smart, green, and resilient modern cities and strengthening urban-rural integration will become mainstream. The trends of new urbanization and high-quality industrial development will reduce the overall demand for steel while maintaining economic vitality.

Ecological civilization, sustainable development, digital and intelligent transformation, and carbon-reduction targets are helping to mainstream the concept of a circular and sharing economy, which will lead to an overall reduction in steel demand. Under this trend, the downstream industries are incorporating volume reduction, resource utilization, and shared development, leading to an extended lifespan of products and infrastructure and an increasing recovery rate of scrapped products. This will further bring down the demand for steel, especially primary steel. In addition, the need to develop a circular economy will force the steel industry to adjust its industrial structure, improve the utilization rate of scrap steel and the output of EAF steel, and reduce the need for primary steel, which requires raw materials including iron ore and coke.

The zero-carbon transition will also increase demand for steel in certain sectors, but the amount is not comparable to the decrease of demand driven by factors mentioned above. Zero-carbon development cannot be achieved without electrification and large-scale clean energy substitution. It is inevitable that the infrastructure related to the production, storage, and delivery of clean energy will increase the demand for steel in the energy industry. As a result, demand for steel from other downstream consumers must be further reduced to compensate for the additional steel demand resulting from the clean energy transition to achieve the overall zero-carbon transition.

• Analysis of influencing factors of steel demand in different sectors.

Nearly 60% of China's steel consumption came from the building industry in 2020, which includes all kinds of buildings, from residential buildings to parking garages, as well as urban infrastructure construction, such as railways, highways, and urban pipeline networks. In addition, other major steel-consuming industries include machinery (16.4%), automobile (5.4%), energy (4.2%), and other industries including home appliance manufacturing, ship manufacturing, light industry, etc. (15.1%).[10] Due to influencing factors such as technological development and demand change (Exhibit 5), the future development trend of steel consumption in China's major steel-consuming industries will be different.

Buildings: With the increase in the rate of urbanization, the construction of buildings, intercity railways, expressways, and other infrastructure in China will remain at a level that will still play a large role in supporting the demand for steel.[11] Most of the demand will come from new urban development, the renovation of old residential areas, and new building construction along with the supporting equipment and services.

In 2020, China's real estate developers built 9,268 million square meters of floor space, 3.7% more than the previous year.[12] In the medium to long run, steel demand in this sector will decrease, because the construction of new buildings and infrastructure will gradually decrease due to the increasing rate of urbanization. At the same time, the building sector’s share of steel demand will gradually decrease. This is due to of the application of emerging non-steel building materials; enhanced law and regulations on steel products, which can avoid unnecessary manufacture or construction; and the extended lifespan and reduced replacement rate of buildings and infrastructure.

Machinery: China's traditional machinery industry includes multiple segments with intense steel consumption, such as petrochemical equipment, machine tools, construction machinery, and more. In general, the overall growth rate of steel-intensive segments is slowing down, with a downward trend in sight. In the long term, the advancement of domestic manufacturing technologies, such as intelligent manufacturing and high-performance equipment, will change steel consumption patterns in the machinery sector.[13] This will further increase the demand for premium steel, special steel, and high-end steel, promoting the transformation of the traditional steel-consuming segments and reducing the overall demand for steel.

Automobiles: There is a significant positive correlation between the number of automobiles and per capita GDP. According to the Development Research Center of the State Council, by 2030, China will have 430 million automobiles by 2030, or 300 automobiles per 1,000 people. This is an increase of more than 50% from 2020, without considering technological substitution and business model innovation.[14] Therefore, in the short run, steel consumption in the automotive industry will further increase. In the medium to long term, improved automotive manufacturing technology, lightweight steel production, and material innovations such as carbon fiber will reduce steel consumption per automobile. At the same time, with the development of an intelligent, shared, and electric automobile industry, the slowing or even declining demand for private vehicles will further reduce steel demand.

Energy: A zero-carbon transition cannot be achieved without electrification and large-scale clean energy substitution, which in turn will drive the expansion of clean energy-related infrastructure and power grids and increase demand for steel. For example, high voltage direct current (HVDC) transmission will continue to grow following a series of national level policies promoting new infrastructure development. During the 14th Five-Year Plan (FYP) period, seven cycles of HVDC transmission lines will be built, adding transmission capacity of 56 million kilowatts,[15] and the total length of HVDC will reach 40,825 kilometers,[16] 1.4 times that of 2019. Under the current technology development level in China, steel consumption per kilometer of HVDC transmission line is 220 metric tons,[17] which lead to a total of 2.7 million tons of steel consumption during the 14th FYP period, and 540,000 tons annually.

In RMI's zero-carbon scenario,[18] solar and wind generation capacity will reach 2,500 gigawatts and 2,400 gigawatts respectively by 2050, 12 times and 11 times higher than in 2019. Under current technology, the average steel consumption of the wind turbine industry is approximately 115 tons per megawatt of generation capacity.[19] With a conservative assumption on technology development, total steel demand of wind turbines will be 250 million tons from now to 2050, which equals 8.36 million tons annually.

The average steel consumption for the solar industry is approximately 50 tons per megawatts in China,[20] leading to ~3.8 million tons of annual steel consumption by 2050. With the increase of generation capacity and efficiency per unit of wind turbines and solar panels, and the weight reduction of construction materials, these estimates will be lower over the years. After all, the reduction of oil and gas share will reduce demand for steel to some extent. However, clean energy and power sector development will drive the growth of steel demand across the sector to a certain extent, though minimal.

Other industries: The downstream market of steel is widely distributed, including home appliance manufacturing, ship manufacturing, container, light industry, and so on. Because the share of steel demand for each sector is small, this analysis will not elaborate on these sectors. Overall, with technological progress, consumption upgrading, and industrial transformation, the demand for high-tech, high value-added, and low steel-consuming products is increasing. Combined with the development and substitution of new materials, longer product life spans, and sustainable low-carbon development trends, steel demand will continue to decline in most industries, supporting steel demand peak as soon as possible.

Exhibit 5: Influencing factors for the demand of steel in different segments

Steel demand =	Overall Development X	Steel Products Demand X	Steel Consumption Per Product
Building	New urbanization Reducing number of new buildings Slowing infrastructure construction Urban-rural integration	Increasing energy efficiency and lifetime of buildings Existing building upgrading and renovation, old residential communities' renovation	Promotion and application of new materials and low carbon materials
Machinery	High quality industrialization, industrial transition	Increasing lifetime of equipment Increasing demand for efficient, intelligent and high performance equipment Energy saving renovation of old facilities	Decreasing demand for steel intensive machineries
Automobiles	Economic growth, increasing demand Increasing number of electric vehicles	Development of intelligent and shared mobility EV batteries reuse and recycle	Lightweight materials application
Energy	Decreasing demand for fossil fuel New infrastructure and HVDC Renewables generation capacity, energy storage CCS	Increasing production efficiency of renewables Maturing production, storage and delivery infrastructure	Technical development and material substitution
Other	Impact of low carbon transformation on traditional industries, industrial transition Increasing demand for high tech and high value -added products	Increasing lifetime of products, consumption upgrade Intelligent manufacturing	Demand for low energy consuming and lightweight products

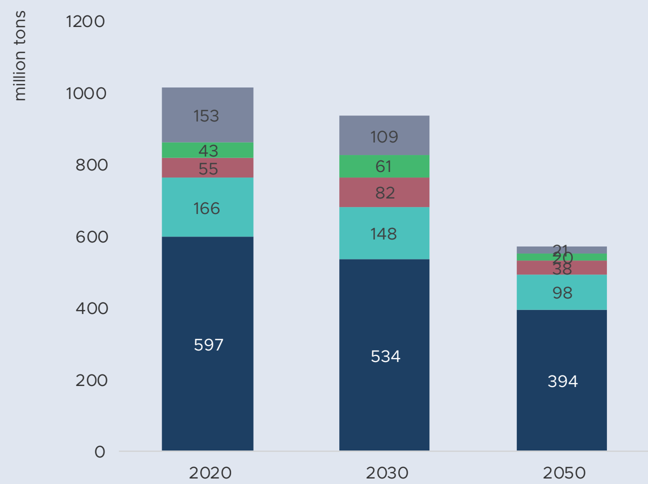
Increasing demand on steel — Decreasing demand on steel

• Forecast of steel demand in different sectors.

Considering the factors above and China's current technology and development plans, RMI estimated the demand for steel in China's major steel-consuming sectors under the zero-carbon scenario. Overall, the total demand for steel showed a downward trend. By 2030, when China peaks its carbon emissions, the overall domestic demand for steel will drop by 8.1% compared with 2020, despite the growth of demand in certain sectors. By 2050, under the zero-carbon scenario, the total demand for steel will drop sharply to 571 million tons, a decline of 38.8% compared with 2030.

Under a more ambitious scenario, the demand from the building sector will have an accelerated reduction of demand for new buildings and will be further impacted by the guidance of green buildings and prefabricated buildings, which will lead to a reduced steel demand of 425 million tons by 2050. This scenario indicates a further slow-downed urbanization rate, a reduced construction requirement, and an increased utilization of existing buildings and infrastructure.

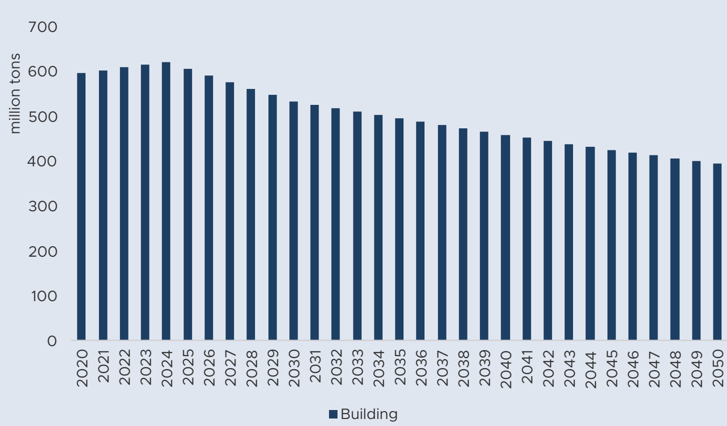
Exhibit 6: Demand of major steel-consuming sectors and their CAGRs in China (2020, 2030, and 2050)

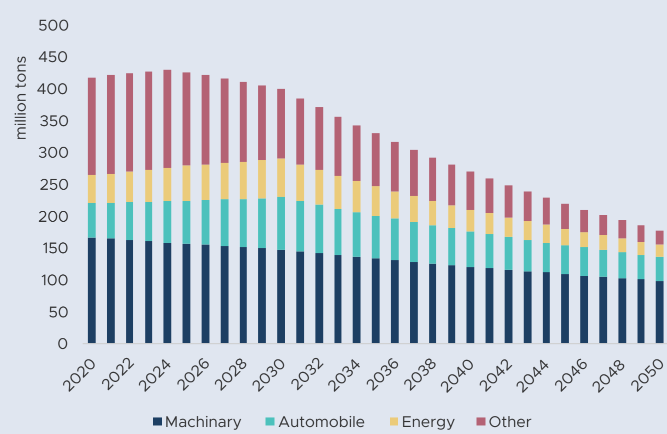


Compound Annual Growth Rate

	2020-2030	2030-2050
Others	-3.34%	-7.85%
Energy	3.64%	-5.54%
Automobile	4.13%	-3.85%
Machinery	-1.20%	-2.00%
Building	-1.11%	-1.50%

Exhibit 7: Demand for steel in the building sector (2020–2050) (left); demand for steel in other steel-consuming sectors (2020–2050) (right)





Different development paths will be adopted in different sectors. Due to the demand of new urbanization and low-carbon development, electric vehicle stock will increase, and the demand for renewable energy and an HVDC transmission network will continue to grow. As a result, the demand for steel in the automobile and energy industries will gradually reach its peak around 2030, followed by a downward trend (Exhibit 7, right). The demand for steel in most other industries will peak around 2024, followed by a significant downward trend of demand after 2030. The building sector in particular, will be the biggest contributor to the decline in steel demand, accounting for around 46% of demand reduction (Exhibit 7, left).

The Import and Export of Steel in China under the Global Low-Carbon Transition

The import and export of steel and related products are also important factors affecting crude steel production. At present, China's steel exports account for about 5% of the total crude steel production, though with fluctuations. The export in this study refers to the direct export of steel (semi-finished products) and does not include the export of products that are made of steel, such as vehicles, which are categorized as indirect export. Steel consumed by indirect export is reflected in the steel demand for domestic downstream industries already. Therefore, in addition to domestic demand, the demand for Chinese steel-made products from overseas countries and regions will also impact domestic steel consumption to a certain extent. However, the trend of import and export of steel in China is highly uncertain, and is dependent on global market status, especially the following three aspects.

- **The change in market competitiveness results in different import and export trends of different products.** As production capacity increases in regions such as Southeast Asia, where production costs are low, China's competitiveness in the market for medium- and low-end products such as ordinary carbon structural steel and lean alloy steel may decrease, leading to reduced exports. In contrast, export of high-value-added steel is likely to increase as China becomes more competitive in this segment of the international market due to technology enhancement.

- **Rising domestic production costs could lead to higher steel imports into China in the future.** The national goals of "carbon peaking" and "carbon neutrality" coupled with increasingly strict environmental laws and regulations will increase the production compliance costs of steelmakers. Combined with the reduction of the export tax rebate for some steel products, the competitiveness of domestic steel products will decrease in the global market.

- **The demand from countries in the Belt and Road Initiative will have a dynamic impact on China's import and export of steel.** The Belt and Road Initiative (BRI) countries have carried out extensive cooperation with China in infrastructure construction such as roads, railways, and ports. The construction of these projects will increase local demand for steel and drive up China's direct export of steel. However, with the increase of domestic capacity in the steel industry, more steelmakers will expand their business internationally, reducing the demand for steel produced in China and reducing exports. In addition, the instability of the international situation will bring uncertainty to the demand for steel in BRI countries and China's export.

This report mainly focuses on quantifying the domestic demand for steel in the next 30 years and does not conduct a quantitative analysis of the import and export of steel and related products. However, once domestic steel demand declines after continuous efforts made by multiple sectors to shift away from a commodity-intensive growth model, the import and export volume of steel products will play a bigger role in domestic steel production. In addition, as China's steel industry is heading rapidly toward low-carbon production, China is likely to become a major green steel exporter after 2040. If this happens, steel production in China may not decrease as fast as domestic demand because of the increase in green steel demand in international markets.

Forecast on the Steel Output in a Zero-Carbon China

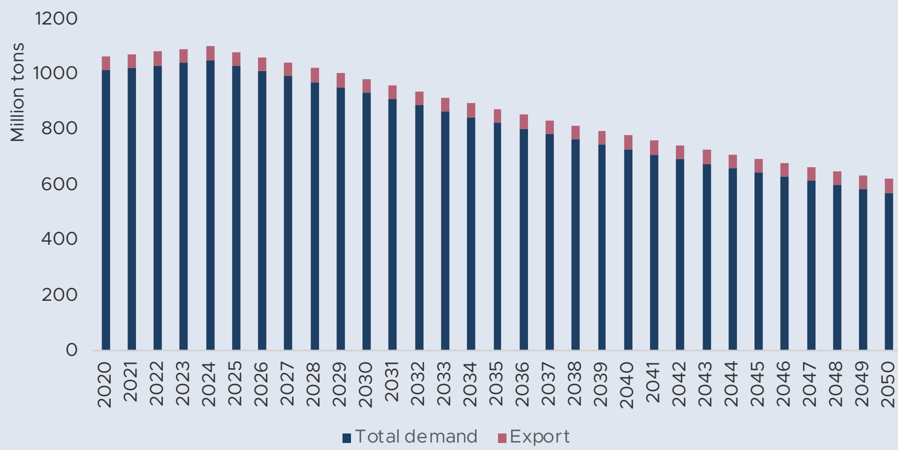
Based on results generated from RMI's model, the trend of crude steel production in China is consistent with the trend of demand for steel in major steel-consuming industries. China's crude steel production will peak around 2024 at 1.1 billion tons (Exhibit 8). This is mainly because the consumption of the building industry, which accounts for more than half of the total, will peak around 2024. Although automobile, energy, and other downstream industries are showing a rapid and stable growing trend, and their steel consumption will peak around 2030, their impact on China's overall crude steel production is small in the short term.

In the medium to long term, China's crude steel production will continue to decline, with total production dropping to 621 million tons by 2050 in the zero-carbon scenario, about 58% of the 2020 level. This is consistent with the IEA's projection in its Sustainable Development scenario (SDS) in Energy Technology Perspectives.[21] Under the more ambitious scenario, total production of steel will be further reduced to 475 million tons by 2050, if net steel export stays at the current level. The result is lower than the majority of projections conducted by domestic think tanks but aligns with IEA's beyond 2-degree scenario. This scenario provides a glimpse of the reduction potential of steel production in China to achieve zero carbon by 2050.

In addition to the demand of downstream industries, crude steel production is also related to several other factors, such as steel inventories and the price of raw materials such as iron ore and scrap. However, since the total inventory is less than 1/1,000 of the annual steel output, and different industries and regions have different actual demands for de-stocking or replenishment, this study does not consider the dynamic change of inventory. It only focuses on the impact of the demand of downstream industries and import and export volume in forecasting steel output. In addition, there are many factors affecting raw material prices in different production routes, making the impact on the output in the actual production process complex and difficult to predict. Therefore, this has been simplified in this report.

Under the zero-carbon scenario, China's crude steel output will peak rapidly in the near future and then decline annually till 2050. However, the reduction in production itself is not sufficient to achieve the goals of carbon peaking and carbon neutrality in the steel industry. Changing the production process, improving energy efficiency, and decarbonizing the production process are all important means to

Exhibit 8: Crude steel production in a zero-carbon China (2020–2050)



achieve carbon-reduction targets. Therefore, this report will focus on the analysis of two existing and dominant steel production processes, EAF steel and primary steel. The report analyzes the future development trends of resource, technology, and cost in each process, and discusses the short-term technology development direction and long-term zero-carbon development prospects in different regions of China.

Chapter 3: Secondary Steelmaking: From Supporting Role to Mainstream

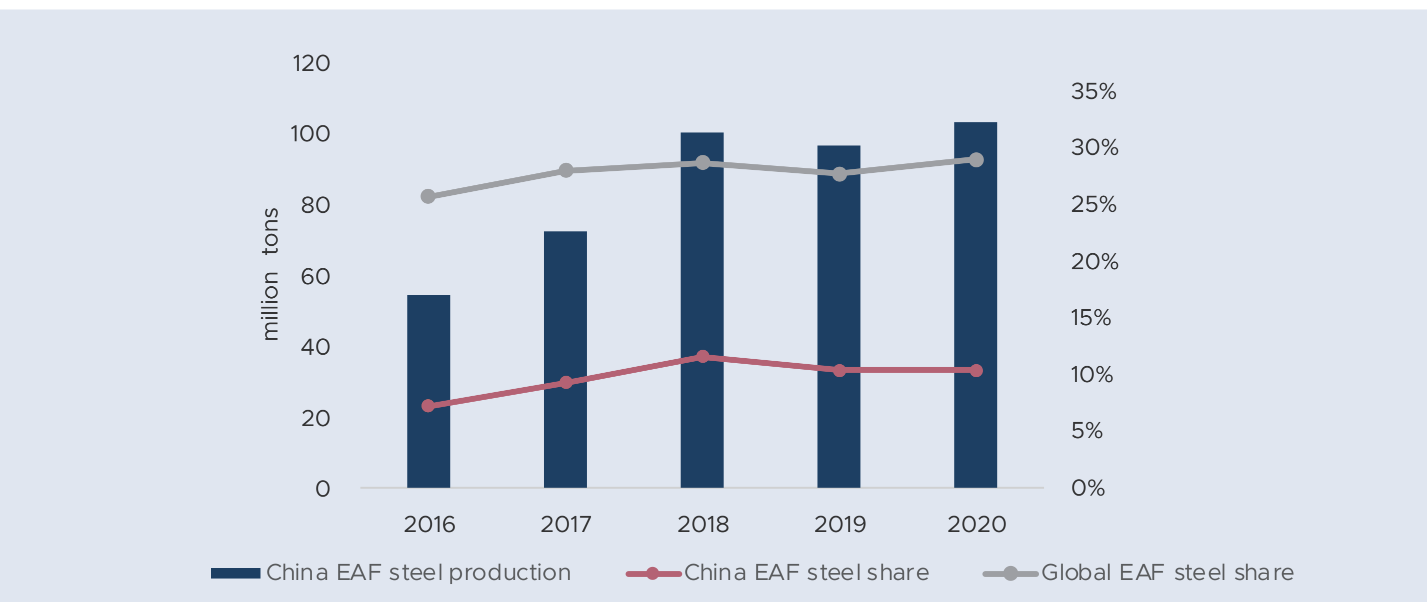
Under the zero-carbon scenario, China's secondary steel production based on scrap will continue to gain momentum, expanding from only about 10% of total steel production today to a high of 60% by 2050. The transformation of secondary steel production from a supporting role to the mainstream is due to several factors: the accumulation of China's steel stock, the guarantee of scrap resource supply, and the cost advantage under the pressure of carbon emissions reductions and preferential power price. Considering scrap resource accumulation and recycling potential, China's secondary steel development will experience three stages: gradual rise, rapid growth, and approaching balance.

Resource Guarantee: Sufficient Supply of Scrap in the Long Run Enables the Scaled Development of Secondary Steelmaking

The share of EAF steel in China has remained low for a long time, mainly due to the limited supply of scrap.[ii] As shown in Exhibit 9, China's EAF steel production fluctuated and grew rather slowly. As of the end of 2020, China's EAF steel capacity was 174 million tons, of which 128 million tons was dedicated EAF capacity.[iii] Of the 1.1 billion tons of China's crude steel output in 2020, EAF steel production accounted for about 10%, 3% higher than the historical low of 7%. But this is still low compared with the world average of about 30%, nearly 70% in the United States, and about 50% in other regions outside China.

In terms of scrap consumption, the total consumption of scrap resources by China's steelmakers has increased from 90 million tons in 2016 to 230 million tons in 2020, with an average annual growth rate of 9.8%. However, compared with the world average scrap consumption of 336 kg/ton, 690 kg/ton in the United States, 550 kg/ton in the EU, and 340 kg/ton in Japan, the scrap consumption in China is still low.

Exhibit 9: Output of EAF steel in China 2016–2020



ii EAF steel represents secondary steel. As the current term is EAF steel, the following paragraphs on status-quo will still use EAF steel.
iii Based on the info from the China Metallurgical Industry Planning and Research Institute and calculated according to the *Implementation Measures for Capacity Replacement in the Iron and Steel Industry* of China's Ministry of Industry and Information Technology.

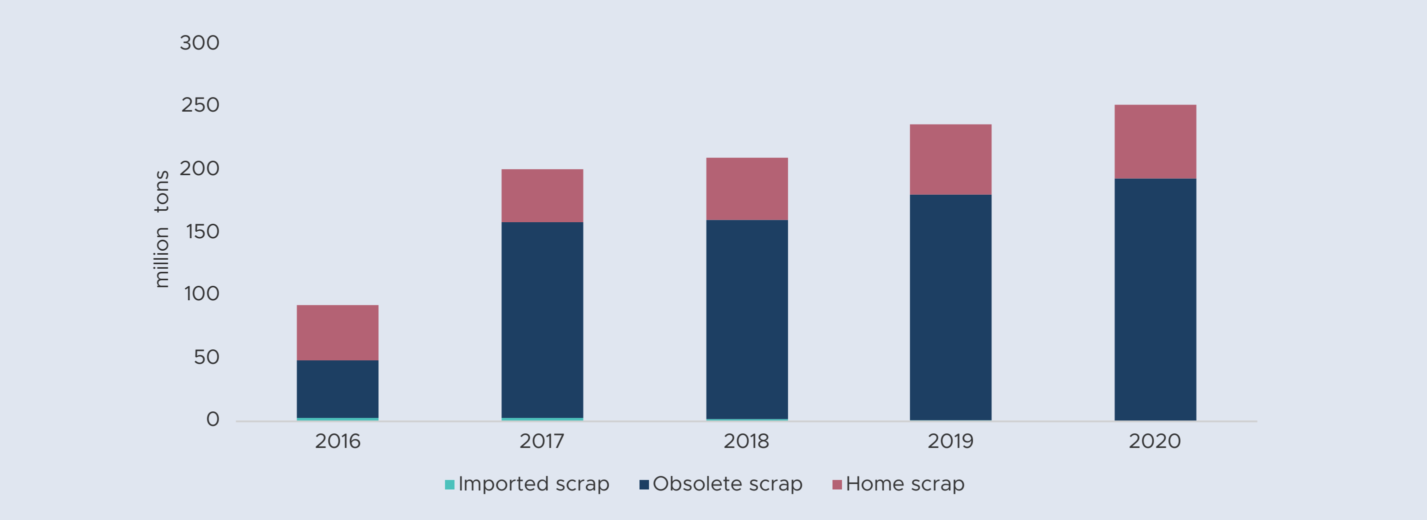
There are two reasons behind China's low share of EAF steel and scrap steel use. One reason lies in the small amount and uneven distribution of available scrap steel. With the continuous accumulation of steel stock in China, the obsolete scrap supply has been growing steadily, with an annual increment of 15–20 million tons. In 2020, China's measured scrap supply was about 260 million tons. However, currently, with China's crude steel output reaching more than 1 billion tons, scrap supply is far from sufficient. The high enthusiasm that steelmakers have for EAF steel, and the fact that the BOF process consumes a large amount of scrap, is causing fierce competition for scrap resources between BF-BOF-based and EAF-based steelmakers. Also, the scrap market is facing imbalance between supply and demand both periodically and regionally. Currently, scrap steel mostly comes from relatively developed areas like southeastern coastal areas.

Another reason is the that the supply and recycling system for scrap steel has yet to improve. By 2019, the Ministry of Industry and Information Technology has acknowledged about 400 companies in the scrap steel industry, and there are in total more than 2,000 related companies in China, with low industrial concentration and standardization. In addition, the tax burden also bring challenges to the healthy development of the industry.

However, China's decarbonization trend will lead to improvements in both aspects mentioned above. First of all, China's scrap steel resource is about to boom. During the 13th Five-Year Plan period, the total supply of scrap resources in China increased on the whole, of which home scrap and obsolete scrap accounted for 20%–25% and 75%–80% respectively, while imported scrap accounted for less than 1% (Exhibit 10). The vigorous development of equipment manufacturing and the emerging and daily products industries being driven by new industrialization and urbanization will further increase the output of scrap resources in China. This will help to improve the construction and standardized management of the scrap resources system.
We estimate that China's social scrap resource production will reach 340 million tons in 2025 and 400 million tons in 2030. This factors in the relationship between scrap resource production, steel stock accumulation, and the steel product life cycle, combined with the actual growth of scrap supply in recent years.

We optimistically estimate that the import volume of recycled steel raw materials will reach about 10 million tons in 2025 and 20 million tons in 2030. This considers the import of recycled steel raw materials being liberalized in early 2021 and the import volume of 13.7 million tons in 2009 which was the highest in recent years.

Exhibit 10: Scrap supply in China 2016–2020



Moreover, the recycling system of scrap steel is continuously improving to be more standardized and at scale. As the country continues to promote the effort of reducing excess capacity in the steel industry, especially after 140 million tons of substandard steel capacity was lawfully banned in 2017, scrap resources in the gray area returned to the formal circulation channels.

Policies are also showing full support, such as the “Industrial Resources Comprehensive Utilization and Industrial Synergy and Upgrading Plan of Jing-Jin-Ji Area (2020-2022)." This policy states calls for coordinating the allocation of resources in the region, taking advantage of existing production capacity, and guiding the concentration of scrap metal resources to advantageous enterprises. Additionally, it calls for support steel producers and scrap steel recycling and processing enterprises to build an integrated large-scale scrap steel processing and distribution center. This is also the direction of the development of the scrap steel recycling industry at the national level.

Cost Driver: The Cost Advantage of Secondary Steelmaking Emerges under Supportive Conditions

From the perspective of cost structure, the cost of steel material accounts for 88%–92% of the total cost of BOF steelmaking. For EAF steelmaking, the cost of steel material accounts for 83%–88% of the total, and the cost of electricity for smelting accounts for 3%–6%. The relative prices of scrap, pig iron, and electricity will affect the cost of primary and secondary steelmaking, thus affecting the competition pattern of different steel production routes.

- **Effect of scrap price.**

Historically, domestic scrap price and rebar steel price are positively correlated. However, due to the sharp rise in iron ore price in recent years, changing steel prices, and in particular the output-restricting environmental and supervision policies that affect the scrap market, scrap steel prices fluctuate greatly. The monthly fluctuation range reaches tens of dollars and the annual fluctuation range reaches more than $150. In addition, the shortage of domestic scrap supply in the short term may lead to an increase in scrap price.

However, with the gradual opening of the import of scrap and the accumulation of domestic steel stock, the scrap supply shortage will be alleviated in the medium and long term, which will again affect the price of scrap. Therefore, the price of scrap in the future is highly uncertain. At present, the domestic scrap recycling system is still imperfect, the general scrap quality is uneven, and the overall circulation of scrap is low. In the future, continuously improving the scrap recycling system and market environment to provide sufficient and low-price scrap supply will be key to ensuring the cost-competitiveness of secondary steel.

• Effect of electricity price

China's power supply has been dominated by coal-fired power generation for a long time, with thermal power generating capacity accounting for about 72% of the total. Due to the imperfect linkage mechanism between coal and power prices and the persistent existence of cross-subsidies, China's industrial power prices are relatively high. At present, the preferential power price for steelmakers is mostly reflected by direct power supply for large-scale users, and the differentiated power price policy implemented by the local government is mainly punitive. A special preferential power price has not been implemented for all-scrap-based secondary steelmakers.

Compared with BOF steelmaking, dedicated EAF steelmaking needs an additional power consumption of about 300 kWh/ton of steel. This translates to an extra $28/ton of steel in power cost alone based on a rough estimated power price of $90/megawatt-hour (MWh), resulting in the high cost of EAF steelmaking. In the future, as the consumption of scrap resources increases and the scale of secondary steelmaking grows, the preferential power price policy may play an important role in reducing the cost of secondary steelmaking and promoting the development of the industry. The comprehensive impact of scrap price and power price on the cost of secondary steelmaking is shown in Exhibit 11.

• Cost comparison of primary and secondary steelmaking.

This study analyzes the impact of scrap price, iron ore price, and electricity price on the cost of primary and secondary steelmaking. Exhibit 12 shows the cost parity lines for primary and secondary steel on corresponding scrap and iron ore prices at different power prices. The area below the cost parity line of the given power price is seen as the situation where secondary steel is more cost-competitive than primary steel, and the price of scrap and iron ore under the corresponding conditions can be correlated in the graph.

For example, at the current cost of about $80/ton of iron ore imported into China, scrap would need to cost less than $230/ton—about half the current norm—to make secondary steel more cost-competitive than primary steel, even at a low electricity price of $30/MWh. At about $210/ton of iron ore, if the electricity price is $30/MWh, a scrap price of $430/ton would make secondary steel cost-competitive. In the future, ensuring scrap supply to keep cost down and a more preferential power price will greatly boost the development of secondary steelmaking.

Exhibit 11: Impact of scrap and power price on the cost of EAF steel

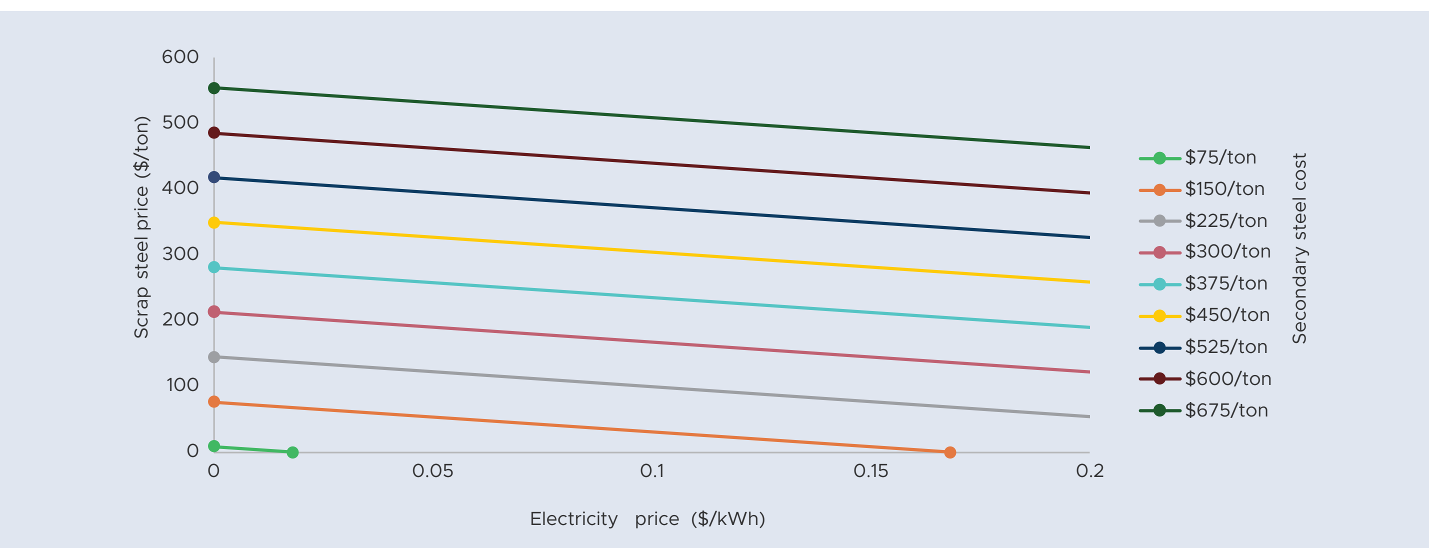
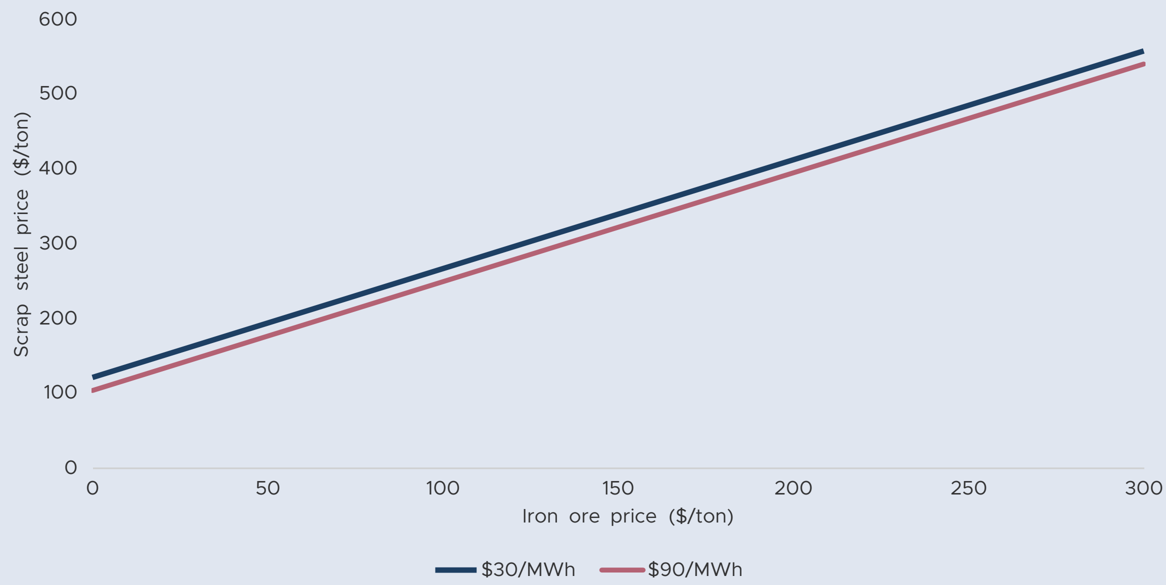


Exhibit 12: Cost parity lines of primary and secondary steelmaking

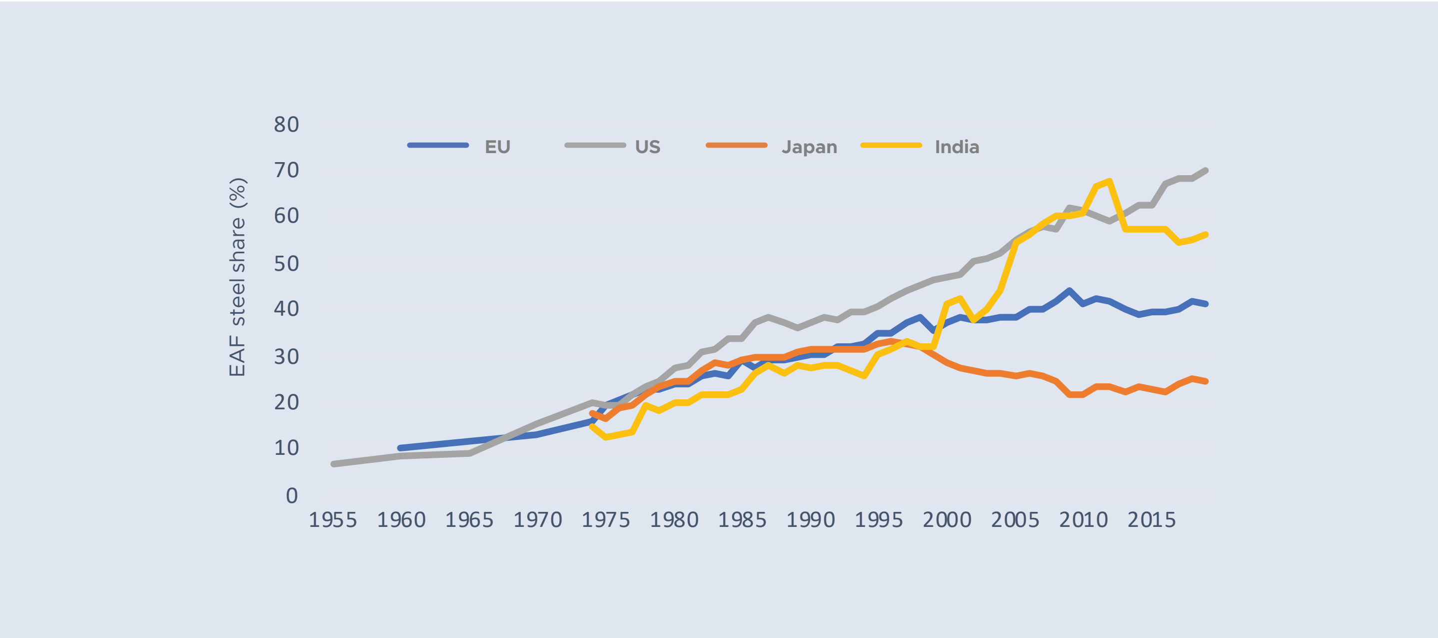


Note: Secondary steelmaking is more cost-competitive in areas below the cost parity lines

From Supporting Role to Mainstream: Development Trend and Paths of Scrap Utilization and Secondary Steelmaking

According to international experience, it takes a long time for countries producing 100 million tons of steel to increase the proportion of EAF steel. The development of EAF steelmaking generally starts to rise in the mid- and later-stage of the peak range of crude steel production. The proportion of EAF steelmaking in the United States has been rising continuously since the middle of the past century and is currently approaching 70%. The proportion of EAF steelmaking in India, Europe, and Japan is about 56%, 41%, and 25% respectively, mainly falling in the period of development plateau. The overall development process of EAF steelmaking in the EU, the United States, Japan, and India shows that the initial stage—when the proportion of EAF steelmaking increases from 10% to 20%—roughly takes 10–15 years. To increase from 20% to 30% takes 5–15 years. And the stage of development plateau may be reached after the proportion of EAF steelmaking rises to the peak and becomes stable (Exhibit 13).

Exhibit 13: Proportion of EAF steelmaking in major steel-producing countries



In addition, there are obvious bottlenecks to continuously increase the proportion of EAF steelmaking in major steel-producing countries. Most of the countries with annual crude steel production of more than 50 million tons have 30% or more of that as EAF. Only the United States and India have a higher proportion of EAF, more than 50%, with the rest falling into the range of 20%–40% (except China).

For example, the proportion of EAF steelmaking in Russia, South Korea, Germany, and Japan is 33.7%, 31.8%, 30%, and 24.5% respectively. Therefore, major steel-producing countries face visible resistance for the development of EAF steelmaking when its proportion reaches the range of 20%–40%. In other words, the proportion of EAF steelmaking in major steel-producing countries generally stagnates in the range of 20%–40% and then develops in fluctuation within this range.

The development paths of EAF steelmaking vary in different countries, mainly subject to each country's industrialization development needs and resource conditions. The United States was one of the first countries to manufacture steel. Due to the large accumulation of scrap resources in the middle and late 20th century, the proportion of EAF steelmaking increased rapidly and exceeded that of BF-BOF steelmaking, which is a typical process transformation determined by scrap resources. Japan, on the other hand, has limited domestic scrap supply, which limits the application of EAF steelmaking. Moreover, due to the large export of scrap, the tight supply of electricity, and the relatively mature primary steelmaking, Japanese steelmakers lack the motivation to develop EAF steelmaking.

China has the characteristics of both above countries. On the one hand, with the advancement of industrialization, scrap resources will be further enriched. On the other hand, a certain lock-in effect exists in China's mature primary steelmaking. But the pressure of carbon neutrality will provide a strong policy impetus to break this lock-in effect and fully promote EAF steelmaking.

In summary, the utilization of scrap and the development path of secondary steelmaking in China will feature the following:

Feature I: The supply of scrap resources will increase fast in the short term, with continuous growth in the medium and long term.

In 2020, China's measurable scrap supply was about 260 million tons. Compared with the current crude steel production of 1 billion tons, the supply of scrap resources in China is far from reaching the level that can support a high proportion of EAF steelmaking.

According to the China Metallurgical Industry Planning and Research Institute, the estimated total scrap supply in China will reach 350 million tons in 2025 and 420 million tons in 2030. Assuming the consumption of scrap in foundry and machinery industries is 30 million tons/year, the total amount of scrap resources available for the steel industry in 2025 and 2030 will be 320 million tons and 390 million tons respectively. By 2050, the steel industry is expected to supply 500 million tons of scrap, which is sufficient to support EAF steelmaking that accounts for up to 60% of the total steel production of 621 million tons.

According to RMI's zero-carbon scenario, in the next 30 years the accumulation of scrap resources will go through two stages. Prior to 2030, as China enters the later stage industrialization and post-industrialization period, steel stock will accumulate rapidly and the amount of scrap resources will increase at a fast rate, with an average annual increase of about 16 million tons. From 2030 to 2050, as infrastructure construction slows down, the accumulation of scrap will continue to increase, but at a slower rate of an average annual increase of only about 5.5 million tons. Therefore, we should promote the development of EAF steelmaking with scrap as much as possible in the next 5 to 10 years.

Feature II: The development of secondary steelmaking in China will experience three stages in the future: gradual rise, rapid growth, and approaching balance.

If China's scrap steel supply can increase as is mentioned above, and preferential policies of capacity replacement, electricity price, environmental production, and land use are in place, scrap-based EAF steelmaking in China will grow rapidly. Overall, there will be three development stages:

- The first stage is the gradual increase in the proportion of secondary steelmaking (2020–2025), with the proportion of China's secondary steelmaking increasing to 15%. Secondary steel will amount to 160 million tons per year, with a growth of over 50 million tons over the five years. During this stage, although the increase in the proportion of secondary steelmaking is limited, the actual capacity will expand rapidly because of the large total base of steel production and the rapid expansion of the supply of scrap resources.

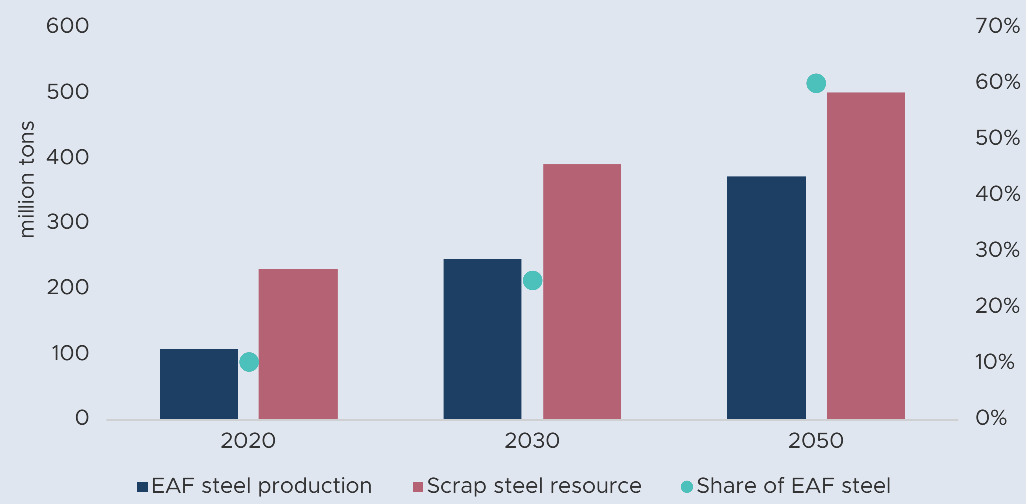
- The second stage will include rapid growth in the proportion of secondary steelmaking (2025–2030), which will increase from 15% to 25%. Secondary steel will increase by 84 million tons over the five years to reach 250 million tons per year. During this period, both the actual capacity and percentage of secondary steel will accelerate.

- In the third stage (2030–2050), the percentage of secondary steelmaking will gradually reach a balance. The production will only increase by about 130 million tons, due to the decrease in overall steel production and the slower accumulation of scrap resources as well as the competition over scrap resources between primary and secondary steelmaking routes. By 2050, secondary steel will take up 60% of total steel production, reaching 370 million tons per year. Overall, this study estimates that the consumption of scrap from secondary steelmaking at this stage will account for over 80% of the total scrap supply.

Feature III: EAF steelmaking technologies will be more efficient and intelligent.

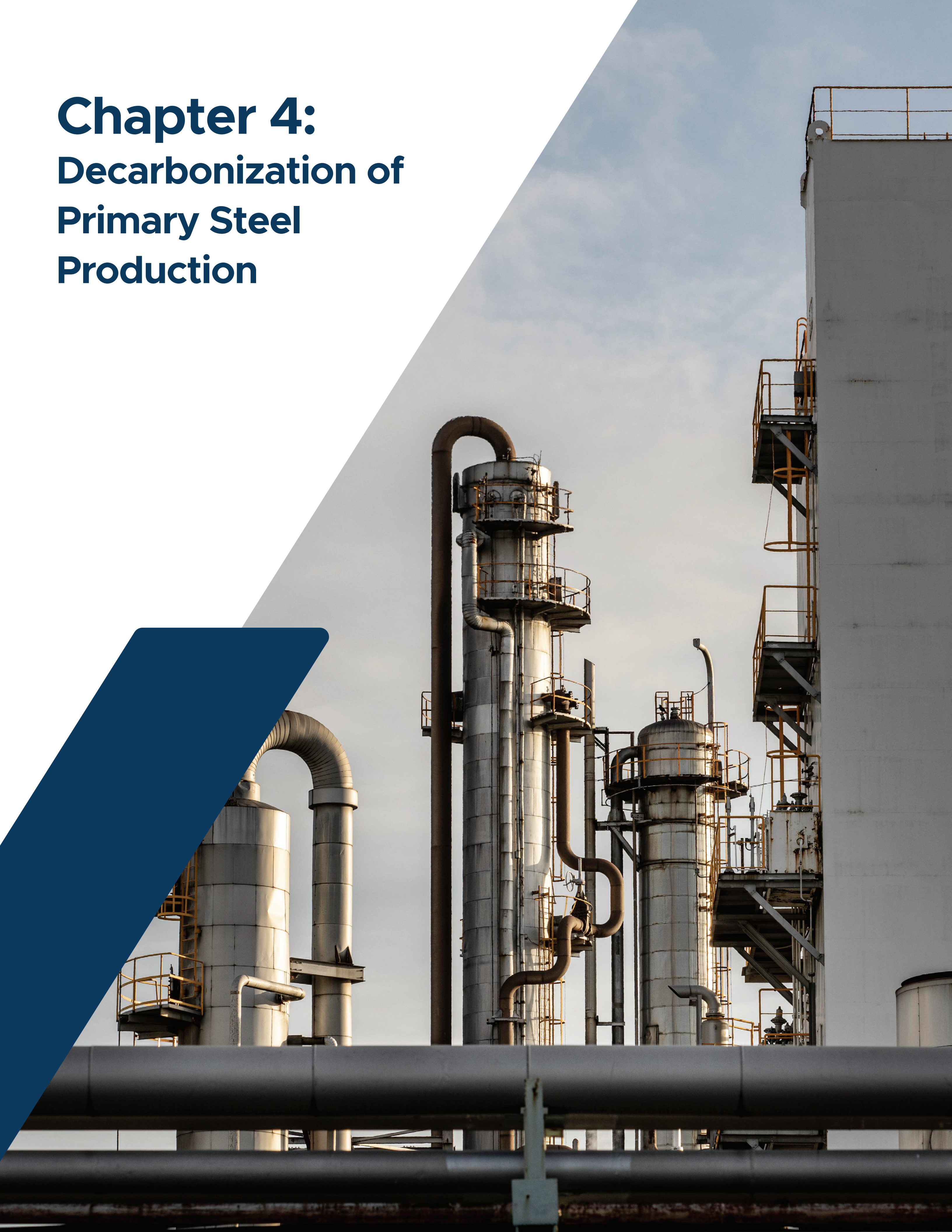
In recent years, new forms of EAF such as Quantum EAF, ECOARC EAF, and CISDI-Green EAF have emerged in China. In the future, the selection of EAF technologies will focus more on the optimization and integration of continuous feeding, preheating of scrap, high efficiency and energy savings, environmental protection, waste heat recovery, and intelligent steelmaking.

Exhibit 14: Scrap steel supply for steelmaking, production and share of secondary steel



In addition, EAF enterprises will have inherent advantages by building intelligent mills. In the future, the focus of intelligent development will be the combination of advanced monitoring measures and the overall optimization control. This will involve a focus more on technologies such as smelting process quality analysis and cost optimization and control, in order to realize the control and optimization of the whole process.

Chapter 4:
Decarbonization of Primary Steel Production

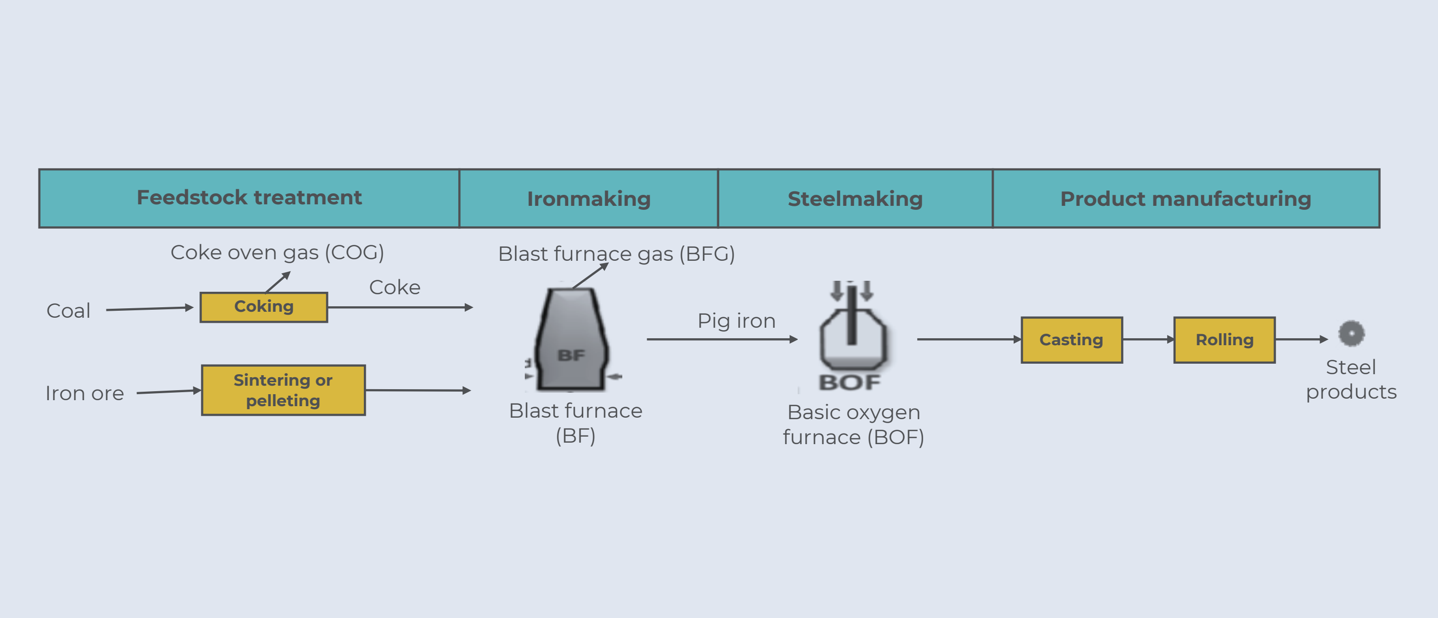


Under the zero-carbon scenario, primary steelmaking will still be a big share of overall steelmaking. Currently, there are many available technologies to improve energy efficiency and reduce carbon emissions. And there are several routes for zero-carbon primary steelmaking including hydrogen-based direct reduced iron (DRI), CCS, and smelting reduction. These routes have the potential to be cost-competitive by 2050. All these incremental and disruptive technologies would help primary steel gradually reach decarbonization.

The Technical Feasibility of Primary Steel Decarbonization

BF-BOF is the dominant steelmaking route in China (Exhibit 15). The route includes feedstock treatment, ironmaking, steelmaking, and product manufacturing processes, using coal and iron ore. The core processes are ironmaking (i.e., reducing the iron ore to iron) and steelmaking (i.e., turning iron into steel by removing impurities and adding alloying elements). Before ironmaking, the iron ore and coal are processed. Iron ore goes through a sintering or pelleting process to enhance its properties and be put into an easy-to-react form. Coke is produced from coal to be used as a reducing agent. After the steelmaking, the hot metal gets cast and rolled to be made into the final steel products.

Exhibit 15: Process illustration of BF-BOF primary steelmaking process



There are many technologies that can be applied to cut primary steelmaking emissions (Exhibit 16). Some are incremental and can be integrated into BF-BOF process, while others will fully replace the conventional primary steelmaking process.

Incremental technologies could reduce the carbon emissions of BF-BOF steelmaking.

- **Energy efficiency improvements:** China's steel industry has worked on energy efficiency improvements for more than 15 years and has made great progress developing and implementing advanced energy-saving technologies. However, there are still some technologies under development that can be applied in the future. Some examples are shown in Exhibit 17.

Exhibit 16: technology options for steel decarbonization

	Routes	Mitigation potential	TRL	Resource capacity	Economics	Easiness of implementation	Potential
Incremental technology	Energy efficiency	15%-20%	●	●	●	●	• microwave sintering, heat recovery, etc. • Digitalization could bring 10%-15% energy saving
	Oxygen blast furnace (OBF)	30%	◔	◔	◔	◑	• Under experiment in China • Could leverage BF facility and operation knowledge
	Hydrogen blending in BF	10%-20%	◕	◕	◕	◕	• Transitional technology with coke oven gas • Piloting in China
	Biomass	30% (95% with CCS)	◔	◔	◔	◕	• Limited biomass resource in China
	CCS	60%	◕	◑	◔	◑	• Limited application in steel sector in China
	Smelt reduction (HIsarna, HIsmelt, COREX, FINEX, etc.)	20% (80% with CCS)	◑	◑	◔	◑	• Several projects running in China • Supported by MII T policy
Fully decar-bonized primary steel	Hydrogen DRI	95%	◕	◑	◔	◔	• Piloting in China and supported by MIIT policy • Need green hydrogen cost reduction
	Hydrogen plasma smelting reduction (HPSR)	95%	◔	◑	◔	◔	• Final stage of Jianlong Steel pilot project (CISP) • Gradually transition from coal-based to hydrogen -based
	Direct electrolysis	95%	◔	◔	◔	◔	• Still in development by Boston Metal, etc.

* The mitigation potential can be fully captured by using zero-carbon electricity. We assume EAF as the steelmaking process after DRI and BOF after smelting reduction.

Exhibit 17: Energy efficiency technology list

Process	Technology	Details
Sintering	Microwave sintering	Reduce carbon intensity per ton of crude steel by10%
	Sintering gas recycling	
Coking	Gas recycling from ascension pipes in coke ovens	
	Coke oven gas reuse	Recycle the CO and H_2 as products or for methanol production
Blast furnace	Increasing pellet share	The energy intensity of pelleting process can be 50% lower than sintering process
	High-coal-low-coke ratio iron making	Save coke consumption
	BF equalizing gas recovery	
Casting and rolling	Heat -free rolling	ESP (EndlessStripProduction) technology, MIDA technology, etc., which could reduce the casting process energy consump-tion by 50%
Digitalization	Smart process digitalization	Increase over all energy efficiency by 10%-15%

• **Oxygen blast furnace:** Using pure oxygen instead of air for coal combustion in the blast furnace increases the CO_2 content of the top gas, which could then be removed for utilization or storage with lower costs. This technology could reduce steel carbon intensity by 30%. However, the technology readiness level (TRL) is still low now, and the technology is still in the experimental stage in China (Bagang Steel under China Baowu Group), Japan, and Europe.

• **Hydrogen blending in blast furnace:** Hydrogen can be recycled from coke oven gas in the existing coking process and be injected into the blast furnace after reformation to increase hydrogen concentration. This process is piloted by COURSE50, ThyssenKrupp, and some Chinese steelmaking companies. It would not only reduce coal consumption and carbon intensity, but also serve as a transitional route to use hydrogen in steelmaking.

• **Biomass:** Biomass can also support steel decarbonization. Biogas could be used as DRI feedstock. Charcoal, converted from biomass sources, could also act as a substitute for coke in the ironmaking process. For example, Brazil currently produces about 10 million tons of pig iron using charcoal.[22] However, due to the limited resource of biomass in China, we do not think it would play a big role in China's steel decarbonization.

• **CCS:** CCS could be applied to steelmaking facilities during pre-combustion or post-combustion. For pre-combustion, CO_2 is usually captured from the top gas from the blast furnace, which is the most carbon-intensive process of the steel mill. The centralized capture way would reach a 60% capture ratio while potentially reducing the cost of CO_2 capture. Post-combustion CCS, which captures CO_2 from various sources of flue gases within the integrated still mill, is also technically possible and could further lower the carbon emissions intensity. However, it may add a significant cost premium to steel production.In this report, we focus on pre-combustion CCS for the steel industry.

• **Smelting reduction:** Smelting reduction (HIsarna or HIsmelt technology, etc.) may cut the sintering and coking processes of ironmaking by having coal directly react with liquid iron. It could reduce coal consumption and thus produce less CO_2 than conventional blast furnaces, while fitting into existing facilities (brownfield construction projects). Further, smelting reduction is more compatible with carbon capture and could help increase the CCS capture ratio to 80%. Now in China, Jianlong Steel and Bayi Steel under the Baowu Group are running this route. And the Xinggang relocation project plans to take the "smelting reduction+EAF" route as well. But this technology still needs further improvement on efficiency rate and equipment tolerance.

Fully decarbonized primary steel technology is a must for decarbonization.

• **Hydrogen direct reduced iron (DRI):** Hydrogen-based DRI offers a fully decarbonized way of ironmaking with a TRL of 6–8. And together with EAF, zero-carbon crude steel can be produced with electricity as the major energy source. Each ton of crude steel would require 3,500–3,800 kWh of electricity consumption in total.

DRI is a mature technology, although hydrogen-based DRI is new in the family. Although hydrogen-based DRI may face the challenges of costs and replacing existing assets, it is a very promising technology for steel decarbonization and is piloted by many steelmakers in China and other countries. The major advantages are: 1) it provides a fully decarbonized steelmaking route, and 2) it could greatly reduce costs in the future. But the hydrogen-based DRI route may have a higher requirement on the iron ore feedstock (e.g., high-quality pelleting) and may increase the difficulty of application.

The HYBRIT project in Sweden has produced the first ton of green steel through this hydrogen-DRI-EAF route. HBIS Group in China also started its construction of the 1.2 million annual ton hydrogen-DRI pilot plant. Baowu Steel and other Chinese steelmakers are also planning to pilot this technology.

Moreover, DRI (or sponge iron) produced could be transported and used in BOF to replace conventional pig iron. This could help leverage existing facilities. For further comparison see Exhibit 16.

• **Hydrogen plasma smelting reduction (HPSR):** Hydrogen plasma smelting reduction is under development and will be deployed in the SuSteel project of Voestalpine and by Jianlong Steel in China. The latter would transition gradually from coal-based smelting reduction to hydrogen-based smelting reduction. But the TRL of this technology is still lower than DRI.

• **Direct electrolysis:** The direct use of electricity to reduce iron via electrolysis is also technically feasible and may become economically viable in the long term. A few steelmakers, such as ArcelorMittal and Boston Metal, have begun to develop this technology to process raw iron ore.

The key to zero-carbon primary steel is to decarbonize the reduction process of iron.

The main approach to decarbonize primary steelmaking is to reduce the reducing agent's carbon intensity. This may mean changing the fundamental ironmaking method. (Exhibit 18).

If keeping the blast furnace as the ironmaking method, then blending hydrogen from coke oven gas or direct production in the process to partially replace coal could be a transitional approach in the short term. But this will not solve the whole problem. A blast furnace must incorporate CCS to significantly reduce carbon emissions.

Additionally, the ironmaking method could be changed to facilitate electrification and accelerate steelmaking decarbonization. DRI and smelting reduction both could help in the short run. For DRI, it would be mostly gas-based in China. It may require a higher quality of iron ore feedstock, which may increase the costs. It is better to pilot DRI where the electricity price is low. For smelting reduction, it could move from coal-based to hydrogen-based transitionally, but the technology must still be improved to support piloting (Exhibit 26). All these routes could be piloted by blast furnace steelmakers to improve the technology, reduce costs, and scale up in the long run.

Exhibit 18: BF-BOF decarbonization transitional routes

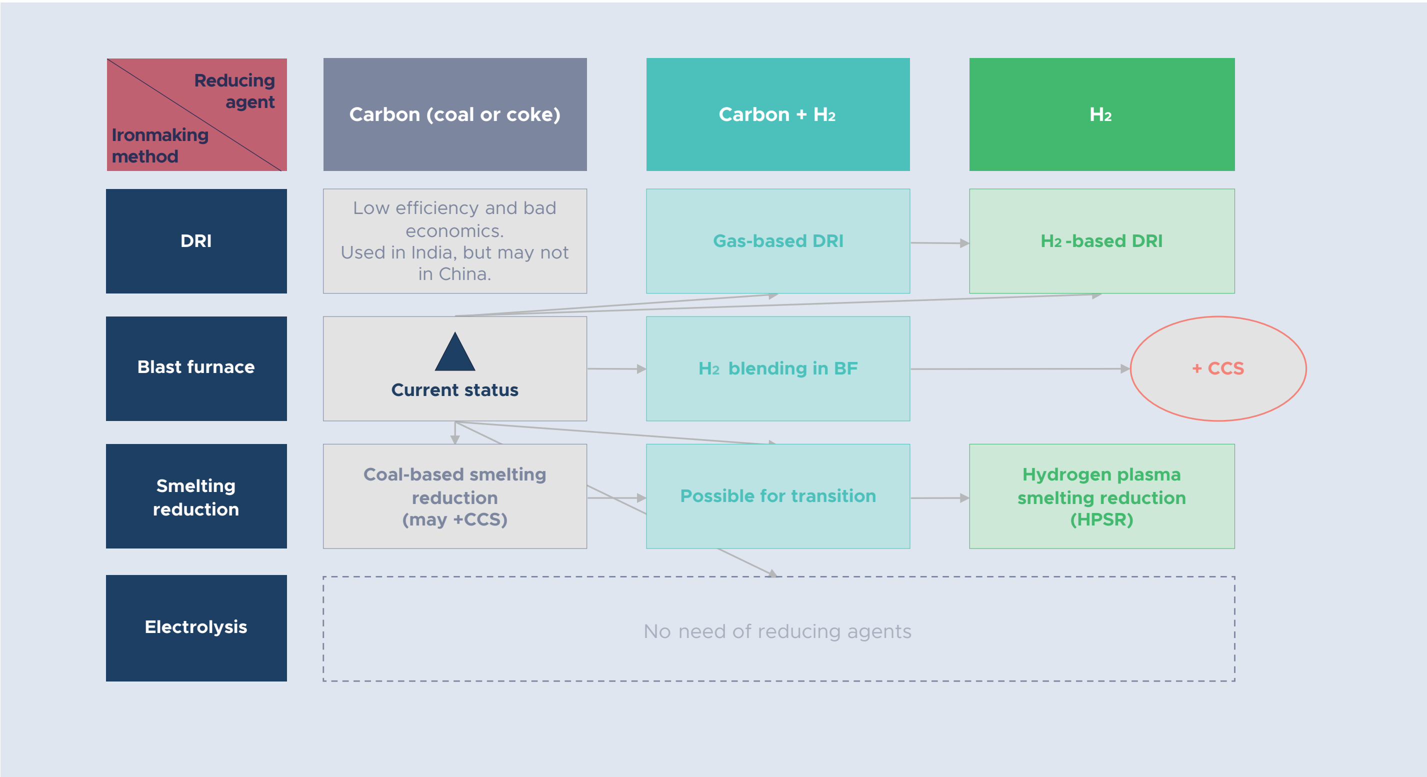


Exhibit 19: Features of transitional BF-BOF decarbonization routes

Transitional routes	H_2 blending in BF	CCS for BF-BOF	DRI	Smelting reduction
Favorable conditions	Any BF with good cash position for low-carbon retrofit	CCS capacity nearby or CO_2 consumer colocation	Cheap renewable to produce hydrogen	No specific location requirement
Constraints	Limit on hydrogen blending ratio	Need CCS capacity needed and potential CO_2 buyers	Pellets or fine powders with good quality are needed. May increase feedstock costs	Needs higher TRL; May need CCS for full decarbonization
Transition options			Could use coke oven gas as transitional gas source	Could transit from coal-based to gas-based then to hydrogen-based
Regions to pilot	All around China	Central China and northern China areas, Sichuan province	Inner Mongolia, Hebei, Shanxi, Liaoning, Sichuan and other provinces with good renewables	Better to be closer to renewables or CCS for further transition

The Economic Feasibility of Primary Steel Decarbonization

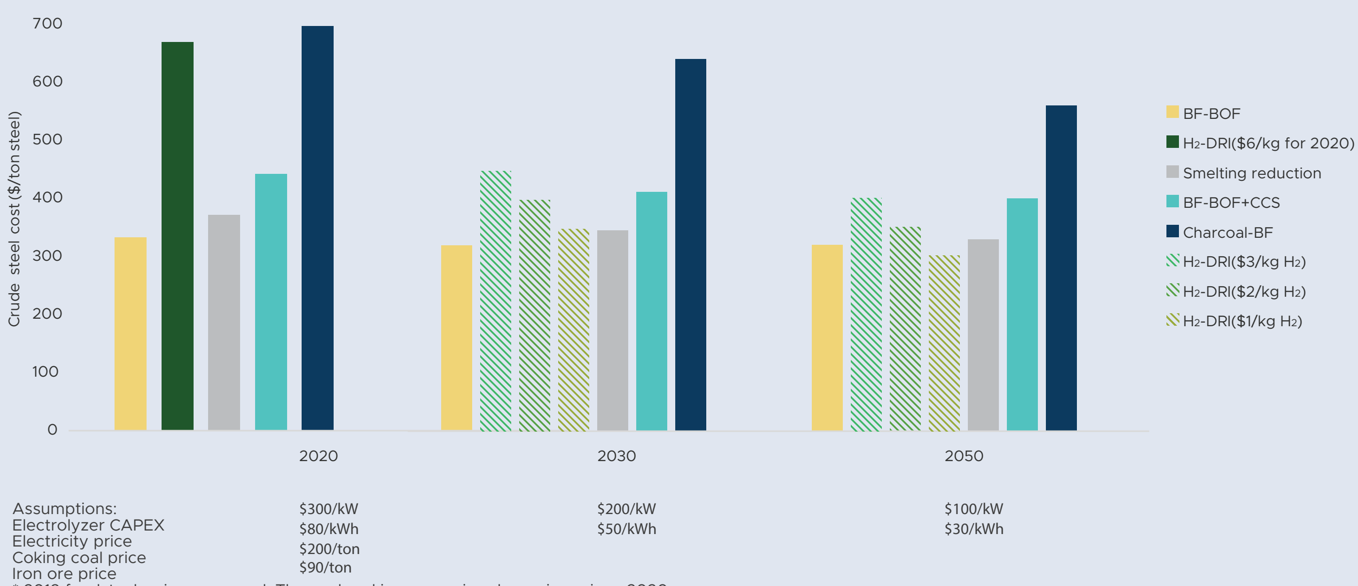
Currently, zero-carbon steel has a 40%–100% cost premium over conventional fossil-fuel-based steel. As shown in Exhibit 20, the crude steel cost from the conventional BF-BOF route is around $400/ton. With a $6/kg hydrogen price now, the crude steel from a hydrogen-DRI route would be 80% higher. The CCS route would also pose a 40% cost premium under an $80/MWh electricity price. And charcoal would have a more than 100% cost premium, making it too expensive to use in China.

In the future, the economic competitiveness of zero-carbon steel would be greatly improved with technology development, economies of scale, and power system development. (Exhibit 20)

First, the capital costs could be reduced. CCS equipment cost is likely to become 10%–20% cheaper in the next three decades. The cost for electrolyzers will fall from its current $300/kW to $100/kW in China. Also, the energy efficiency of water electrolysis could be improved.

Further, with the massive renewable capacity growth in China, the electricity price is expected to drop significantly in the next 30 years. With electricity costing $50/MWh in 2030 and $30/MWh in 2050, the cost premiums of CCS-based steel would drop to 30% in 2030 and 27% in 2050. The electricity price drop will also result in the massive cost reduction of green hydrogen. Many countries including Germany and the United States have set targets to bring the cost of hydrogen down to $2/kg by 2030 and $1/kg by 2050. This would significantly improve the cost-competitiveness of hydrogen-based steelmaking routes as shown in Exhibit 20.

Exhibit 20: steelmaking cost of different routes now and in the future

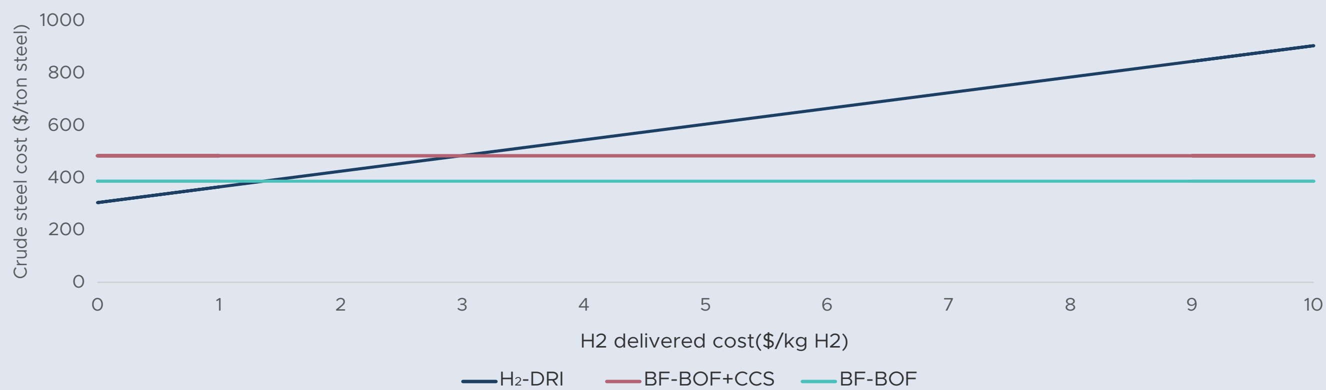


* 2019 feedstock prices are used. The coal and iron ore prices have risen since 2020.

For greenfield projects, hydrogen-based steelmaking is possible, and may be the only zero-carbon choice to reach cost parity with conventional steelmaking. According to RMI analysis, as shown in Exhibit 21, if the delivered hydrogen cost is lower than $3/kg, hydrogen-based DRI steelmaking is a more economic choice than CCS by 2050. And if the delivered hydrogen cost could fall to less than $1.5/kg, the H_2-DRI based crude steel could even be cheaper than conventional BF-BOF-based crude steel for greenfield projects. While for CCS route, it is not possible to reach under conventional steelmaking cost, because it always has an add-on cost.

This would mean that, if the electricity price falls to less than $30/MWh, hydrogen-based DRI would be more favorable than BF-BOF greenfield projects, considering a majorly on-site hydrogen production case (Exhibit 22). In real cases, it may require some additional hydrogen transportation cost for delivery. However, the cheap renewables especially in Western China could further support the hydrogen cost requirement.

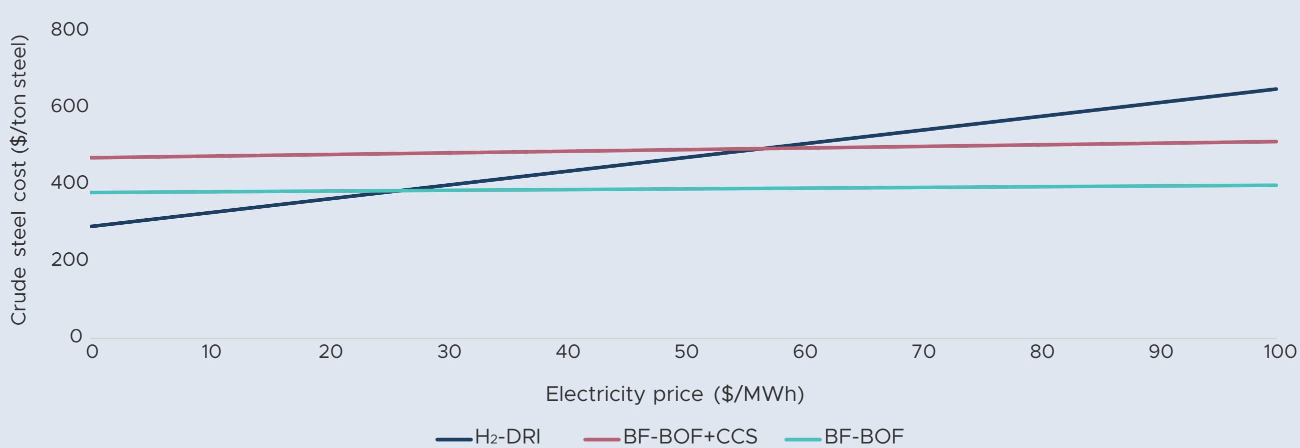
Exhibit 21: Steelmaking cost based on hydrogen cost in 2050 (Greenfield case)



* Note: Smelting reduction is not included in the sensitivity analysis due to lack of data reference.

Assumptions: 1) On-site CCS and other utility electricity price=$30/MWh; 2) Other assumptions same as Exhibit 20.

Exhibit 22: Steelmaking cost based on electricity cost in 2050 (Greenfield case)

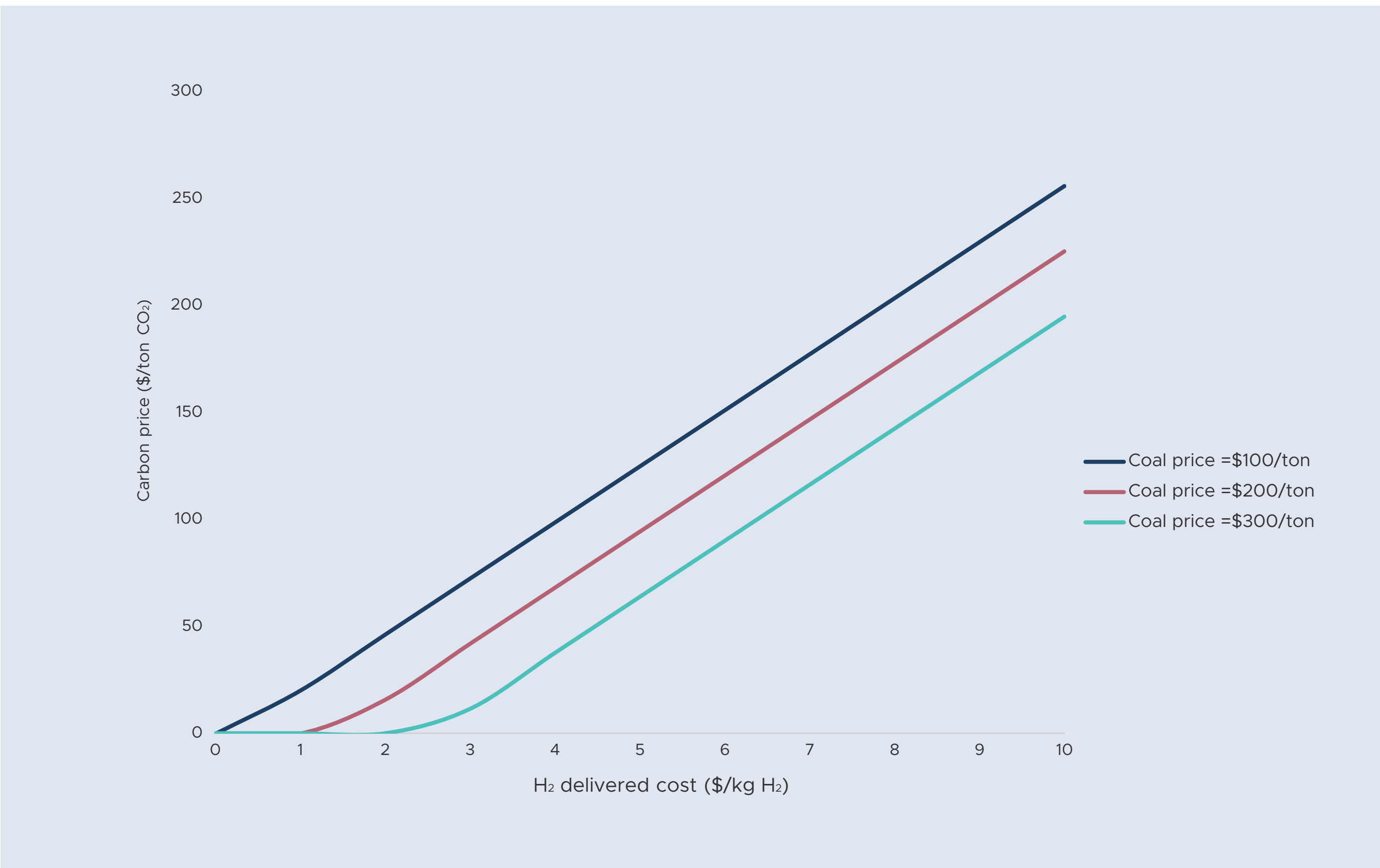


* Note: Smelting reduction is not included in the sensitivity analysis due to lack of data reference.

Assumptions: 1) Hydrogen storage cost = $0.2/kg; 2) Other assumptions same as Exhibit 20.

The cost parity would also be affected by other factors: coking coal price, carbon price, etc. The higher the coking coal price and the higher the carbon price, the more favorable green hydrogen will be. As shown in exhibit 23, if the coking coal price reaches $300/ton, hydrogen-DRI based steel would meet cost parity with conventional steel at a $2/kg hydrogen cost, which is the target of many countries by 2030. Also, if a carbon price is imposed on steelmaking and coal consumption, the cost parity conditions would be significantly loosened for hydrogen-based green steel. With the current coal price at $200/ton, if the carbon price reaches $50/ton CO_2, hydrogen-based DRI could break even with crude steel at a hydrogen cost of $3/kg.

Exhibit 23: Cost parity line of hydrogen-DRI with conventional steel under electricity price and carbon price (Greenfield case, 2050)



The CO_2 abatement costs in Exhibit 24 also show that CCS and hydrogen-based DRI could both be implemented at a cost under $100/ton CO_2 by 2050. And hydrogen-based DRI could offer even an abatement cost near zero or even less, with a low hydrogen cost.

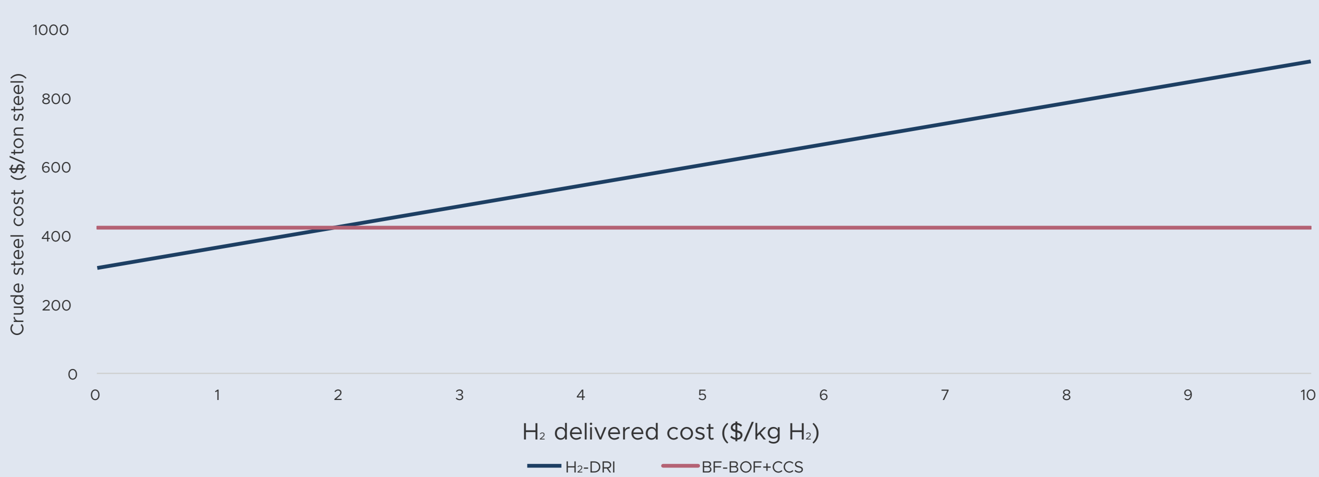
As for brownfield projects, CCS could save costs by leveraging more existing facilities. As shown in Exhibit 25, by 2050, when the hydrogen delivered cost is higher than $2/kg, CCS may be more favorable; when hydrogen is less than $2/kg, switching to hydrogen-based DRI could still gain economic benefit (assuming a constant electricity price for CCS).

Decarbonized steelmaking technologies including hydrogen-based DRI and CCS have large potential in the future to gain economic feasibility, especially for the DRI route. The key drivers are technology development, electricity price reduction, carbon price mechanisms, and coal restriction.

Exhibit 24: CO_2 abatement cost of different technology routes

Assumptions: same as Exhibit 20.

Exhibit 25: Steelmaking cost based on hydrogen cost in 2050 (Brownfield case)



Assumptions: 1) Onsite CCS and other utility electricity price=$30/MWh; 2) Other assumptions same as Exhibit 20.

Chapter 5:
The Roadmap of China's Steel Zero-Carbon Transition

In this chapter, we describe the roadmap of China's steel zero-carbon transition from both time and space dimensions. From the time perspective, we analyze short-term actions and long-term vision, to depict the steps toward a zero-carbon future. From the geographic perspective, we illustrate the actions of different regions' steelmakers and the ultimate zero-carbon steelmaking landscape, based on existing capacity, resources, and cost factors. Also, this chapter lists some potential creative new dynamics of the steel sector under the zero-carbon vision.

The Pathway of China's Steel Industry under the Zero-Carbon Scenario

Under the zero-carbon scenario, steelmaking in China would gradually move from a coal-dominant route to zero-carbon routes (Exhibit 26).

Under the zero-carbon scenario, by 2030, secondary steel would account for 25% (245 million tons), twice that of current production. The scrap demand would increase to 270 million tons per year. From the perspective of the scrap market, a more systematic regional scrap market will gradually take shape by 2030, especially in developed areas such as the Bohai region, the Pearl River Delta, and the Yangtze River Delta where the supply of scrap is expanding. Then a more reliable scrap collection and sorting system will be established, and the price stability of scrap will be improved.

Steelmaking enterprises can also extend their value chain upstream to the scrap market and establish their own supply system. In terms of electric furnace capacity, dedicated electric furnaces in Southwest and North China will continue to expand their capacity and benefit from gradually decreasing electricity prices. Integrated steel mills will also expand the ratio of electric furnaces and scrap blending, which will increase the development of scrap.

In addition, by 2030, blending hydrogen in blast furnaces can be applied on a large scale as a transition means for clean-up, as shown in Exhibit 27. Technologies such as direct reduced iron and carbon capture will be commercially ready with improving technology and decreasing costs. The pilot projects can be greenfield projects or based on existing blast furnace or electric furnace capacity to reduce investment costs. It is expected that direct reduced iron and carbon capture routes will each have a 2.5% capacity share, contributing a total of about 50 million tons of steel capacity per year. Other technologies such as smelting reduction will also begin to be piloted and are expected to contribute to a portion of the zero-carbon primary steel capacity.

By 2040, secondary steel production and zero-carbon primary steel production would further expand to replace the fossil-fuel-based route. Secondary steel production will grow to 310 million tons per year by 2040. The availability of scrap will increase, and the recovery ratio and quality will continue to improve.

And, by 2040, technologies such as direct reduced iron and carbon capture will gradually enter the scale-up stage (Exhibit 27). The cost premium will decrease and the application scale will expand driven by factors such as lower hydrogen cost, higher carbon price, and equipment scale expansion. Smelting reduction technologies will also continue to improve and transition to hydrogen plasma smelting reduction, further expanding the pool of decarbonization steelmaking technologies. It is expected that the production share of direct reduced iron and carbon capture routes will each reach 7%, contributing a total of about 108 million tons of steel capacity per year.

By 2050, under the zero-carbon scenario, a secondary route could support 60% of steel production. The scrap demand would reach 410 million tons per year. As for primary steel production, hydrogen-based routes and CCS-based routes would both scale up and contribute nearly 20% each and 200 million tons per year in total. This would mean 7 million tons of hydrogen and 170 million tons of CCS capacity needed per year. Further, hydrogen plasma smelting reduction and other zero-carbon primary steelmaking technologies might also reach commercial scale and play a big role in the future. In this case, energy-related carbon emissions in China's steel sector will decrease to 190 million tons per year or even lower, more than 90% less than the 2020 level.

Exhibit 26: The production route of China's steel sector under the zero-carbon scenario (2020–2050)

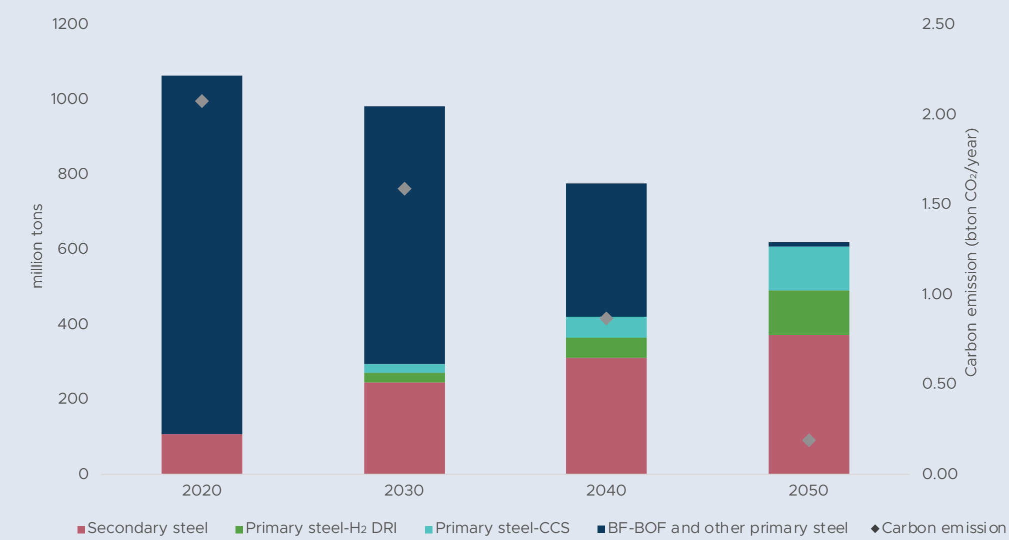
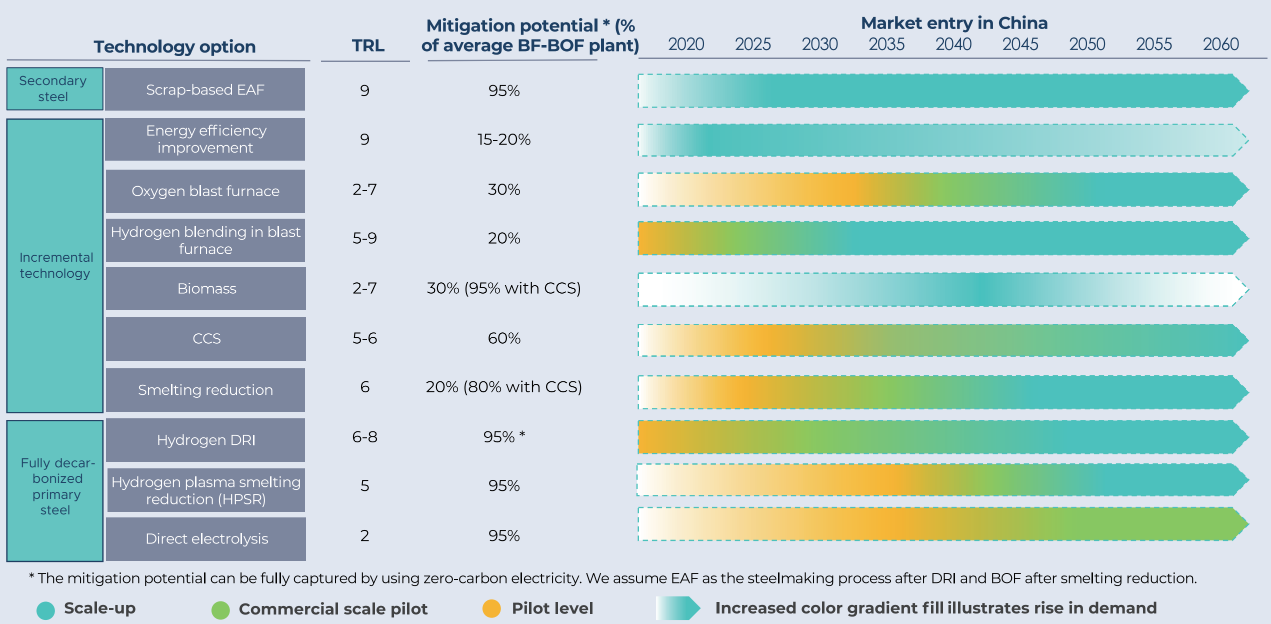


Exhibit 27: Steel decarbonization technology market entry sequencing

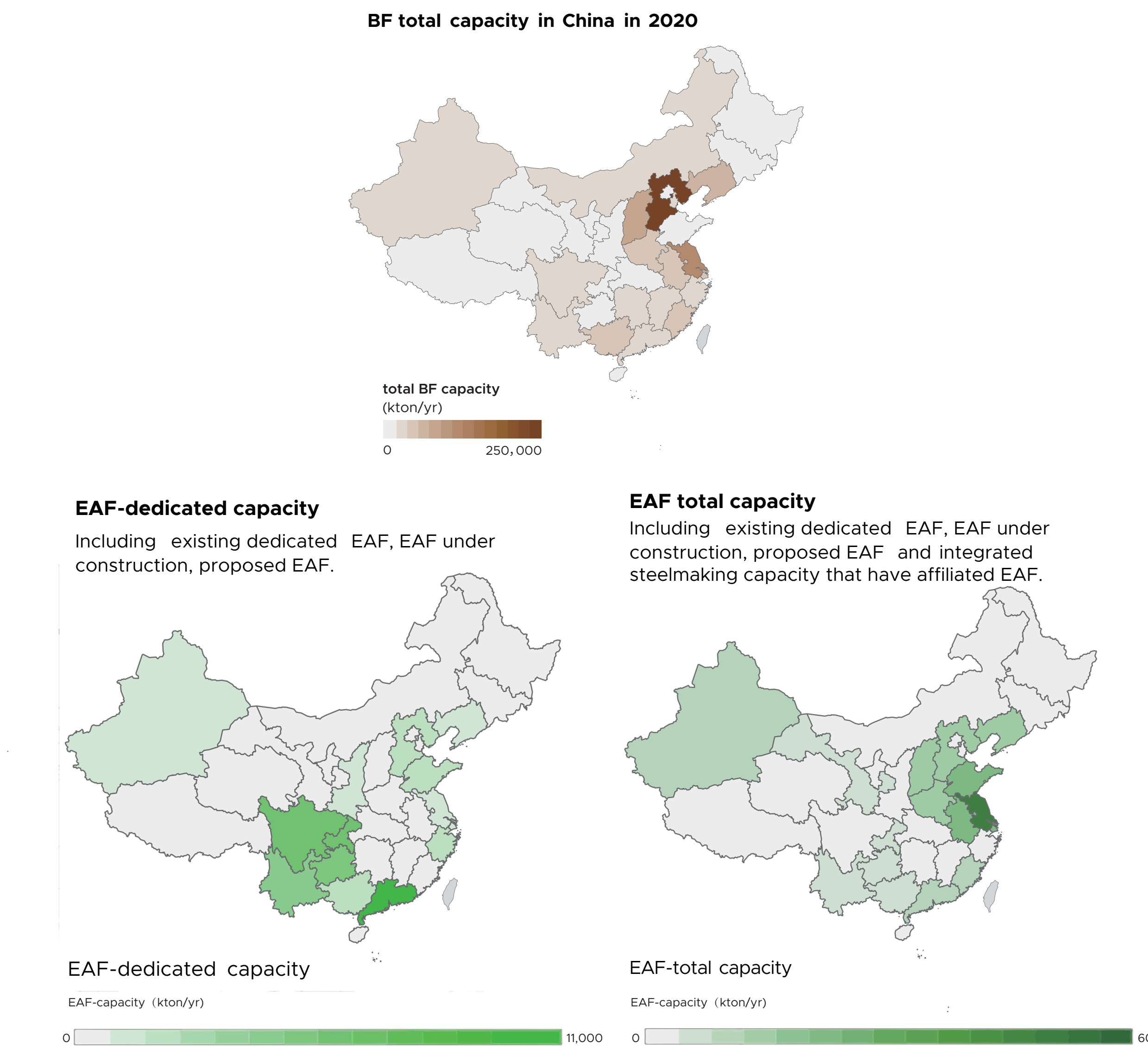


The Geographic Landscape of China's Steel Industry Decarbonization

The distribution of zero-carbon steel routes will be affected by geographic factors.

Steelmaking decarbonization would present geographic distribution characteristics due to the existing steelmaking profile, resource availability (renewables and CCS capacity), and cost-competitiveness in different locations.
First, looking at the existing steelmaking profile, central and eastern China are dominated by BF-BOF, while EAF is mostly located in the southwest. As shown in Exhibit 28, the blast furnace capacity concentrates in the central and east areas, with Hebei, Jiangsu, and Shanxi provinces making up 40%. As for EAF capacity, dedicated EAF capacity, which means the mill is fully electrified and scrap-based, is mostly located in southwest China, including Sichuan, Yunnan, and Guangdong provinces. There is also affiliated EAF capacity, which is integrated with BF or BOF to provide flexibility, and which could also support the scaling up of the EAF route.

Exhibit 28: Steelmaking capacity geographic distribution in China

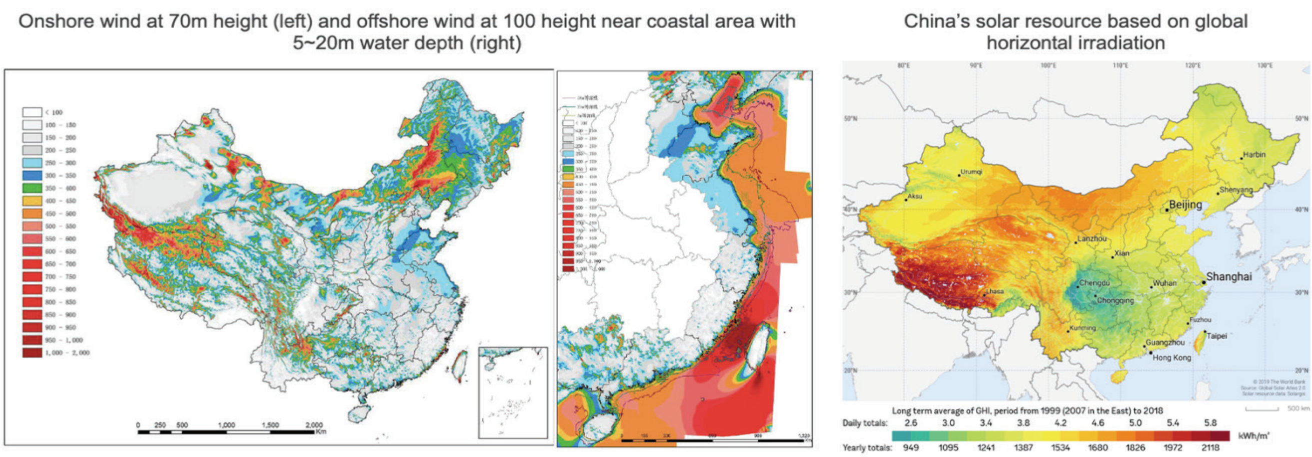


Second, the cheap renewable electricity in Western and northern China would benefit the DRI and hydrogen plasma smelting reduction routes, which need large-scale power consumption. As shown in Exhibit 29, Northern China has relatively good wind and solar resources, and most provinces in the north have introduced mechanisms to lower renewable electricity prices due to high curtailment. As for Southwest China, a rich hydro power resource and negotiation pricing mechanism are both available.

For coastal China, the average electricity prices for industrial users are higher than the north and west now, but they may benefit from future development of power market reform and offshore wind power. So green hydrogen-based DRI and other technologies may be more favorable in Northern and Western China, and have the potential to also scale up in the east in longer term.

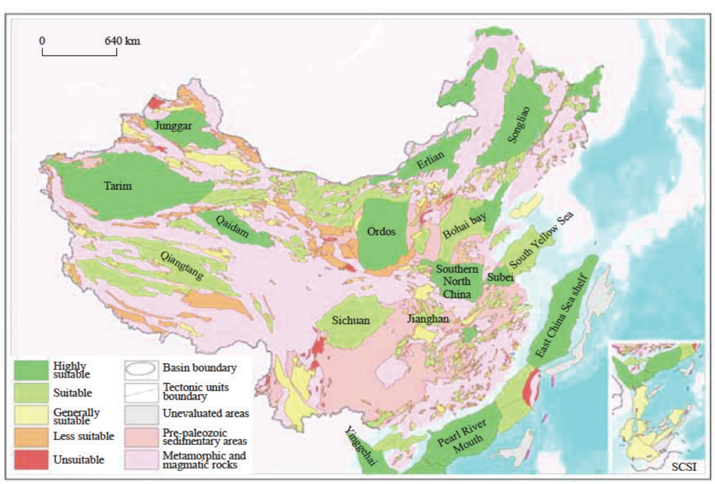
Further, CCS routes have favorable conditions in the Northeast, Northwest, Bohai Bay area, and Sichuan Basin (Exhibit 30). If considering CCS for steel plant decarbonization, it needs to match with nearby storage capacity to reduce CO_2 transportation cost.

Exhibit 29: Geographic distribution of renewable resources in China



Source: Energy Research Institute, IEA (2011), Development Roadmap for China's Wind Power 2050 (left); Solargis (right).

Exhibit 30. CO_2 storage capacity in China



Source: The King Abdullah Petroleum Studies and Research Center, Policy lessons from China's CCS experience, 2018.

The geographic landscape and evolution of China's steel industry decarbonization.

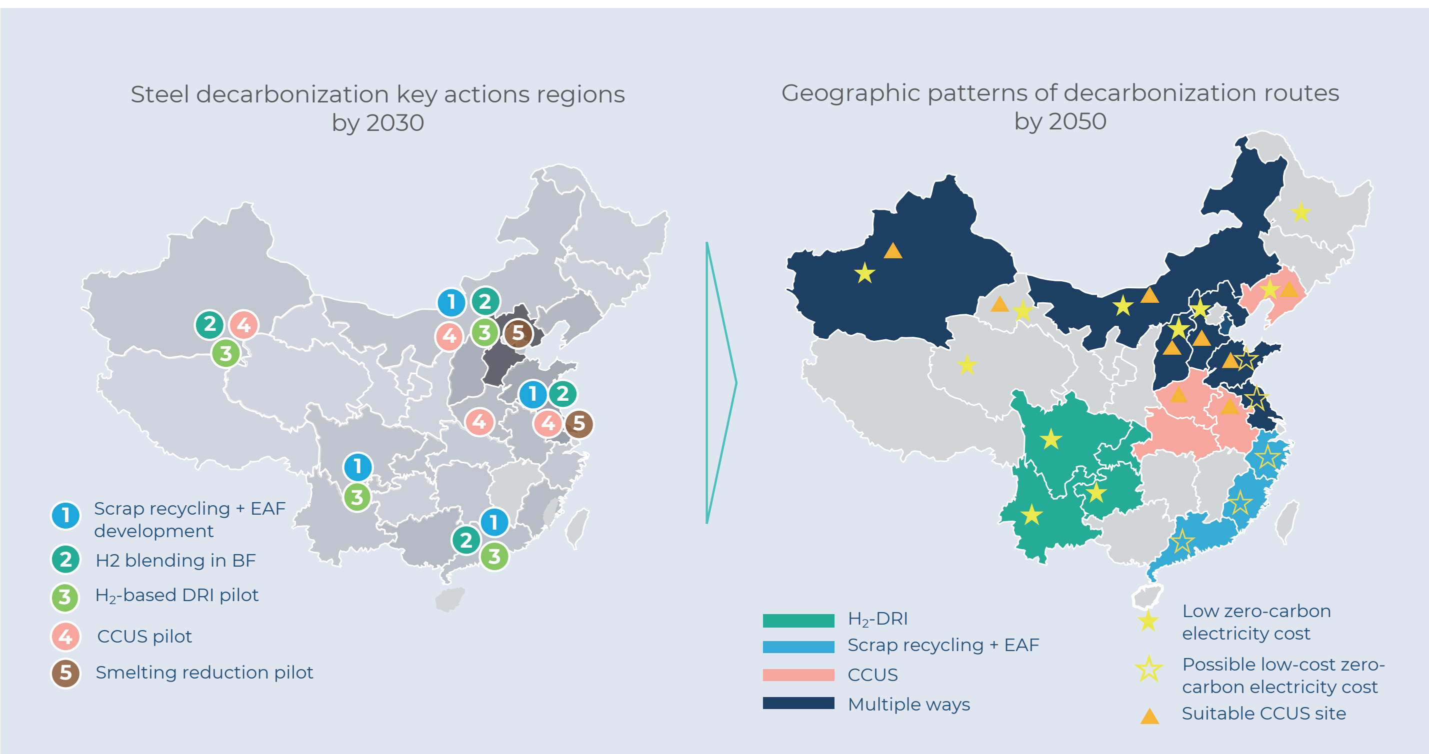
Considering all the factors and constraints, RMI has laid out the geographic landscape of China's steel industry decarbonization.

By 2030, five key actions can be taken as transitional routes to decarbonize the steel industry in China. (Exhibit 31-left): 1) EAF scaling up around coastal provinces where scrap supply is sufficient, and in Northern and Southwestern China where there is a good foundation for EAF; 2) H_2 blending in BF around China to reduce coal consumption; 3) H_2 -based DRI pilots in Northern and Southwestern China where renewables are cheap; 4) CCUS pilots in the Bohai Sea region, Central China area, and Xinjiang province to meet CCS capacity; and 5) smelting reduction pilots in the Bohai Sea region. Those piloting could help further develop the technologies, lower the costs, and support scaling.

By 2050, those technology routes would together support the steel industry to meet the carbon-neutrality target. (Exhibit 31-right). The steel industry would have a combination of decarbonized technology routes based on technology readiness, economic competitiveness, resource availability and other factors. It may show certain regional characteristics as shown in Exhibit 31-right.

The H_2-DRI route may be favorable in southwest China, given its great hydropower resource and experience in EAF. Coastal China may emphasize scaling up scrap recycling and EAF steelmaking, due to the supply of scrap and the lack of cheap renewables. Places where CCS capacity is available, such as the Central China area, may use the CCS route. And in Northern China, steelmakers could enjoy multiple favorable conditions and choose all those routes based on their specific projects and transition costs in the future. Through all those routes, it would be technically and economically feasible for China's steel industry to meet the carbon-neutrality goal.

Exhibit 31: Final map of China's steel decarbonization



It should be noted that the lifetime and product requirement would also impact the pathways and distributions of zero-carbon decarbonization. First, the average age of China's blast furnace fleet is still young—less than one-third of the total lifetime right now. If changing the process and reducing the carbon emissions of steelmaking toward the carbon-neutrality goal, steelmakers and investors need to think about how to handle the stranded asset issues.

Second, the scrap-based EAF process is limited on product type due to contamination. It cannot produce a low-carbon steel product, such as the thin flat sheets needed for automobiles. But the DRI route may help solve this problem. Direct reduced iron product has much lower contaminants, and could therefore supplement scrap when EAF is called upon to make high-quality flat products and low nitrogen steels.

Meanwhile, the carbon-neutrality trend may create new business models and change the dynamics of the steel industry both domestically and internationally.

• Possibility 1: Relocating the facility from the east to the west/north.
For new steelmaking projects by 2050, hydrogen-based DRI may be cheaper than BF-BOF, with cheap renewables and a potential carbon price (Exhibit 32-left). If so, opening new steel capacity in the future in western/northern China, where the renewables are sufficient and cheap, may be a better choice than eastern China. Steelmakers may even have an option to relocate their capacity within the group to pilot decarbonized routes.

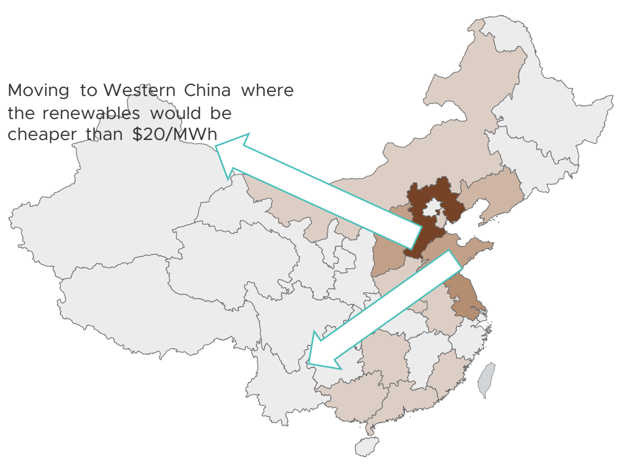
• Possibility 2: Establishing a new global sponge iron market.
Direct reduced iron, also called sponge iron, can be compacted and transported over long distance. The sponge iron can be used not only in EAF but also in the BOF process to extend the life of an existing BOF facility. This will alleviate the stranded asset risks under the carbon-neutrality target.

If separating the ironmaking and steelmaking process, producing sponge iron through DRI where renewables are cheap (e.g., in Western China) and then transporting it for EAF and BOF around China, may create a new market for green sponge iron. The new value chain structure may benefit from the low cost of green sponge iron, continuous usage of existing BOF, and large development of EAF with high-quality products.

Moreover, Australia, Brazil, and other iron ore owners may also become sponge iron exporters and create a global market (Exhibit 32-right). These countries have the advantages of cheap iron ore and renewable resources, which would enable them to expand on the decarbonized steel value chain.

Currently, there is an international pig iron trade market, especially between the United States and Europe. A new market of sponge iron would further support the decarbonization of the whole steel industry, including in China.

Exhibit 32. New possibility of steel value chain dynamics under the carbon neutrality target



a. Relocating the facility from the east to the west/north

b. Establishing a new global sponge iron market

Chapter 6:
Policy Recommendations

To achieve full decarbonization of China's steel industry in the next 30–40 years will hardly be a process of the industry's own development. It will undoubtedly be accelerated by the internalization of the external cost of climate impacts through policies. This will play a key role not only in pushing the industry to reach a carbon peak as soon as possible, but also in the ultimate achievement of carbon neutrality.

As can be seen from the analysis in previous chapters, promoting the comprehensive decarbonization of the steel industry involves all aspects of steel production and consumption. On the production side, policy formulation should not only focus on decarbonization, but also take into account the coordination of other policy objectives of the industry. Policy should be used to redefine the foreign trade and investment strategies of China's steel industry from the perspective of overall industrial decarbonization. On the demand side, a favorable market environment should be created to support zero-carbon steel.

Our policy recommendations include:

• **Starting from the final purpose, define quantitative carbon-neutrality targets, drive high-quality emissions peaking, and periodically adjust the dynamic implementation path for carbon neutrality during the post peak period.** Since carbon neutrality is the ultimate goal and core driving force of this round of steel industry transformation, it is necessary to clarify the quantified goal of decarbonization of the industry. In other words, we must answer the question of whether the steel industry needs to achieve near-zero emissions, net-zero emissions, or negative emissions in order to support China's carbon-neutrality efforts.

After the final decarbonization target of the industry is defined, the peak year, peak emissions amount, and post-peak emissions reduction rate of the whole industry should be deduced. Even further, a carbon emissions cap for the whole industry at different phases can be established. For example, based on the analytical results of Chapter 5 under RMI's net zero scenario, the caps for 2030, 2040, and 2050 could be 1.6, 0.9, and 0.2 gigatons of carbon emissions respectively (Exhibit 26).

As pointed out in Chapter 2 of this report, China's steel production will peak soon, and the carbon peak of China's steel industry will be mainly driven by output, assuming that the production process and efficiency are unlikely to change rapidly. Therefore, before reaching the peak, policies should push the industry to reach a high-quality peak and restrain the rush to install carbon-intensive assets. After reaching the peak, the progress of industrial decarbonization actions and the development trend of related processing technologies should be evaluated regularly, and the target, schedule, and implementation path of decarbonization of the industry should be adjusted dynamically.

• **Constantly tap the potential of energy efficiency improvements based on traditional high-carbon steelmaking processes in the periods before and 5–10 years after peaking.** China's steel assets, dominated by BF-BOF facilities, are generally young and have a long remaining lifetime compared with the ones in developed countries. Improving energy efficiency is generally considered to be a means of decarbonization with positive economic benefits.

To make full use of assets, policy should promote energy efficiency technologies such as effective top gas reuse and smart energy control systems to decarbonize the industry in all segments of steel production. Specifically, further improving the energy efficiency of BF-BOF assets can alleviate the upward pressure of carbon emissions caused by the small increase in steel production before the steel industry peaks its emissions. It will also reduce the peak emissions of the whole industry and contribute to the early end of the "plateau" of carbon emissions and the formation of a downward trend of carbon emissions after the peak.

With the phaseout of carbon-intensive steelmaking assets 5–10 years after the carbon peak of the industry, the carbon reduction benefits of energy efficiency improvement based on the related assets will also decrease gradually.

• Promote the rapid capacity substitution of secondary steelmaking in the periods before and 10-15 years after peaking, rationally allocate policy resources before the complete decarbonization of the whole industry, and pay more attention to the coordinated development of secondary steelmaking and zero-carbon primary steelmaking. As described in Chapters 3 and 4 of the report, the absolute output and proportion of primary steelmaking are large. With the rapid fall of demand for steel and the rapid deployment of CCUS- and hydrogen-based steelmaking being unlikely, secondary steelmaking substitution may be cost-effective under appropriate policy support.

Secondary steelmaking can quickly achieve a certain scale of emissions reductions contributing to the industry's carbon peaking. Therefore, in the periods before and 5–10 years after peaking, policies should accelerate the development of secondary steelmaking by supporting capacity substitution, cultivating scrap industry, and favoring electricity use for EAF steelmaking. To ensure scrap supply, policy should drive far more aggressive recycling, with strong regulation mandating the maximum possible recycling of steel from the auto, appliance, and construction industries, with quantitative recycling targets set.

In the middle and late stages of industry decarbonization (i.e., the 15–20 years before the achievement of zero carbon), the cost difference between zero-carbon primary steelmaking and secondary steelmaking will gradually vanish, making these steelmaking routes competitive in certain applications. This is mainly for two reasons. Hydrogen-based steelmaking, CCUS, and other technologies and processes will generally form a more mature industrial system after years of development and improvement; and as the release rate of scrap resources slows down, the dividend of the reduction of scrap collection cost will shrink gradually.

In addition, competition for limited scrap resources between primary and secondary steelmaking may help keep the cost of scrap resources low for a period. Based on the evolution of this trend, policies should focus more on the coordination of the development pace between secondary steelmaking and zero-carbon primary steelmaking routes, to avoid bias of either route due to the policy intervention. Reasonable balance of primary and secondary steelmaking capacity might be made by market forces, particularly after the participation of steelmakers in the carbon market becomes relatively mature.

• Promote the decarbonization of primary steelmaking in a step-by-step way according to the incremental cost of the substitutions of fuel/feedstock and process equipment. According to the analysis in Chapters 4 and 5 of this report, the decarbonization costs of primary steelmaking may include the operating-cost substitutions of feedstock/fuel and the fixed-cost substitution of process equipment.

In the early stage of decarbonization, China's primary steelmaking still needs time to mature since direct reduced iron, smelting reduction, and direct electrolysis technologies are positioned in different stages on the path to maturity. Therefore, in this period, minimal disruptive substitution of existing process equipment should be carried out. Instead, carbon emissions reductions should be achieved through additional fixed investment (such as installation of CCUS facilities) and higher operating costs (such as applications of hydrogen, electricity, and biomass) based on existing technology routes.

To be specific, policies should encourage improving the utilization level of by-product hydrogen in the coking process of the blast furnace, provide financial support to steelmakers for producing and utilizing hydrogen energy, and cultivate the demand and habit for hydrogen consumption in the steel industry. Policies should also encourage fully utilizing existing assets mainly consisting of blast furnaces.

At the same time, efforts should be made to actively promote the research and development and demonstration of technology routes such as smelting reduction and direct reduced iron that can be applied to hydrogen-based ironmaking in the future. It is also important to accelerate the test demonstration and scale of CCUS, and encourage cross-industry cooperation to promote the utilization of resources after carbon capture.
In the middle and late stages of the decarbonization of primary steelmaking, considering that the original BF assets are gradually entering retirement age and the new

technologies and processes are gradually mature, the policy focus should be shifted to accelerating investment in new assets. Specifically, the hydrogen supply system for the steel industry and CCUS industry should be gradually improved and the cost of hydrogen and CCUS should be continuously decreased. Additionally, large-scale production and operation of technology routes such as smelting reduction and direct reduced iron should be promoted according to different resource conditions in different regions.

• **Focus on the coordination of carbon-peaking and carbon-neutrality goals with other industrial development goals, and fully mainstream carbon reduction into the industrial policymaking process.** The next stage of China's steel industry development will focus on the promotion from scale to quality, with specific policy areas including phasing out outdated capacity, increasing industrial concentration, developing intelligent manufacturing, and promoting service-oriented manufacturing.

While these policies will automatically contribute to the industry's carbon reduction, policies and measures are still needed to promote greater synergy and achieve a lot more carbon emissions reductions. In specific, carbon reduction should be considered an important quantitative indicator to design and evaluate industrial policies such as eliminating backward production capacity, preliminary project approval, and evaluating corporate mergers and acquisitions. In addition, new constraints related to zero-carbon steel production, such as the availability of renewable energy, carbon capture and storage, and geological resources mentioned in Chapter 5 of this report, should be considered in the green-field project planning and approval process.

• **Recognize the importance of an appropriate carbon pricing mechanism to help accelerate the decarbonization of China's steel sector, and expediate China's national carbon market to cover the steel sector under the emerging global carbon tariffs.** Foreign trade and investment policies will also affect the decarbonization process of the industry both at the national and global level, and policy focus should be different for different trading and investment partners.

Regarding developed countries and regions such as Europe and the United States, the focus should be on the impact of the proposed carbon border adjustment mechanism (CBAM). Currently, China doesn't export much steel to developed economies. However, as the steel industry decarbonizes, China should proactively prepare for carbon tariffs. This includes speeding up the process of involving the steel industry in the carbon market so that China can keep pace with developed countries on carbon price mechanisms and minimize the impact of CBAM.

Regarding developing countries, in the early stage of its decarbonization, China's steel industry should be cautious of overseas investment and maintain a reasonable scale of exports. After green zero-carbon steel production technology becomes mature, the large-scale investment and export of green steel projects should be accelerated, joining others to lead the growth of zero-carbon production on a global level.

• **Establish a standardization system for zero-carbon steel products and cultivate the market for scaling up.** Steel decarbonization is a gradual and lengthy process. During this process, the production cost of zero-carbon steel will be significantly higher than that of fossil fuel-based metallurgical products for a long time. Passing this cost premium on to consumers with the ability and willingness to pay, will provide a sustainable driving force for the development of a zero-carbon steel industry. Therefore, standardizing zero-carbon steel will become important for introducing demand-side policies, such as:

—developing a national-level carbon emissions accounting and certification system for steel products;

—introducing a mandatory carbon emissions standard for steel to the construction material procurement process, first applying to the key national public infrastructure projects and then expanding to more public projects owned by governments at all levels, thus encouraging state-owned enterprises to purchase green zero-carbon steel;

—linking green steel consumption with carbon-neutrality targets for local governments and enterprises.

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