March 2023

Net-Zero Roadmap for China's Steel Industry

Ali Hasanbeigi [1], Hongyou Lu [2], Nan Zhou [2]

[1] Global Efficiency Intelligence

[2] Lawrence Berkeley National Laboratory

Acknowledgements

The author would like to thank Dr. Yang Fuqiang, Dr. Chen Jiong, and Zhu Hong of Peking University, Dr. Chen Yu of the China Steel Development Research Institute, Dr. Zhang Chunxia of the Chinese Society of Metals, Dr. Li Bing of the Metallurgical Planning Institute, Dr. Zhang Qi of the Northeastern University, and Dr. Li Xiuping of the China Iron and Steel Research Institute, Chan Yang of European Climate Foundation, Lynn Price of Lawrence Berkeley National Laboratory, Chris Bataille of Columbia University, and Navdeep Bhadbhade of Global Efficiency Intelligence for their valuable input on this study and/or their insightful comments on the earlier version of this document.

Disclaimer

Recommended citation: Hasanbeigi, A., Lu, H., Zhou, N. 2023. Net-Zero Roadmap for Chinese Steel Industry. Lawrence Berkeley National Laboratory, and Global Efficiency Intelligence. LBNL-2001506

https://eta.lbl.gov

https://www.globalefficiencyintel.com

Executive Summary

Iron and steel manufacturing is one of the most energy-intensive industries worldwide, accounting for around 7% of global greenhouse gas (GHG) emissions and 11% of global carbon dioxide (CO_2) emissions. In 2021, China accounted for 53% of global steel production. The Chinese steel industry produced 1,033 million tonnes (Mt) of crude steel in 2021, of which 89.4% was produced by primary steelmaking plants using blast furnace-basic oxygen furnace (BF-BOF) and 10.6% was produced by the electric arc furnace (EAF) production route.

China has pledged to peak its CO_2 emissions before 2030 and achieve carbon neutrality before 2060. China's steel industry is expected to peak its CO_2 emissions before 2030. This peak in steel industry CO_2 emissions is mainly driven by the peaking of domestic steel demand. Steel production in China has one of the highest carbon intensities in the world because the majority of steel is produced by the energy-and carbon-intensive BF-BOF steelmaking process.

The goal of this study is to develop a roadmap for deep decarbonization of the Chinese steel industry. We analyzed the current status of the Chinese steel industry and developed scenarios for 2050 to assess different decarbonization pathways that can substantially reduce the CO_2 emissions of the steel industry in China.

We included five major decarbonization pillars in our analysis: 1) demand reduction, 2) energy efficiency, 3) fuel switching, electrification, and grid decarbonization, 4) technology shift to low-carbon steelmaking, 5) carbon capture, utilization, and storage (CCUS).

Our analysis to 2050 shows that under a business-as-usual (BAU) scenario, due to steel demand reduction, moderate energy efficiency improvement, technology shift (primarily to the EAF production route), and decarbonization of the grid, annual CO_2 emissions will decrease by 54% between 2020 and 2050. Chinese steel production drops 23% in the same period under the BAU scenario (Figure ES1).

The Net-Zero scenario has the largest reduction in annual CO_2 emissions in the steel industry, as it includes a more ambitious contribution of demand reduction, energy efficiency measures, fuel switching, technology shift to low-carbon steel production, and CCUS. Under the Net-Zero scenario, total CO_2 emissions from the Chinese steel industry will decrease to about 78 $MtCO_2$ per year in 2050, a 96% reduction compared to the 2020 level.

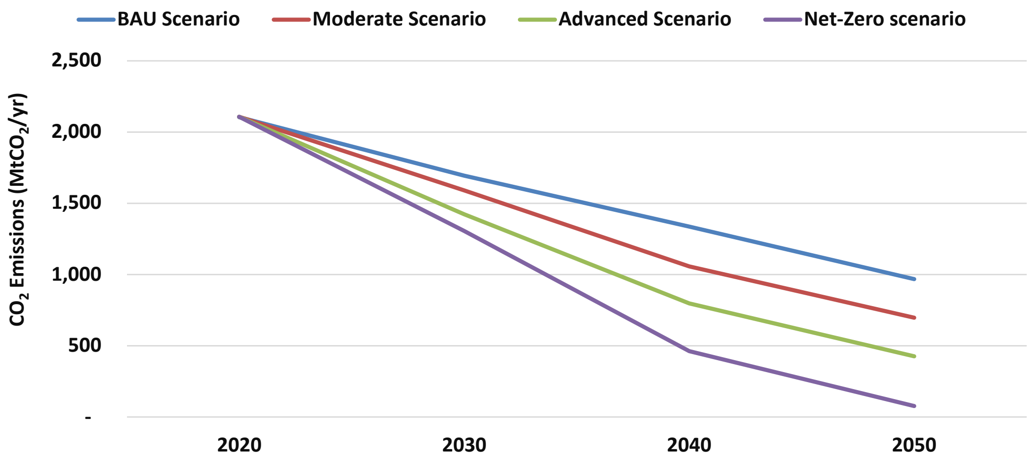


Figure ES1. Total annual CO_2 emission in the steel industry in China under various decarbonization scenarios, 2020-2050 (Source: this study)

The contribution of each decarbonization pillar to the CO_2 emissions reductions in the Net-Zero scenario for the steel industry in China in 2050 is shown in Figure ES2. In this scenario, the technology shift (primarily to scrap-based EAF steel production) makes the largest contribution to CO_2 emissions reduction, followed by demand reduction and fuel switching, electrification of heating, and electricity grid decarbonization.

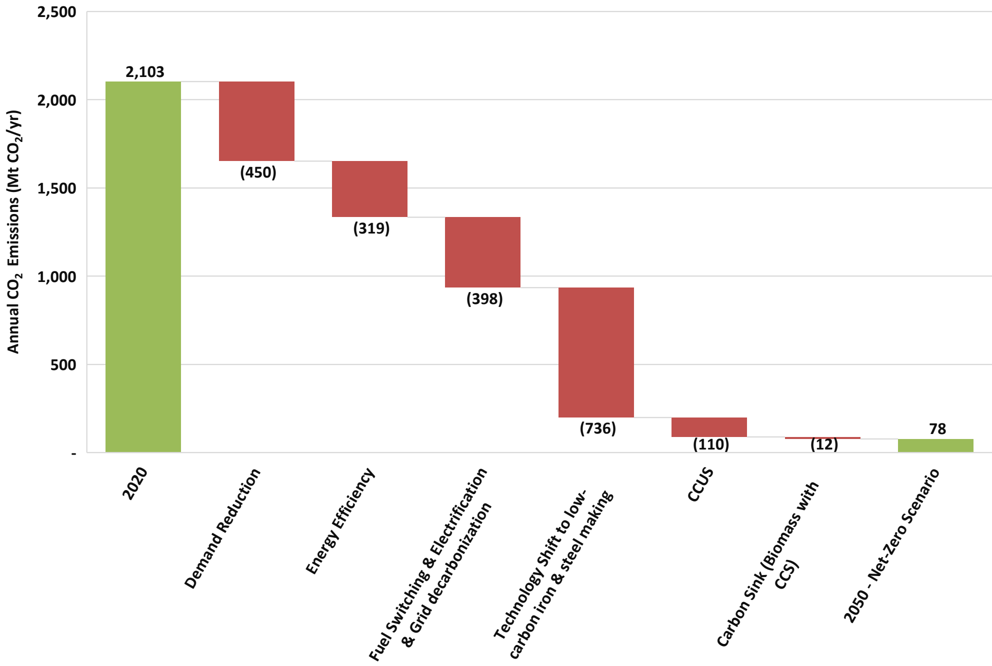


Figure ES2. Impact of CO_2 emissions reduction options in the Net-Zero Emissions scenario for the Chinese steel industry (Source: this study)

The Near Zero Emissions scenario is technologically achievable with the most commercially available technologies, such as scrap-EAF and direct reduced iron (DRI)-EAF, and near commercial technologies, such as hydrogen-DRI steelmaking.

Achieving the results shown in the Net-Zero Emissions scenario requires unprecedented uptake of low-carbon technologies, ranging from aggressive energy efficiency improvements to large-scale adoption of commercialized decarbonization and low-carbon ironmaking technologies, switching to secondary steel manufacturing, and significantly increasing the use of lower-carbon fuel in China's iron and steel industry. The primary goal, however, should be phasing out of carbon-intensive BF-BOF steelmaking.

In the near term, we recommend the Chinese government to discourage the installation of any new blast furnaces (BFs) in China. There will be a substantial increase in domestic steel scrap availability in China, even in the near term (by 2030), that could replace the need for the construction of new BFs. Instead, there will be a need to build new EAF steelmaking plants. The Chinese government can also discourage the relining of BFs as much as possible and encourage the installation of H_2-DRI or H_2-ready DRI plants to produce iron from iron ore. Relining BFs is a substantially capital-intensive investment that will extend BFs' lifetime for another 15-plus years while keeping their carbon emissions almost at the same level. Relining BFs will result in stranded assets that are not in line with China's carbon peaking and carbon neutrality goals. The capital cost to reline a BF could be even higher than the capital cost of building a new DRI plant. In addition, as China and the rest of the world build a few H_2-DRI plants in the next few years and gain experience and confidence in this low-carbon ironmaking technology and as the price of green H_2 drops in the coming years with the large programs and incentives in place in China, the shift to H_2-DRI could become even more attractive in the coming years than relining BFs, and it will certainly be a more climate-friendly investment.

The government should continue to push for energy efficiency through benchmarking, retrofits, and incentives; while improving steel products' recycling system to increase scrap quality and availability. The Chinese government should be ahead of the companies by providing standards and policy guidance in terms of carbon emission standards for steel products and hydrogen applications in metallurgy. Steel companies, while continue pursuing decarbonization, need to consider implementing life-cycle emission standards as well as emission labels for their steel products.

In the mid-term, the government should plan and guide the industry adjustments, especially in terms of phasing out blast furnaces and potentially relocating steel mills to match local renewable resources. The Chinese government can also leverage market forces and set up green public procurement (GPP) programs for steel to incentivize low-carbon steel production. Steel companies, in the mid-term, will face even higher pressure and competition to adopt low-carbon technologies. We recommend steel companies join an industry group or a public-private partnership to have access to the latest development in technologies (H_2 DRI, CCUS, smart manufacturing, etc.) and policies. We recommend steel companies develop pilots and demonstration programs to use, test, and further improve low-carbon iron and steelmaking technologies.

We suggest that the Chinese government provide financial, regulatory, and policy support on technology innovation in the areas of investing in high-risk and high-return breakthrough technologies, developing tech-to-market programs and encouraging technology pilots, tests, and validation.

Table of Contents

1 Introduction

Iron and steel manufacturing is one of the most energy-intensive industries worldwide. The use of coal as the primary fuel for iron and steel production globally means that iron and steel production has among the highest carbon dioxide (CO_2) emissions of any industry. The iron and steel industry accounts for around a quarter of greenhouse gas (GHG) emissions from the global manufacturing sector (IEA 2019).

The world's steel demand is projected to increase from 1,951 million tonnes (Mt) in 2021 to up to 2,500 Mt in 2050 (IEA 2020a). While in 2021, China accounted for 53% of global steel production, India will lead in terms of production growth in the future. Africa and the Middle East are the other two regions with the highest projected growth rate in steel production by 2050 (IEA 2019). This projected increase in steel consumption and production will drive a significant increase in the industry's absolute energy use and CO_2 emissions in the absence of substantial efforts to decarbonize the iron and steel industry.

China has pledged to peak its CO_2 emissions before 2030 and achieve carbon neutrality before 2060. China's steel industry is expected to peak its CO_2 emissions before 2030 (MIIT 2022). The government aims to improve comprehensive energy intensity by 2% from 2020 to 2025 and implement Energy Efficiency "Top Runners" programs in the steel industry (China Government Website 2022). The industry is also expected to increase the share of electric arc furnaces (EAFs) from the current 10.6% to 15% by 2025 and 20% by 2030.

In addition, the production of any new iron and steelmaking capacity is strictly limited. "Orderly" development of secondary steelmaking is encouraged through a preferential capacity swap policy to replace old primary steelmaking with scrap-based EAF steelmaking. The government also supports the development of hydrogen-based steelmaking (MIIT 2022).

China launched its national Emissions Trading System in July 2021. Currently, it only covers the power sector (Tan, 2022), but the steel industry is expected to join soon, with government support for the development of a life-cycle carbon emissions data management system (China Government Website 2022).

Figure 1 shows a simplified flow diagram of steel production using blast furnace - basic oxygen furnace (BF-BOF), direct reduced iron-electric arc furnace (DRI-EAF), and scrap-EAF production routes. Iron ore is chemically reduced to produce steel by one of these three process routes: BF-BOF, smelting reduction, or direct reduction. Steel is also produced by the direct melting of scrap in an EAF. BF-BOF and EAF production routes are the most common today. In 2021, the BF-BOF production route accounted for approximately 71% of the crude steel manufactured worldwide, and EAF production accounted for approximately 29% (worldsteel 2022). In China, almost 90% of steel is produced by BF-BOF primary steelmaking route.

There are emerging technologies that aim to reduce energy use and emissions from the steel industry, such as the ones described in IEA (2020a) and Hasanbeigi et al. (2013). For example, hydrogen DRI-based EAF (H_2-DRI EAF) steelmaking, where hydrogen (H_2) is produced by electrolysis using renewable electricity, is one of the key deep decarbonization technologies that is being piloted (SAAB 2021) and is being seriously considered by both industry and policymakers. This and other emerging technologies are discussed in more detail later in this report.

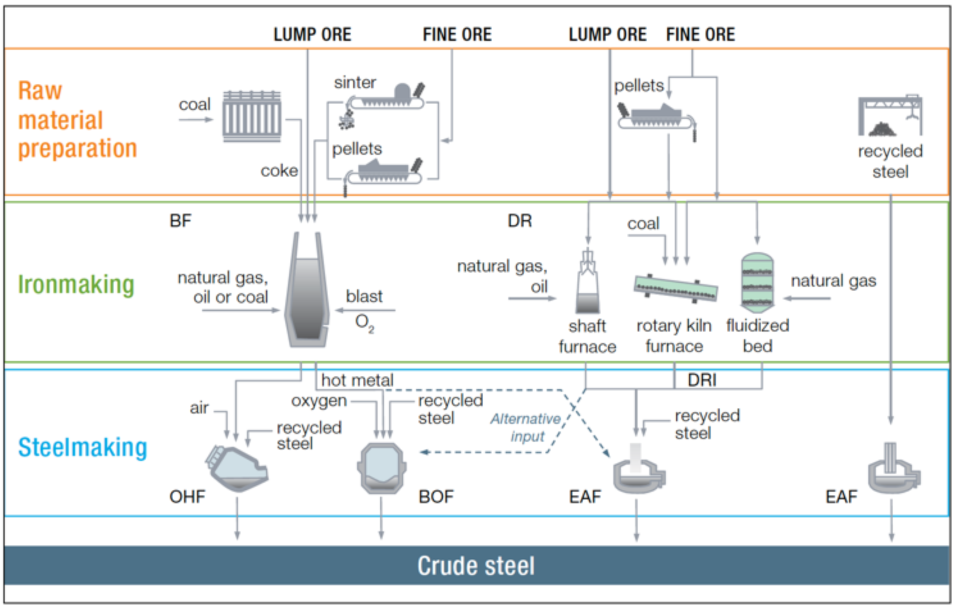


Figure 1. Steelmaking production routes (worldsteel 2020)

This report presents the current status of production, energy use, and emissions of the steel industry in China. It develops a net-zero decarbonization roadmap for the Chinese steel industry that is data-driven to achieve mid-century net-zero CO_2 emissions. In addition, it includes the milestones of what the industry can accomplish in 2030, 2040, and 2050 under several scenarios. It concludes with brief policy recommendations and action plans for the government, industry, and other key stakeholders in China.

2 China's Steel Industry Production and Trade

World steel production more than doubled between 2000 and 2021 (Figure 2). In 2021, China accounted for 53% of global steel production, a significant increase since 2000 when its share was only 15% (worldsteel 2022). The 2008 drop in world steel production shown in the figure was due to the global economic recession. The 2014 global production drop was mainly caused by a slowdown in the Chinese economy and chronic overcapacity, which resulted in shutting down illegal induction furnaces and old steel plants in China. In 2020, world crude steel production decreased by about 1% because of the global COVID-19 pandemic.

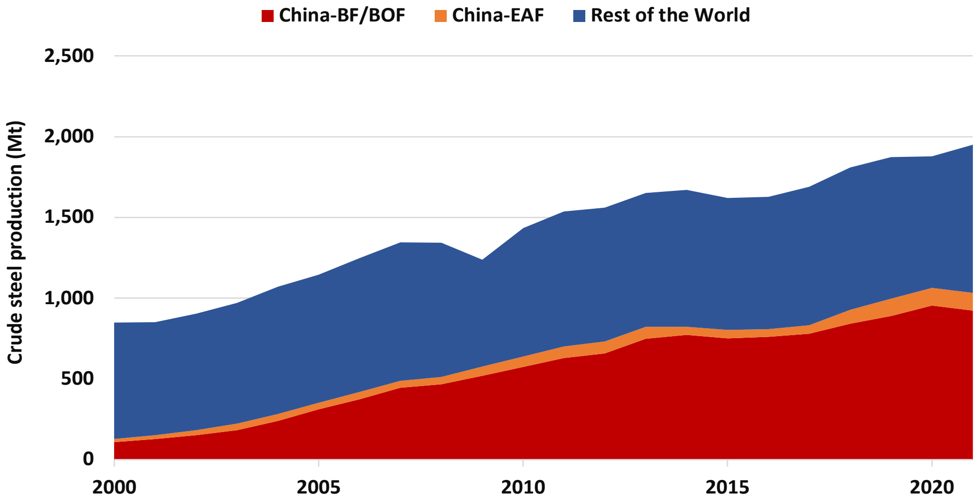


Figure 2. Crude steel production in China and the rest of the world, 2000-2021 (worldsteel 2021, 2022)

Figure 3 shows the top 10 steel-producing countries in the world. In 2021, these top 10 producing countries accounted for 83% of world steel production, and China is by far the largest steel production country (worldsteel 2022).

The top 20 steel exporting countries account for over 90% of total world steel exports. According to worldsteel (2022), China, Japan, Russia, India, and Ukraine were the top five net exporters (export minus import), and the EU-27, U.S., Thailand, Mexico, and Poland were the top five net importers (import minus export) of steel in 2021.

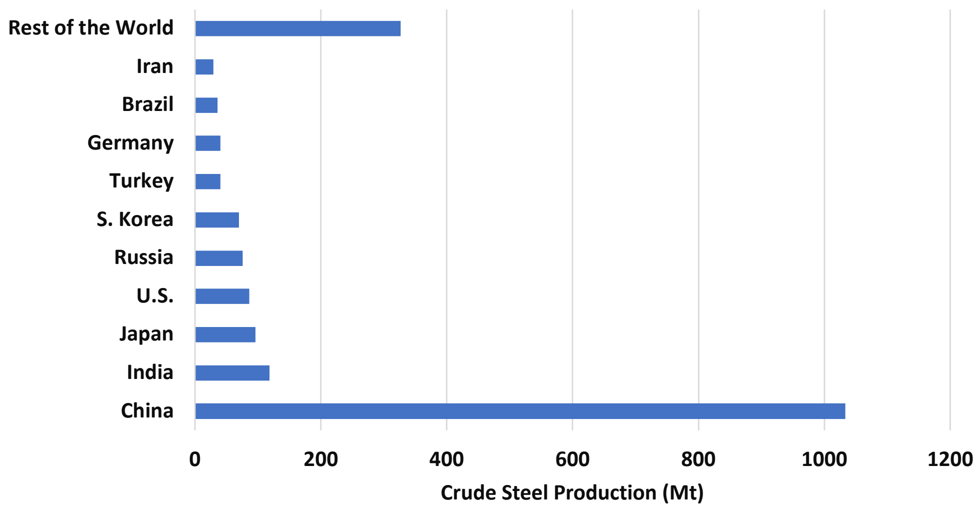


Figure 3. Top 10 steel-producing countries in 2021 (worldsteel 2022)

The Chinese steel industry produced 1,033 Mt of crude steel in 2021, of which 89.4% was produced by primary steelmaking plants using blast furnace-basic oxygen furnace (BF-BOF) and 10.6% was produced by the electric arc furnace (EAF) production route. China also imported 27.8 Mt and exported 66.2 Mt of steel mill products in 2021. Therefore, only 6% of the total steel produced in China is exported, and the remaining 94% of steel production in China is to satisfy the Chinese domestic demand. The top 5 largest steel companies in China are China Baowu Group, Ansteel Group, Shagang Group, HBIS Group, and Jianlong Group (worldsteel 2022).

Hebei Province accounted for 23% of total crude steel production, followed by Jiangsu (11%); Shandong (8%); Liaoning (7%), and Shanxi (6%) (Figure 4) (Editorial Board of China Iron and Steel Industry Yearbook, 2021). The buildings and infrastructure construction sector is the largest consumer of steel in China (59%), followed by machinery (16%), the automobile industry (6%), the energy sector (4%), and other steel products (Qianzhan Research Institute 2020; L. Guo and He 2021).

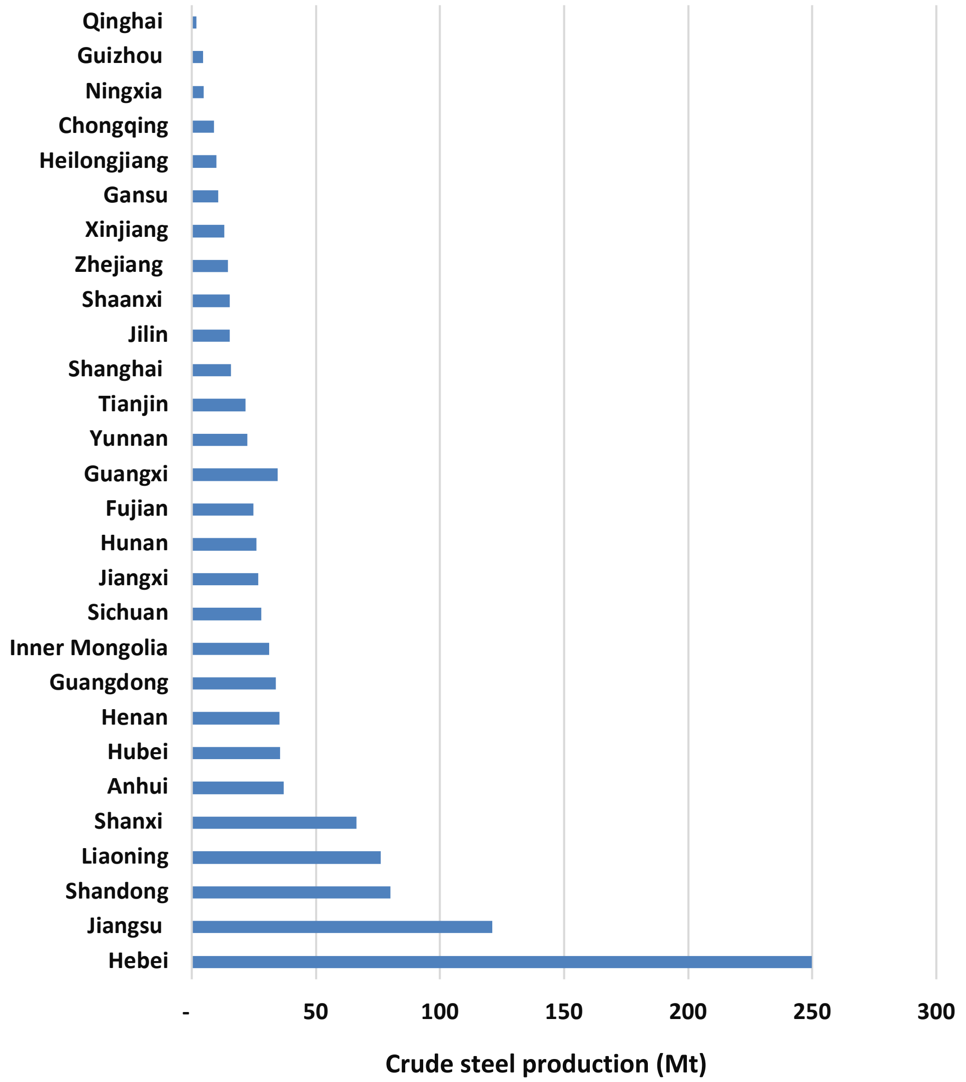


Figure 4. Crude steel production by province in China in 2020 (NBS 2021)

3 Global Steel Industry's CO_2 Emissions

The global steel industry emitted around 3.6 gigatons of CO_2 ($GtCO_2$) in 2019 (Figure 5). Global BF-BOF steel production emitted around 3.1 $GtCO_2$, and global EAF steel production emitted around 0.5 $GtCO_2$ in 2019.

EAFs in China and India have higher CO_2 intensities because of their use of a large share of pig iron or coal-based direct reduced iron (DRI) as feedstock instead of steel scrap. As a result, the production of steel in EAFs in these two countries causes an increase in global EAF's CO_2 emissions (Hasanbeigi 2022).

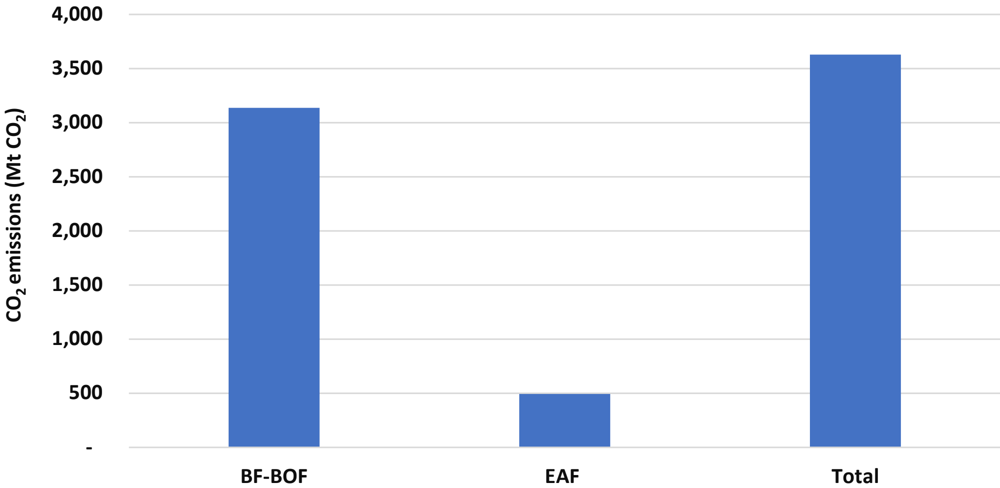


Figure 5. Global steel industry CO_2 emissions in 2019 by process type (Hasanbeigi 2022)

In our previous study (Hasanbeigi 2022), we estimated the total CO_2 emissions from the steel industry in each of the countries studied based on our estimated CO_2 intensities for BF-BOF and EAF by country and the amount of production in each country. Figure 6 shows the results of this analysis, with China standing out as responsible for 54% of the global steel industry's CO_2 emissions in 2019.

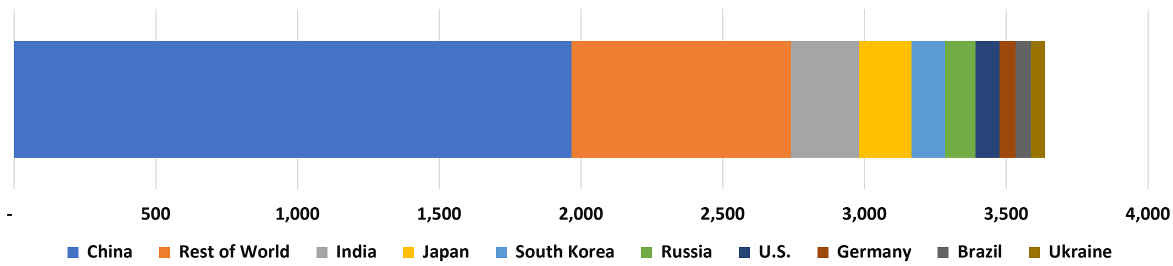


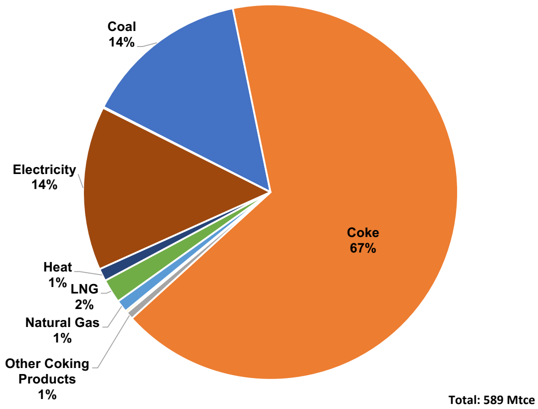
Figure 6. Total CO_2 emissions ($MtCO_2$) from steel production in major producing countries 2019 (in $MtCO_2$) (Hasanbeigi 2022)

Based on the total steel industry emissions presented above and the global GHG emissions of 52 $GtCO_{2-e}$ in 2019 (including non-CO_2 GHG emissions as well) reported in UNEP (2020), the global steel industry accounts for around 7% of total global GHG emissions. Based on the total steel industry emissions presented above and global CO_2 emissions of 33 $GtCO_2$ in 2019 reported in IEA (2020b), the global steel industry accounts for around 11% of total global CO_2 emissions.

4 The Profile of Energy Use and Emissions in China's Steel Industry

4.1. Energy use in China's steel industry

In China, the steel industry accounted for around 34% of the total fuel used in the Chinese manufacturing sector in 2020 (NBS 2022). Figure 7 shows the shares of different energy inputs (on the left) and the shares of different energy types consumed (on the right) in the steel industry in China. The left chart highlights the energy inputs, while the right chart provides a more detailed breakdown in terms of end-use energy consumption, taking into consideration of waste heat recovery. Coke had the largest share and accounted for 67% of the Chinese steel industry's final energy use. In a steel plant, energy is used in different end-uses for different purposes. Process heating, especially in BFs, to convert iron ore into pig iron/hot meta,l has the highest share of the end-use energy use in the steel industry in China.



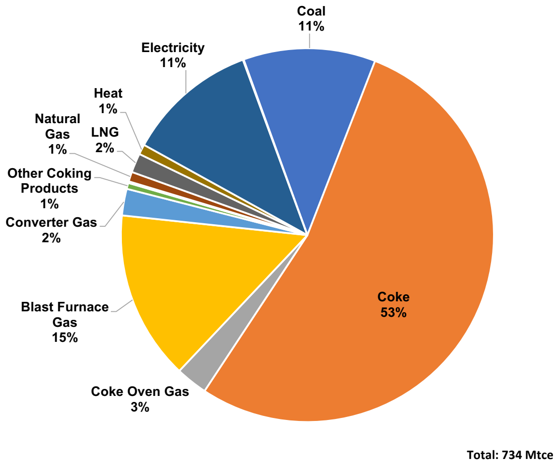


Figure 7. Share of different energy inputs to the industry (left) and energy types consumed (right) in the steel industry in China in 2020 (NBS 2022)

Note: electricity consumption is shown in the final energy and is not converted to primary energy.

4.2. Benchmarking energy and CO_2 emissions intensities of the Chinese steel industry

International benchmarking of energy intensity and CO_2 emissions intensity can provide a point against which a company or industry's performance can be compared to that of the same type of company or industry in other countries. Benchmarking can also be used for assessing the energy and emissions improvement potential that could be achieved by the implementation of energy efficiency or CO_2 reduction measures. Also, on a national level, policymakers can use benchmarking to prioritize energy saving and decarbonization options and to design policies to reduce energy and GHG emissions.

In our previous study, we conducted benchmarking of the energy intensity and CO_2 emissions intensity of the iron and steel industry in 15 major steel-producing countries plus the EU-27 region (Hasanbeigi 2022). Below we show some key results from that study to highlight the position of the Chinese steel industry's energy intensity and CO_2 emissions intensity in an international context.

4.2.1. Benchmarking total steel industry energy and CO_2 emissions intensities

When considering the total final energy intensity of the entire steel industry in 15 major steel-producing countries plus the EU-27 region in 2019, Italy, Turkey, Mexico, and the U.S. have the lowest energy intensity among the countries studied by Hasanbeigi (2022) (Figure 8). This is primarily because of a significantly higher share of EAF steel production in total steel production in these countries. EAF is a secondary steel production process that primarily uses steel scrap and therefore uses less energy to produce a ton of steel compared to BF-BOF. In other words, a higher share of scrap-based EAF production helps reduce the overall energy intensity of the steel industry in a country. It should be noted that EAFs can also use DRI or even pig iron which are energy-intensive feedstocks for EAFs. In some countries like India, a high amount of coal-based DRI is used in EAFs, and in China, a large amount of pig iron that is produced by energy-intensive blast furnaces is used in EAFs, both resulting in significantly higher energy and emissions intensity for the steel produced by EAFs in those countries. However, other factors also impact the energy and CO_2 emissions intensity of the steel industry, as discussed later in this chapter.

In contrast, Ukraine, China, India, and Brazil have the highest energy intensities among the countries studied (Figure 8). Ukraine, China, and Brazil also have the lowest share of EAF steel production. While India's steel industry has a high share of EAF steel production (56 %), the energy intensity of this production is relatively high mainly because, unlike many other countries, a substantial amount of DRI is used as the feedstock to EAFs in India (around 50% of total EAF feedstock). Unlike recycled steel scrap, DRI is produced from iron ore using the direct reduction process, which is an energy- and carbon-intensive process. In addition, India is one of the few countries in the world that uses coal-based DRI technology instead of natural gas-based DRI. This contributes to higher energy intensity and emissions for DRI-EAF steel produced in India.

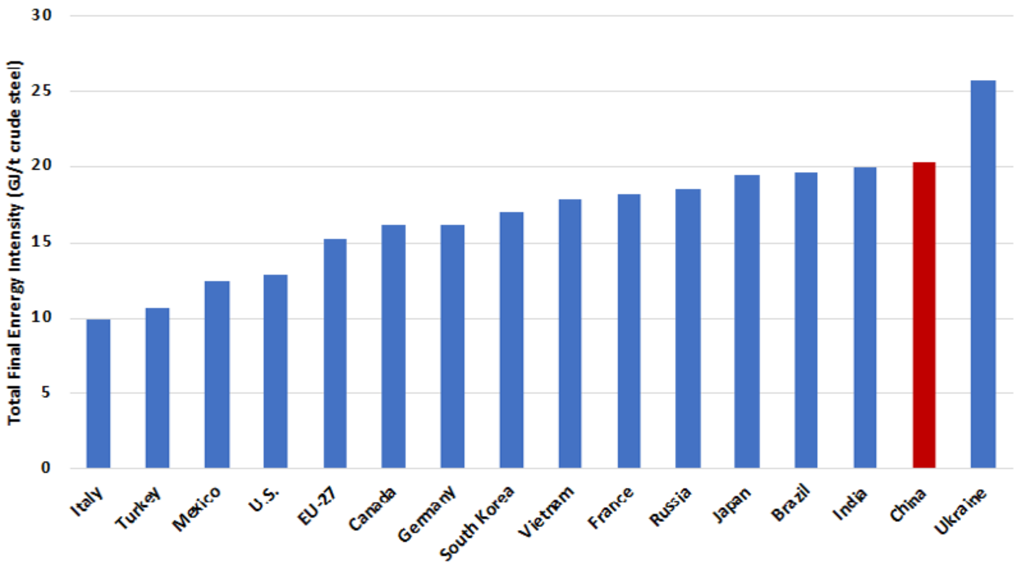


Figure 8. Total final energy intensity of the steel industry in the studied countries/region in 2019 (Hasanbeigi 2022)

The ranking of the CO_2 emissions intensity of the steel industry among the countries studied (Figure 9) is slightly different from the energy intensity ranking. Italy, the U.S., and Turkey have the lowest, and Ukraine, India, and China have the highest CO_2 emissions intensity. The U.S. CO_2 emissions intensity is low mainly because of the higher share of scrap-based EAF steelmaking and partly because of the high share of natural gas used in the U.S. steel industry (54% of total fuel used). Natural gas has a significantly lower emissions factor per unit of energy compared to coal and coke, which are the primary types of energy used in the steel industry in China and many other countries. The U.S. also has a lower CO_2 grid emissions factor than Turkey and Mexico. Other factors affecting the CO_2 emissions intensity of the steel industry are discussed at the end of this chapter.

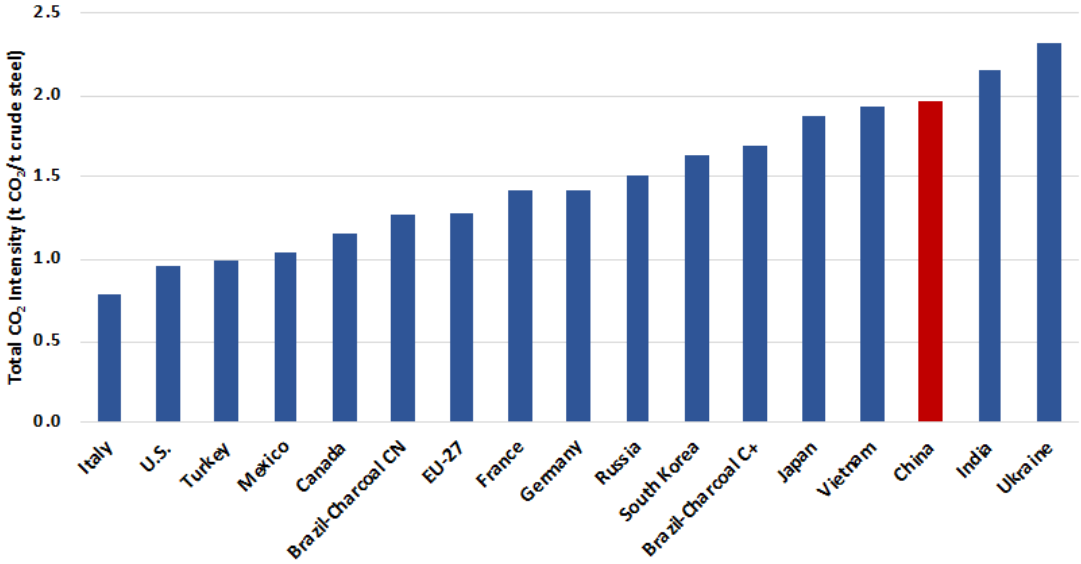


Figure 9. Total CO_2 emissions intensity of the steel industry in the studied countries/region in 2019 (Hasanbeigi 2022)

Note: Brazil-Charcoal CN refers to when charcoal is considered carbon neutral. Brazil-Charcoal C+ refers to when charcoal is not considered carbon neutral because of questions and concerns regarding the sustainability of biomass used in the steel industry in Brazil.

4.2.2. Benchmarking BF-BOF primary steel production's CO_2 emissions intensities

Because BF-BOF and EAF steel production routes are quite different and thus their CO_2 emissions intensity are also significantly different from each other, it is crucial to dive deeper and benchmark the steel production in each country for each production route in order to give a more fair and accurate view of the energy and carbon-intensity of steel production in each country.

Figure 10 shows the CO_2 intensity of BF-BOF primary steel production in the studied countries in 2019 (Hasanbeigi, 2022). It is worth highlighting that even though China has the 3rd highest CO_2 intensity for its entire steel industry (Figure 9), its ranking improved improves when only the CO_2 intensity for the BF-BOF steel production route is benchmarked. Although the very low share of EAF steel production in China results in a high total CO_2 intensity for its entire steel industry, more than 80% of the BF-BOF steel production capacity in China was built after the year 2000, with an average age of plants around 15 years (IEA 2020c). Many of these new plants are using more efficient production technology. In addition, in the past ten years, China has been aggressively shutting down old and inefficient steel plants. India has the highest CO_2 intensity of BF-BOF steel production mainly because of many old and inefficient BF-BOF plants still operating in India. It should be noted, however, that some of the newly built steel plants in India are among the world's most efficient.

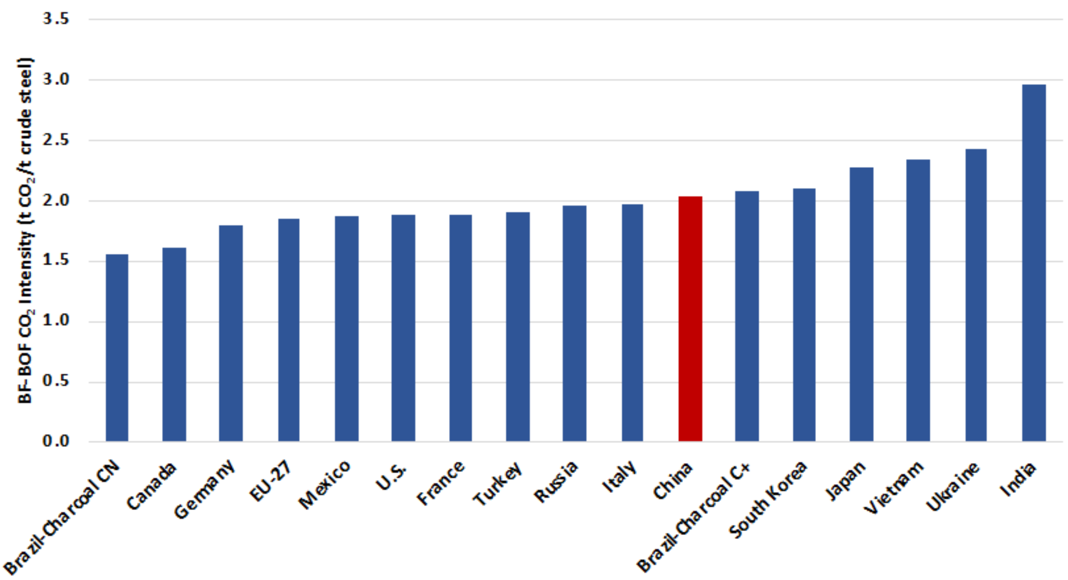


Figure 10. The CO_2 intensity of BF-BOF steel production in the studied countries/region in 2019
Note: Brazil-Charcoal CN refers to when charcoal is considered carbon neutral. Brazil-Charcoal C+ refers to when charcoal is not considered carbon neutral because of questions and concerns regarding the sustainability of biomass used in the steel industry in Brazil.

No single factor can be used to explain the variations in energy and CO_2 intensity among countries. In addition to the energy intensity of BF-BOF plants, another key factor affecting the CO_2 intensity of BF-BOF steel production is the mix of fuel used in BF-BOF plants in each country. The U.S., Mexico, and Canada have among the lowest, and India, Vietnam, and China have among the highest weighted average CO_2 emissions factors of fuels in their steel industries. If charcoal is considered carbon neutral, Brazil has the cleanest fuel mix, and if charcoal is not considered carbon neutral, then Brazil has the highest carbon-intensive fuel mix for the steel industry.

4.3.3. Benchmarking EAF steel production's CO_2 emissions intensities

EAF steel production is less energy- and carbon-intensive than BF-BOF steel production, especially when most or all of EAF feedstock is recycled steel scrap[1].

Figure 11 shows the CO_2 intensity of EAF steel production in the 15 countries plus the EU-27 region studied (Hasanbeigi 2022). Brazil and France have the lowest, and India and China have the highest CO_2 intensity of EAF steel production. A key reason why the CO_2 intensity of EAF steel production in India, China, and Mexico are significantly higher than that in other countries is the type of feedstock used in EAF in these countries. In most countries, steel scrap is the primary feedstock for EAF. In India and Mexico, however, a substantial amount of DRI (around 50% in India and 40% in Mexico) is used as feedstock in EAFs (worldsteel 2021). In China, instead of DRI, a significant amount of pig iron (around 50% of EAF feedstock), which is produced via blast furnaces, is used as feedstock in EAFs. Both DRI and pig iron production is highly energy-intensive processes, which result in higher energy and CO_2 intensity of EAF steel production when used as feedstock in EAFs. Vietnam's high CO_2 intensity of EAF steelmaking can be mainly attributed to its very high electricity grid CO_2 emissions factor.

1 Note: the embodied energy and carbon in recycled steel scrap are usually not included in EAF energy and emissions intensities calculations.

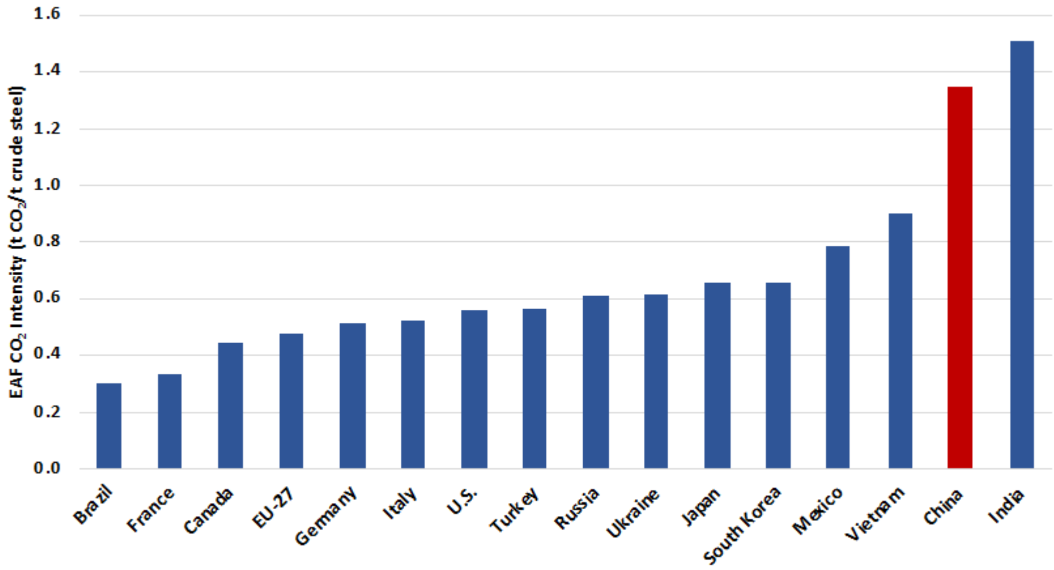


Figure 11. The CO_2 intensity of EAF steel production in the studied countries/region in 2019 (Hasanbeigi 2022)

Another important factor that influences the CO_2 intensity of EAF steel production is the electricity grid CO_2 emissions factor. Over half of the energy used in EAF steelmaking (including rolling and finishing) is electricity. The share of electricity in total energy use decreases as the share of DRI used in EAF steelmaking increases. Therefore, if the emissions factor of the electricity used in the steel industry is lower, it will significantly help to reduce the CO_2 intensity of EAF steel production. France, Brazil, and Canada have the lowest electricity grid CO_2 emissions factors due to large nuclear (in France) and hydro (in Brazil and Canada) power generation. India, Vietnam, and China have the highest electricity grid CO_2 emissions factors among studied countries due to the large share of coal used in their power generation.

Some of the key factors that could explain why the Chinese steel industry's energy and CO_2 emissions intensity values differ from other countries are:

1) The low share of EAF steel in total steel production
2) The coal and coke heavy fuel mix in the iron and steel industry
3) The higher electricity grid CO_2 emissions factor
4) The type of feedstocks in BF-BOF and EAF
5) The level of penetration of energy-efficient technologies
6) The steel product mix in each country
7) The age of steel manufacturing facilities in each country
8) Capacity utilization
9) Environmental regulations
10) Cost of energy and raw materials
11) Boundary definition for the steel industry

5 Net-zero Roadmap for the Steel Industry in China

5.1. Decarbonization scenarios

After analyzing the current status of the Chinese steel industry and its energy and CO_2 intensity, we developed a decarbonization roadmap to 2050 for the Chinese industry using four main scenarios:

1. **Business as Usual (BAU) scenario**: The BAU scenario assumes a slow improvement in energy efficiency and fuel switching and slow adoption of CCUS technologies, which is likely to happen with current business practices and current policies and regulations.
2. **Moderate Technology and Policy (Moderate) scenario**: This scenario assumes higher energy efficiency improvement, more fuel switching to lower carbon fuels, and a slightly higher rate of the shift to EAF steel production. It also assumes low adoption of CCUS technologies.
3. **Advanced Technology and Policy (Advanced) scenario**: This scenario assumes significantly higher energy efficiency improvement using commercially available technologies, more aggressive fuel switching to lower carbon fuels and switching to scrap-based EAF steelmaking, and a small adoption of transformative technologies such as H_2 DRI-EAF.
4. **Net-Zero scenario**: This scenario assumes the most aggressive energy efficiency improvement using commercially available technologies, more aggressive fuel switching to lower carbon fuels, and the highest rate of the shift to scrap-based EAF steelmaking and a moderate adoption of H_2 DRI-EAF steelmaking.

5.2. Decarbonization pathways for the Chinese steel industry

We included five major decarbonization pillars in our analysis, which are: 1) demand reduction, 2) energy efficiency, 3) fuel switching, electrification, and grid decarbonization, 4) technology shift to low-carbon steelmaking (e.g., scrap-based EAF, H_2-DRI EAF, etc.), 5) carbon capture, utilization, and storage (CCUS). Each of these pillars and their impact on the decarbonization of the Chinese steel industry are discussed in more detail in the following sections.

We forecasted the total final energy use and CO_2 emissions of the steel industry in China up to 2050 under different scenarios by applying varying levels of different decarbonization pillars. The results of our analysis are shown in Figure 12.

In the BAU scenario, due to steel demand reduction resulting in a 23% drop in steel production, moderate energy efficiency improvement, technology shift (primarily to EAF), and decarbonization of the grid up to 2050, the annual CO_2 emissions will decrease by 54% from 2020 to 2050. The total annual CO_2 emissions of the Chinese steel industry will drop from 2,103 $MtCO_2$/year in 2020 to 968 $MtCO_2$/year in 2050 under the BAU scenario.

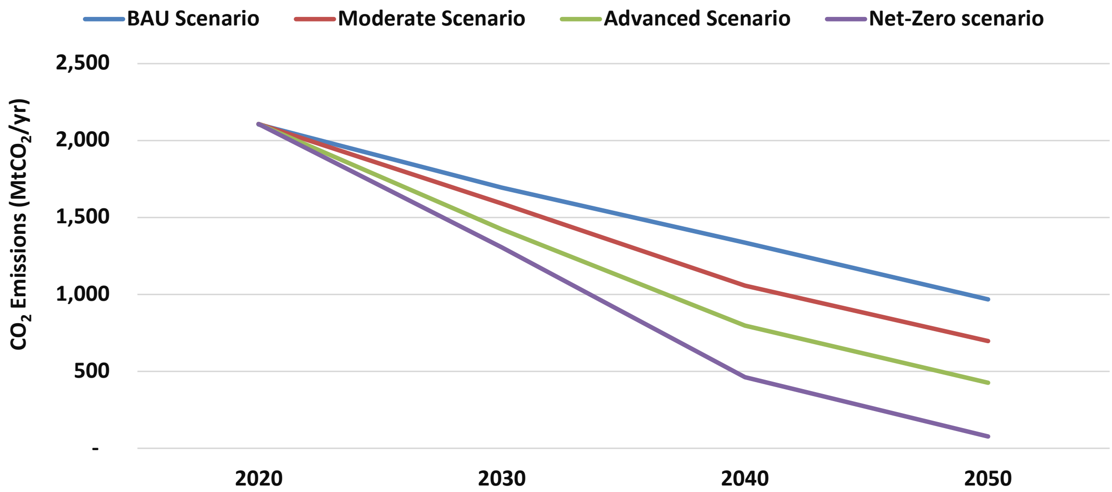


Figure 12: Total annual CO_2 emission in the steel industry in China under various decarbonization scenarios, 2020-2050 (Source: this study)

The Net-Zero scenario has the largest reduction in annual CO_2 emissions in the steel industry, as it includes an aggressive contribution of demand reduction resulting in a decrease of 38% in steel production, energy efficiency measures, fuel switching, technology shift to low carbon steel production, and CCUS. Under our Net-Zero scenario, the total CO_2 emissions from the Chinese steel industry will decrease to about 78 $MtCO_2$ per year in 2050, a 96% reduction compared to the 2020 level (Figure 12).

Figures 13-14 show the contribution of each decarbonization pillar to the CO_2 emissions reductions in the Net-Zero scenario for the steel industry in China in 2050. In this scenario, the technology shift pillar (primarily to scrap-based EAF) makes the largest contribution to CO_2 emissions reduction, followed by demand reduction and fuel switching, electrification of heating, and electricity grid decarbonization. Results of our analysis show that the contributions of energy efficiency and CCUS will be lower than the other decarbonization options.

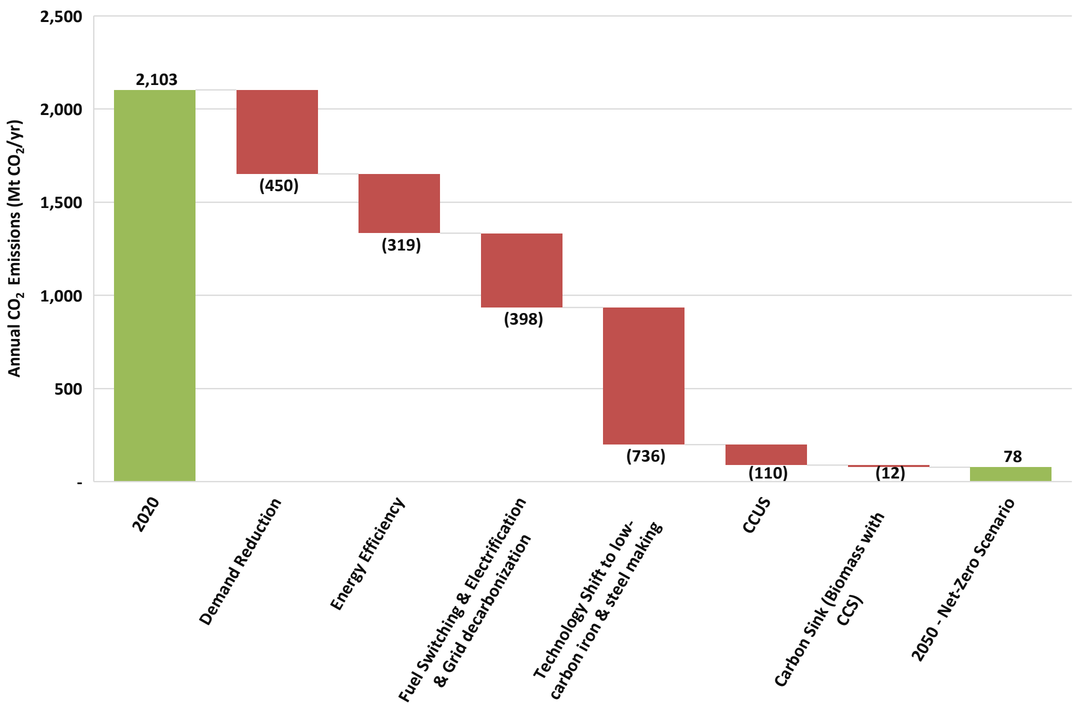


Figure 13. Impact of the decarbonization pillars on CO_2 emissions of the Chinese steel industry under Net-Zero scenario (Source: this study)

Figure 14 shows the impact of the decarbonization pillars on CO_2 emissions of the Chinese steel industry to bring the BAU scenario's CO_2 emissions down to the Net-Zero scenario's level. The area of the graph that represents each pillar in different colors shows the cumulative contribution of each decarbonization pillar to the total decarbonization of the steel industry in China during the period 2020 to 2050.

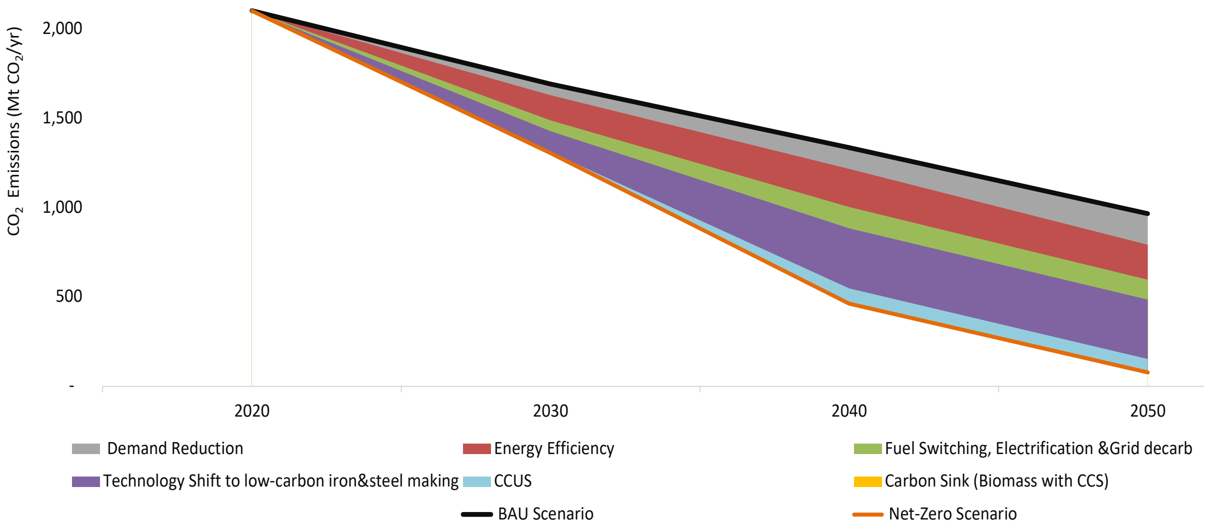


Figure 14. Impact of the decarbonization pillars on CO_2 emissions of the Chinese steel industry to bring the BAU scenario's CO_2 emissions down to the Net-Zero scenario's level (Source: this study)

6 Impact of Decarbonization Pillars on China's Steel Industry

6.1. Demand reduction

The first step in developing the Chinese steel industry decarbonization pathways was to develop projections for steel production in China during the period 2020 to 2050. Steel demand and production in China is a key drivers of the industry's CO_2 emissions.

Several sources report that the Chinese steel demand has already peaked or is going to peak in the next few years due to a combination of uncertainties in the real-estate sector and the slow growth in manufactured export products. China's 2021 steel production dropped 2.8% compared to 2020, and output from January to November of 2022 declined 1.4% compared to the same period before. The production of China's steel industry is expected to decline thereafter. The projections of future steel production were made after reviewing projections provided in other studies such as IEA (2020), Zhou et al. (2020), CISA (2022), Chen et al. (2021), and MPP (2021). Most analyses show that China's steel production and demand will decline in the coming years and decades (Figure 15) to the range of 600-750 Mt of steel by 2050.

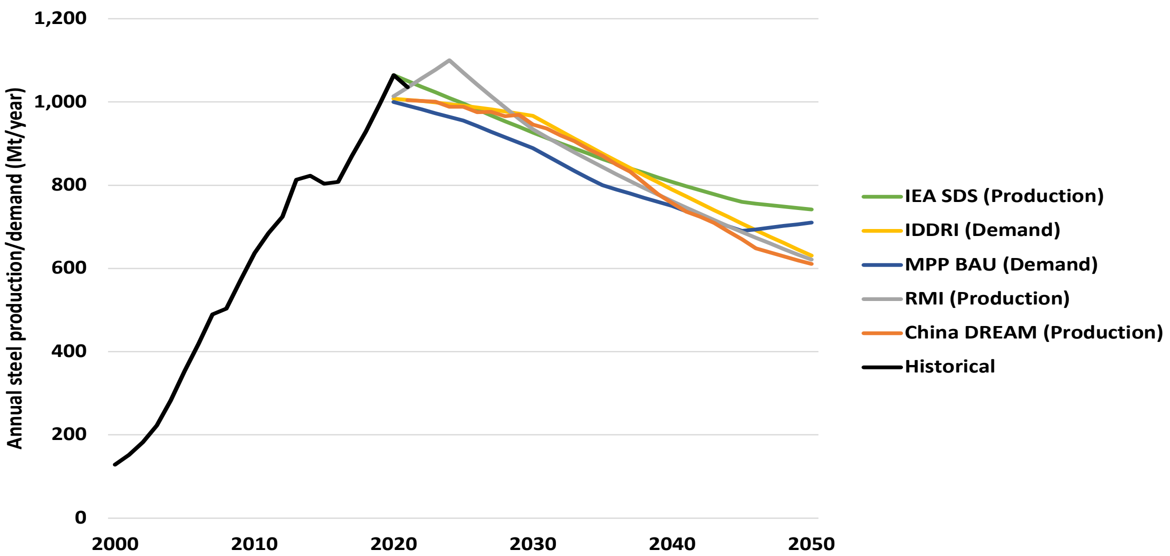


Figure 15. Projections of China's steel production and demand in different studies (Mission Possible Partnership 2021; J. Chen, Li, and Li 2021; IEA 2020; Bataille, Stiebert, and Li 2021)

Notes: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario; IDDRI = The Institute for Sustainable Development and International Relations; MPP = Mission Possible Partnership; BAU = business as usual; China DREAM= China Demand Resources Energy Analysis Model.

IEA (2020) cited the key driving factor of their assumption is the ongoing government-led structural change, expecting China's steel production will decline to about 740 Mt by 2050 under IEA's Sustainable Development Scenario (SDS). Bataille et al. (2021) used the approach of long-term development convergence on per-capita steel consumption in key countries and regions to estimate China's steel demand. The authors expected China's current per-capita steel consumption (slightly below 1200 kg per capita) will significantly decline to about 250 kg per capita by 2050 because a significant portion of the energy, transport, water, and sanitary infrastructure has been developed in the country (Bataille, Stiebert, and Li 2021). RMI expected

China's urbanization process would slow down in the coming decades, thus resulting in a drop in overall steel demand in China, especially in the buildings and machinery sectors (J. Chen, Li, and Li 2021). Lawrence Berkeley National Laboratory's China DREAM Model, which is a bottom-up end-use energy demand model, also estimated China's steel production will decline to about 610 Mt by 2050 based on a combination of physical steel demand modeling by end uses (e.g., building stock turnover) and value-added projections for other steel products (Zhou et al. 2020) .

From a value-chain perspective, the main downstream steel demand includes buildings and construction, machinery, automobiles, energy systems, hardware products, steel wood furniture, home appliances, railway, shipping, containers, and other industries.

In 2020, about 59% of steel was used in buildings and construction projects, including buildings for the real estate industry and infrastructure such as roads, highways, bridges, airports, and industrial construction projects (Figure 16). The buildings sector alone accounted for 35% of total steel demand. The development of construction projects also drives up indirect consumption of steel in machinery demand, hardware products, and home appliances, which accounted for 16%, 3%, and 1% of China's steel production in 2020. The automobile industry, energy sector, and other segments of steel demand accounted for another 6%, 4%, and 7% of steel production, respectively (Qianzhan Research Institute 2020).

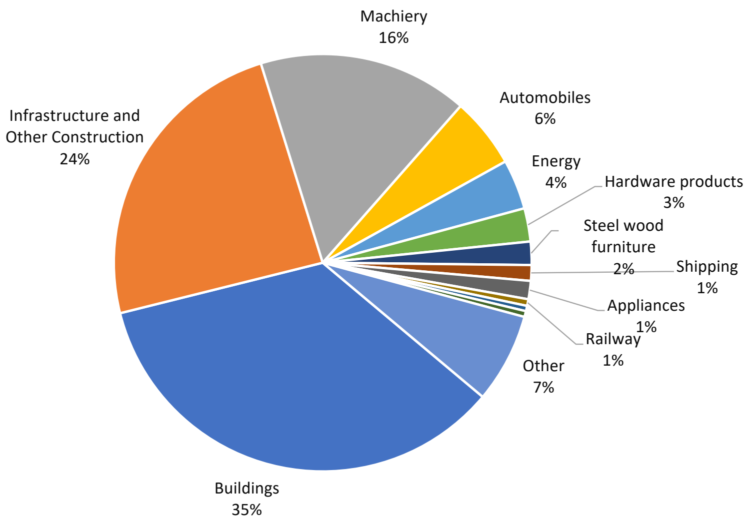


Figure 16. China's steel demand by end-use in 2020 (Qianzhan Research Institute 2020; L. Guo and He 2021)

It is expected that steel demand from China's buildings sector will decline in the future, driven by a shrinking population and saturation of building stocks. Given the building sector has been the largest end-use of China's steel, this will have a significant impact on China's overall steel demand. The new stimulus on infrastructure projects would increase steel demand, but given a weaker global economy and COVID-19 restrictions in China, it will not be able to offset the steel demand decline from the real estate industry.

Future steel demand may also be driven up by new growth areas in automobiles (e.g., electric vehicles) and energy sectors (e.g., grid expansion, renewable energy generation, CCS systems). Studies expect that the new steel demand may be offset by intelligent and smart manufacturing, material substitution, recycling, and shared mobility (Chen, Li, and Li 2021).

Given all of this information on the future demand for steel in China, Figure 17 shows the projections of Chinese steel production up to 2050 under the four different scenarios developed for this study. Chinese steel production is expected to decline from 1,065 Mt in 2020 to 820 Mt and 660 Mt in 2050 under BAU and Net-Zero scenarios, respectively.

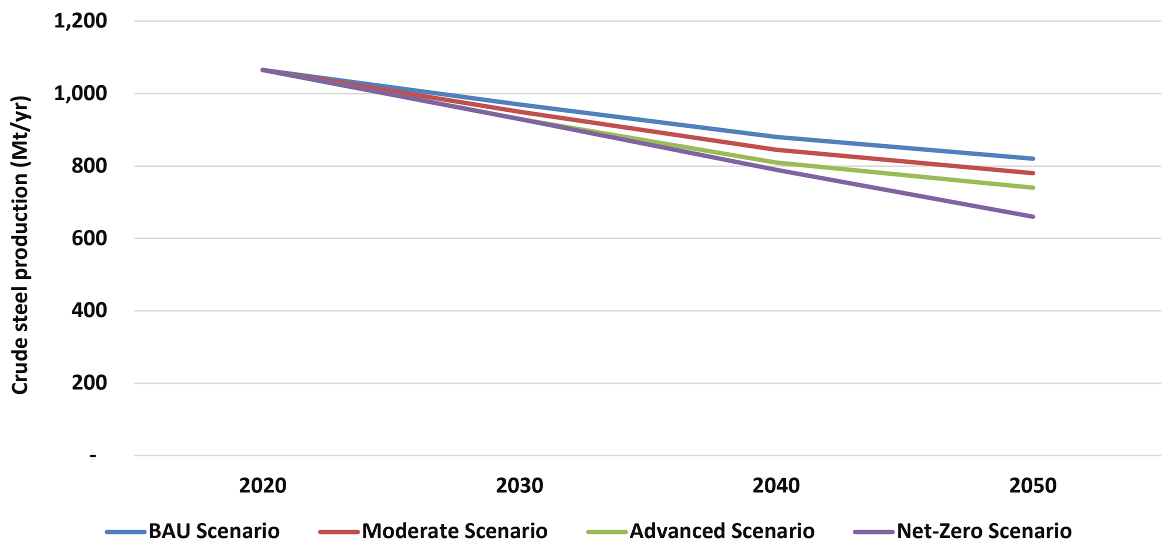


Figure 17. The annual steel production forecast for China used in this study, 2020-2050 (Source: this study)

Material efficiency measures

Material efficiency, i.e., delivery of goods and services with less material, is another key strategy that will have an important impact on China's steel demand. As shown in Table 1, multiple strategies exist in each of the product life-cycle stages, ranging from steel product design (e.g., improving design to have lighter products, optimizing to minimize material use, and design for longer life, reusability and ease of high-quality recycling), steel product manufacturing (e.g., improving material efficiency in the production and fabrication processes, increasing material waste recycling), steel product use (e.g., extending the building and product lifetime, intensifying product use, and switching to other low-carbon alternative materials, such as mass timber for mid-low rise buildings), and steel product end-of-life (e.g., increasing building component direct reuse, increasing the recycling rate of steel products, and remanufacturing of steel products).

Table 1. Material efficiency measures to reduce steel demand

Value Chain Stages	Measures	Material Savings Potential (%)	Applicability	References
Design	Improved steel product design • Lightweight materials • Optimize material use • Designing for circular principles	13	Buildings, vehicles, and steel products	(Carruth, Allwood, and Moynihan 2011; Zhou et al. 2019)
Manufacture	Improving semi-manufacturing yields	7	All applications	(Mission Possible Partnership 2021; Material Economics 2019)
	Improving product manufacturing yields	13	Product steel	(Mission Possible Partnership 2021; Material Economics 2019)
Use	Extending building and steel product lifetime	25	Buildings, vehicles, and steel products	(Hertwich et al. 2019)
	Use of mass timber	50	Buildings	(Y. Dong et al. 2019; H. Guo et al. 2017)
Recycle	Direct component reuse (without melting)	15	Buildings and industrial steel use	(Eberhardt, Birgisdóttir, and Birkved 2019)

Established literature suggested that individual material efficiency strategies have a large material-saving and GHG-mitigation potential, especially for steel used in buildings and vehicles. Implementing these strategies can significantly potential to reduce steel demand (Hertwich et al. 2019)the more efficient use of these materials presents a significant opportunity for the mitigation of (GHG) .

There may be tradeoffs between individual material efficiency strategies and energy efficiency. For example, measures to improve building operational energy efficiency or decarbonize building energy use, such as additional insulation, heat exchange ventilation system, passive solar design, and heat storage, would likely increase the material consumption of buildings. Increasing building lifetimes while saving materials may increase building operational energy use when older buildings are designed for less stringent standards. Using wood materials also requires consideration of the sustainability (e.g., long-term soil carbon damage and reductions) and availability of the materials, which may limit the applications of using mass timber in China. Thus, it is important to conduct a comprehensive life-cycle analysis to evaluate such tradeoffs.

The cost of material efficiency measures is sparse and limited in the literature. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) provided an aggregated cost of $20-50 USD per tonne of CO_{2eq} reduced across all material efficiency strategies in the industry sector (IPCC 2022). A UK-focused study estimated that various material efficiency measures would cost from negative to about £874 ($1,206 USD[2]) per tonne of CO_{2eq} reduced (Table 2). Negative values of some of the material efficiency measures indicate investing in these measures saves money.

Table 2. Cost of steel-saving material efficiency measures (Durant et al., 2019)

Material Efficiency Measure	End-use Sector	Steel Reduction	Cost ($USD)
Steel beam reuse	Construction	40% reduction	$385 to $1,206/t$CO_2$
Specifying optimal lightweight beams	Construction	36% reduction	$92 to $283/t$CO_2$
Choosing smaller cars	Transport	20% reduction	$-1,380 to $585/t$CO_2$
Specifying high-strength steel car bodies	Transport	12% reduction	$-2,946 to $-973/t$CO_2$

6.2. Energy efficiency

There are a variety of energy efficiency technologies that are already available to be deployed on a commercial scale in the steel industry. Technologies such as waste heat recovery for different processes, coke dry quenching (CDQ), Top-Pressure Recovery Turbine Plants (TRT), and many others are commercially available for deployment (JISF 2022a,b). Also, cutting-edge technologies can assist with energy management systems, drawing from smart manufacturing and the Internet of Things; such technologies include predictive maintenance and machine learning or digital twins[3] to improve process control (Hasanbeigi et al. 2013).

Improved energy efficiency may result in other benefits that complement the energy cost savings, including:

- Decreased business uncertainties and reduced exposure to fluctuating energy costs
- Increased product quality and switch to higher added value market segments
- Increased productivity
- Reduced environmental compliance costs related to the reduction of greenhouse gases and criteria air pollutants

2 Based on the average 2021 exchange rates: 1 British Pound = 1.38 USD.

3 A digital twin is a digital representation of an intended or actual real-world physical product, system, or process that serves as the effectively indistinguishable digital counterpart of it for practical purposes, such as simulation, integration, testing, monitoring, and maintenance.

The experiences of various iron and steel companies have shown that with a modest investment in energy-efficient technologies and measures, energy and cost savings with favorable payback periods (e.g., under three years) can be found. However, for some major energy efficiency technologies, large investments will be needed. These large capital investments may be hard to justify by energy cost savings alone; however, additional productivity and product quality, and environmental compliance benefits can improve the economics of such an investment. Every plant will be different and based on each unique situation, the most favorable selection of energy efficiency opportunities should be made to address the specific circumstances and design of that plant (Worrell et al. 2010). Table 3 shows a list of some commercialized energy efficiency measures and technologies for the iron and steel industry.

Table 3. Examples of commercialized energy efficiency measures and technologies for the iron and steel industry (JISF 2022a, Worrell, et al. 2010)

No.	Energy-Efficiency Measures / Technologies	No.	Energy-Efficiency Measures / Technologies
	Sintering	32	Improving process control in EAF
1	Heat recovery from the sinter cooler	33	Refractories using engineered particles
2	Reduction of air leakage	34	Direct current (DC) arc furnace
3	Increasing bed depth	35	Scrap preheating
4	Use of waste fuel in sinter plant	36	Plastic waste and used tire injection in EAF (emerging technology)
5	Improve charging method	37	Airtight operation (emerging technology)
6	Improve ignition oven efficiency	38	Bottom stirring/gas injection
		39	Contiarc Furnace (emerging technology)
	Coke Making	40	Comelt Furnace (emerging technology)
7	Coal moisture control		
8	Programmed heating in coke oven		**Casting and Refining**
9	Variable speed drive on coke oven gas compressors	41	Integrated casting and rolling (Strip casting)
10	Coke dry quenching (CDQ)	42	Efficient Ladle preheating
11	Next generation coke making technology (SCOPE21) (emerging technology)		
			Shaping
	Iron Making – Blast Furnace	43	Use of energy-efficient motors
12	Injection of pulverized coal in BF to 130 kg/t hot metal	44	Installation of a lubrication system
13	Injection of natural gas in BF		
14	Injection of oil in BF		**Hot Rolling**
15	Injection of plastic waste in BF	45	Recuperative or regenerative burner
16	Injection of coke oven gas in BF	46	Flameless oxyfuel burners
17	Top-pressure recovery turbines (TRT)	47	Controlling oxygen levels and variable speed drives on combustion air fans
18	Recovery of blast furnace gas	48	Insulation of reheat furnaces
19	Improved blast furnace control	49	Hot charging
20	Slag heat recovery (emerging technology)	50	Process control in hot strip mill
21	Preheating of fuel for hot blast stove	51	Heat recovery to the product
22	Improvement of combustion in hot blast stove	52	Waste heat recovery from cooling water
23	Improved hot blast stove control	53	Walking beam furnace for reheating
	Steelmaking – basic oxygen furnace (BOF)		**Cold Rolling**
24	Recovery of BOF gas and sensible heat	54	Continuous annealing
25	Variable speed drive on ventilation fans	55	Heat recovery on the annealing line
26	Control system for oxygen supply to BOF process	56	Reduced steam use in the acid pickling line
27	Programmed and efficient ladle heating	57	Automated monitoring and targeting systems
	Steelmaking – EAF		**Cross-cutting measures**
28	Converting the furnace operation to ultra-high power (UHP)	58	Preventative maintenance in steel mills
29	Adjustable speed drives (ASDs) on flue gas fans	59	Energy monitoring and management systems in steel mills
30	Oxy-fuel burners/lancing	60	Motor systems and steam systems optimization
31	Post-combustion of flue gases	61	Smart sensors and real-time monitoring systems

6.3. Fuel switching, electrification, and grid decarbonization

In terms of fuel switching, several alternative fuels, such as natural gas, biomass, biogas, and on a longer time horizon, hydrogen, can replace coal or coke as a fuel or reducing agent in the iron and steelmaking processes.

In terms of electrification, reheating furnaces can be electrified, and electric induction furnaces can also be scaled up. Ladle and tundish heating can be switched to resistance, infrared, or plasma heating. The use of EAF steel production, which is also a form of electrification, is not shown under the electrification pillar in our analysis, and it is shown under the technology shift pillar. In terms of grid decarbonization, all processes in steel production that use electricity can be decarbonized by using low-carbon electricity.

In our analysis, we projected the fuel mix used in China's steel industry (Figure 18) by shifting to lower carbon fuels. For example, in the Net Zero scenario, we assumed the coal and coke consumption in China's steel industry will be reduced substantially by 2050, and the share of electricity will increase because of a shift in production process routes towards EAFs, as shown earlier. We also assumed a small share of sustainable biomass and hydrogen for heating (in addition to hydrogen used in H_2-DRI plants) in 2040 and 2050. Sustainable biomass fuel is considered carbon neutral and, combined with CCS, will provide a carbon sink in this industry.

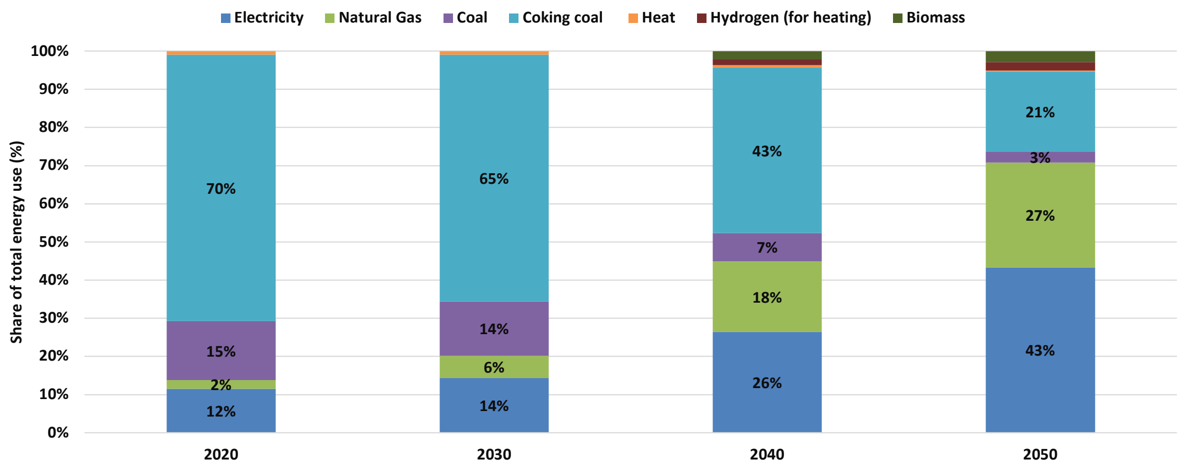


Figure 18. Energy mix projections for China's steel industry under the Net-Zero scenario, 2020-2050 (Source: this study)

Note: The electricity demand to produce hydrogen that is used as a reducing agent in H_2-DRI is shown under "electricity" in this figure.

The largest increase in the share of the total energy mix is for electricity. Its share increases from 12% in 2020 to 47% in 2050 in the Net-Zero scenario, primarily driven by the substantial increase in the share of EAF from total steel production (from 10% in 2020 to 60% in 2050 under the Net-Zero scenario).

The share of natural gas is also assumed to increase substantially during this period under the Net-Zero scenario. This is partly driven by the production of natural gas-based DRI and partly by overall fuel switching from coal to natural gas, which has lower carbon intensity. Most of this natural gas will need to be imported.

Another key factor in the decarbonization of the Chinese steel industry is the carbon intensity of the electricity used in this sector. China has one of the highest carbon-intensity power sectors in the world because of its heavy reliance on coal for power generation. Figure 19 shows the power sector's CO_2 emissions factors in major steel-producing countries in 2019.

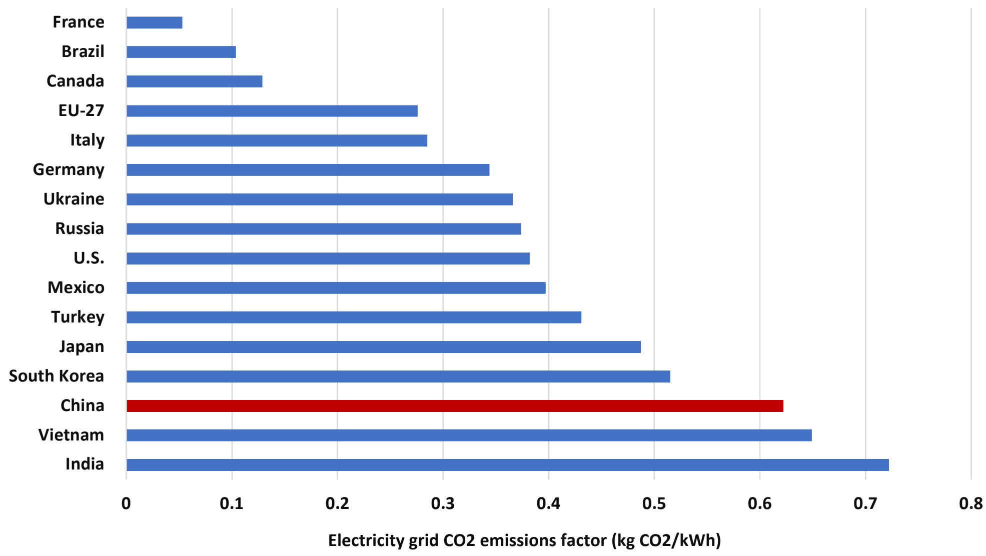


Figure 19. Electricity grid CO_2 emissions factors in the studied countries in 2019 (IEA 2021)

As China shifts to more EAF steel production, the role of the power sector's CO_2 emissions intensity in the steel industry CO_2 intensity will become even more important. Figure 20 shows the power sector's CO_2 emissions intensity forecast in China under different scenarios used in this study. We have assumed that China's power sector will achieve carbon neutrality by 2050 under the Net-Zero scenario. Even in the BAU scenario, the Chinese power sector's CO_2 emissions intensity is assumed to drop by 66% between 2020 and 2050.

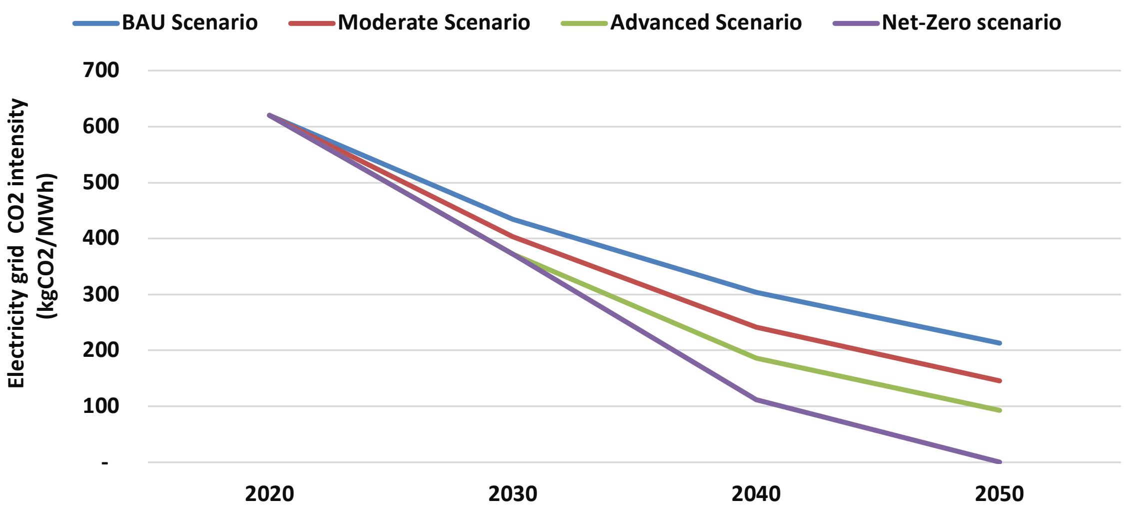


Figure 20. Electricity grid CO_2 emissions intensity forecast in China under different scenarios (Source: this study)

6.4. Technology shift to low-carbon steel production technologies

Another important pillar that influences CO_2 emissions projections is the share of each steel production route in total steel production in China up to 2050. Figure 21 shows the contribution of each production route to total steel production in China under all scenarios up to 2050.

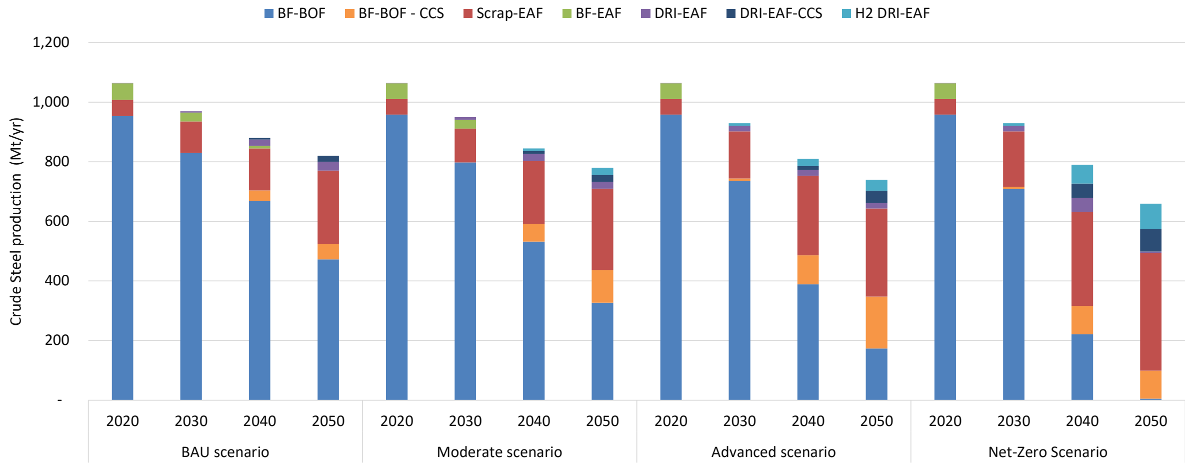


Figure 21. Crude steel production by technology type under each scenario, 2020-2050 (Source: this study)

To highlight the share of each steelmaking technology in total production in the Net-Zero scenario, Figure 22 shows the share of each steel production technology (as %) under the Net-Zero scenario up to 2050. Under this scenario, the scrap-based EAF production route will account for 60% of total steel production in China in 2050, followed by BF-BOF with CCS (14%), H_2-DRI EAF (13%), and DRI-EAF with CCS (11%).

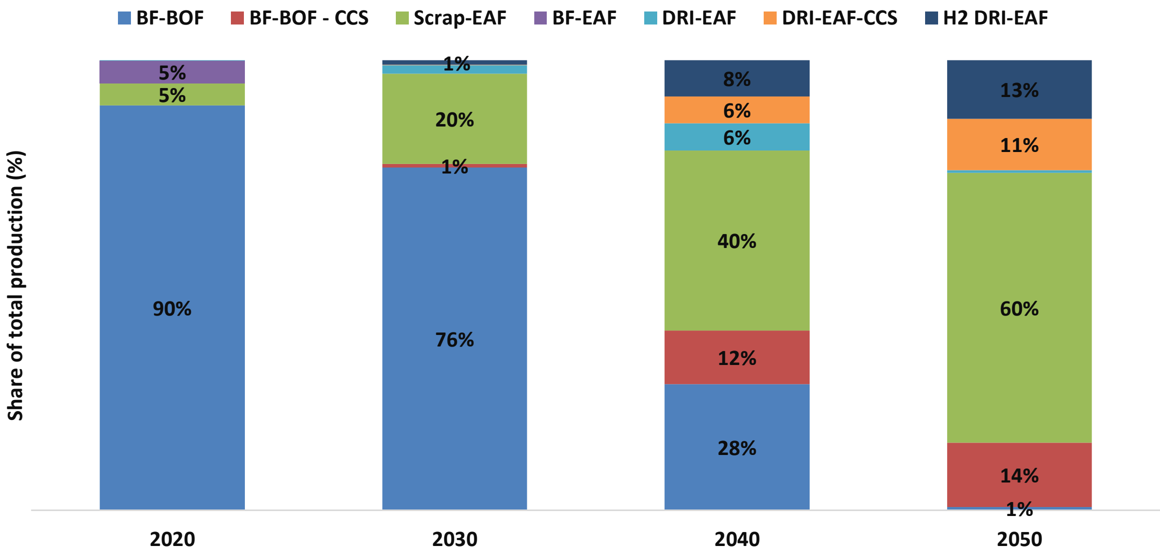


Figure 22. Share of steel production technologies under Net-Zero scenarioup to 2050 (Source: this study)

Two low-carbon technologies are most impactful in our roadmap to reduce GHG emissions in China's steel industry: 1) scrap-based EAF and 2) green H_2-DRI-EAF steelmaking. Each of these processes is discussed in further detail below. Another technology that is discussed below is injecting hydrogen-rich gases in blast furnaces. Given the large young fleet of BFs in China, this technology is being prioritized in the near-to-medium term in China, followed by using enriched hydrogen in the DRI process. This can help to reduce the use of coal and coke in

BFs and reduce the CO_2 emissions intensity of intensity production by BF-BOFs in China. A hydrogen-DRI process that is based on using pure hydrogen has been viewed as a key technology for the mid-to-long term in China (CISA 2022).

We recommend the Chinese government to discourage the installation of any new blast furnaces (BFs) in China. There will be a substantial increase in domestic steel scrap availability in China, even in the near term (by 2030), that could replace the need for the construction of new BFs. Instead, there will be a need to build new EAF steelmaking plants. The Chinese government should also discourage the relining of BFs as much as possible and encourage the installation of H_2-DRI or H_2-ready DRI plants to produce iron from iron ore. Relining BFs is a substantially capital-intensive investment that will extend BFs' lifetime for another 15-plus years while keeping their carbon emissions almost at the same level.

Relining BFs will result in stranded assets that are not in line with China's carbon peaking and carbon neutrality goals. The capital cost to reline a BF could be even higher than the capital cost of building a new DRI plant. In addition, as China and the rest of the world build a few H_2-DRI plants in the next few years and gain experience and confidence in this low-carbon ironmaking technology and as the price of green H_2 drops in the coming years with the large programs and incentives in place in China, the shift to H_2-DRI could become even more attractive in the coming years than relining BFs, and it will certainly be a more climate-friendly investment.

6.4.1. Electric Arc Furnaces

EAFs are mainly used to produce steel by recycling ferrous scrap. DRI and pig iron can also be fed to the EAF as a scrap substitute. EAFs are equipped with carbon electrodes that can be raised or lowered through the furnace roof to provide the necessary energy by an electric arc. Energy consumption in EAF-steelmaking is much lower than BF-BOF steelmaking, as the energy-intense reduction of iron ore has already been carried out in the BF (or in a DRI or a Smelting Reduction plant) when the steel was originally produced prior to recycling. EAF steelmaking can use a wide range of scrap types, direct reduced iron (DRI), pig iron, and molten iron (up to 30 percent) as the feed charge. The liquid steel from an EAF is generally sent to a Ladle Metallurgy Station (LMS) to improve the steel quality. Recycling scrap to make steel saves virgin raw materials as well as the energy required for converting them and reduces the CO_2 intensity of steel production.

As of 2021, EAFs only accounted for 10.6% of total steel production in China (worldsteel 2022), which is significantly below the world average of 28% and below the level in industrialized countries (U.S.: 70%; EU: 42%; South Korea: 32%; Japan: 24%) (China Steel News 2020). China's large BF-BOF capacity, which is on average less than 15 years old, limited scrap availability, and higher cost of the EAF-production process are some of the key factors that lead to lower adoption of EAFs in China.

Based on the assumed penetration rate of EAFs in the Chinese steel industry and the rate of scrap used in EAFs and BOFs under different scenarios, we have estimated the scrap consumption in China's steel industry during 2020-2050 for each scenario. The scrap demand in 2050 under the Net-Zero scenario is around 500 Mt. This amount of scrap will very likely be available in China based on scrap availability forecasts from various studies, discussed below. (Figure 23)

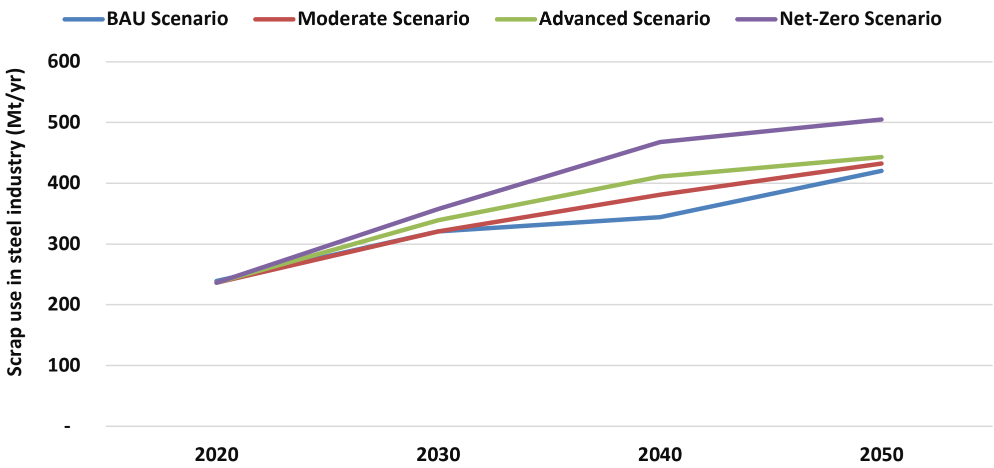


Figure 23. Scrap consumption forecast in China's steel industry, 2020-2050

Scrap availability

In China, scrap is currently used in two ways: 1) melted in basic oxygen furnaces (BOFs) along with molten iron and 2) melted directly in EAFs. Due to the massive amount of steel production from BF-BOFs, around 70% of China's scrap is currently used in BOFs, while only 30% of the scrap is used in EAFs. As of 2021, total scrap consumption by China's steel industry was around 252 Mt (China Metallurgical News 2021).

Recent studies have estimated China's scrap availability outlook, as shown in Figure 24. The China Iron and Steel Association (CISA) projects that the Chinese steel industry will have about 350 Mt/year of scrap available by 2030 and 500 Mt/year by 2050 (CISA 2022). Early in 2022, China's Ministry of Industry and Information Technology (MIIT) estimated 300 Mt/year of scrap available for the steel industry by 2025 (Ministry of Industry and Information Technology 2022). Based on steel product lifespans and the recycling rate, Xuan and Yue 2016 projected that China's steel scrap availability will reach 318 Mt/year in 2030. Shangguan et al. (2020) used two methods to estimate scrap availability in China, including the estimation of steel product stocks and steel product lifespan and showed that scrap availability would reach 322-346 Mt/year by 2030.

These Chinese assessments are in agreement with other international studies, including Mission Possible Partnership (MPP), RMI, and IEA, which estimated that China's scrap availability will reach 279 to 390 Mt/year by 2030 (Mission Possible Partnership 2021; J. Chen, Li, and Li 2021; IEA 2020). For 2050, studies expect China's steel scrap availability to increase further to 400-600 Mt/year (Mission Possible Partnership 2021; J. Chen, Li, and Li 2021; IEA 2020).

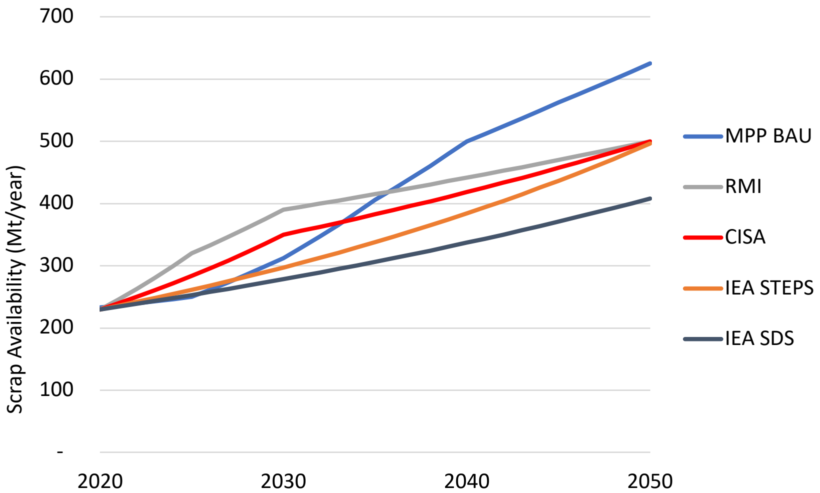


Figure 24. Scrap availability outlook for China's steel industry in other studies (Mission Possible Partnership 2021; J. Chen, Li, and Li 2021; IEA 2020)

Notes: MPP = Mission Possible Partnership; BAU = business as usual; CISA = China Iron and Steel Association; STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario; MIIT = Ministry of Industry and Information Technology of China.

China's steel industry faces several challenges in improving the rate of scrap usage. First, high electricity costs and high scrap prices make EAF steelmaking less economically attractive (China Steel News 2020). Starting on July 1, 2019, imported scrap is listed as one of the prohibited solid wastes to import. This restricts the scrap supply for China's steel industry. Second, China's steel recycling industry is fragmented, with many small, inefficient facilities with old technologies (Xuan and Yue 2016; Wübbeke and Heroth 2014). This reduces the recycling output and efficiency as well as quality, resulting in lower-quality scrap with hazardous and impurity contamination (Q. Zhao and Chen 2011). In addition, these small scrap recycling facilities also face several challenges in receiving recycling incentives in China, such as difficulty accessing tax rebates, which indirectly increases the cost of scrap (D. Guo and Zhang 2021). Lastly, while studies have found that at the national level, China will likely have a scrap availability boom after 2030, specific scrap availability varies by province and region. Provinces in eastern China will see scrap exceeding demand around 2030, while provinces in central and western China will likely have more scrap available after 2040 (Song et al. 2020).

Financial, technological, and regulatory support can improve the current scrap supply system and increase scrap usage in China's steel industry. For example, providing preferential tax treatment (e.g., tax relief or tax rebates) for scrap recycling facilities, developing recycling and management standards, promoting advanced recycling technologies to reduce contamination, allowing the import of steel scrap, and providing economic incentives and/or differential electricity pricing to EAF steelmakers can be considered. In addition, national and provincial circular economy policies, such as localized waste management and inter-province scrap circulation, could be pursued.

6.4.2. Direct reduced iron (DRI) production

At present, MIDREX and HYL/Energiron are the most widely available direct reduction (DR) processes as alternatives to BF iron production. These processes employ shaft furnaces and H_2-rich gas (usually from natural gas) as the reducing agent. If direct reduced iron (DRI) is paired with the EAF to produce steel, it results in lower CO_2 emissions compared to the BF-BOF steel production route (Rechberger et al., 2020).

Hydrogen DRI (H_2-DRI) production

Another alternative pathway to achieve a further reduction of CO_2 emissions is the utilization of hydrogen produced from renewable energy (green hydrogen) as the energy source and reducing agent for the production of DRI (H_2-DRI), thus, releasing H_2O instead of CO_2.

Hydrogen demand for the H_2-DRI process reported in the literature is 50-70 kg H_2 for 1 tonne of steel (Vogl et al., 2018). Presently the majority of hydrogen is produced through fossil fuel-based carbon-intensive processes such as natural gas reforming, methane partial oxidation, methane reforming, and automatic thermal or coal gasification. Non-fossil fuel-based processes like electrolysis also represent a small share of overall H_2 production worldwide (Wang et al.,2021).

At present, H_2-DRI is currently under development through several projects, mainly in Europe. A few of the prominent projects are shown in Table 4.

Table 4. H_2-DRI steel production projects around the world (SEI 2022)

Company	Country (in which project/investment is taking place)	Location	Project scale	Hydrogen type	Year Online
SSAB	Sweden	Luleå	pilot	Green electrolytic	2021
SSAB	Sweden	Gällivare	demo	Green electrolytic	2026
ArcelorMittal	Spain	Gijon	full scale	Green electrolytic	2025
H2 Green Steel	Sweden	Svartbyn	full scale	Not stated	2024
POSCO	South Korea	N/A	full scale	Not stated	Not stated
LKAB	Sweden	Kiruna, Malmberget, Svappavaara	full scale	Green electrolytic	2029
Fortescue Metals	Australia	Pilbara	full scale	Green electrolytic	2023
Voestalpine	Austria	Donawitz	pilot	Not stated	2021
ArcelorMittal	France	Dunkirk	full scale	Blue	2021
ArcelorMittal	Germany	Eisenhüttenstadt	pilot	Green electrolytic	2026
Tata Steel	Netherlands	Ijmuiden	full scale	Not stated	2030

Currently, China only has a few DRI projects, with most of them using H_2-rich gases coming from coking or other industrial processes, as shown in Table 5. For example, Hebei Iron and Steel Group (HBIS), the seventh-largest steel-producing company in the world, signed a contract with Tenova in 2020 to develop a DRI plant with a total capacity of 0.6 Mt/year using enriched coke-oven gas that has a 70% hydrogen concentration (Tenova 2020; The International Energy Net 2021). HBIS also plans to develop a second-stage DRI plant, with 0.6 Mt/year in capacity, using green hydrogen (The International Energy Net 2021). The largest steel production company in China and the world, Baowu Steel, is building a DRI facility in its Zhanjiang Steel facility. With a total investment of ¥1.89 billion RMB (US$293 million[4]), the project has a total capacity of 1 million tonnes per year (NE21 2022).

4 Exchange rate used in this study: the average 2021 exchange rate, i.e., 1 US Dollar = 6.45 Chinese Yuan (renminbi, or RMB). Source: https://www.macrotrends.net/2575/us-dollar-yuan-exchange-rate-historical-chart

Table 5. DRI production projects in China

Project Name	Applications	Steel Company	Capacity	Project Status	Company Steel Roadmap
Paradigm Project	COG syngas DRI and (future) green H_2 DRI	Hebei Iron and Steel Group (HBIS)	1.2 million tonnes per year in two stages.	Plan to operate the 1st stage by 2021	Pledged to reach carbon peaking by 2022 and achieve carbon neutrality by 2050
Zero-carbon steel pilot	H_2 DRI and industrial-scale production of H_2 and COG	Baowu Steel (Zhanjiang Steel)	1 million tonnes per year	Plan to complete construction by the end of 2023	Pledged to reach carbon peaking by 2023 and achieve carbon neutrality by 2050
H_2 Metallurgical Project	Industrial byproduct syngas DRI	Rizhao Steel	500,000 tonnes DRI per year	Launched in May 2020	Not available
Jianlong-Inner Mongolia Saisipu Company H_2 DRI project	COG syngas DRI	Jianlong Steel	300,000 tonnes per year	Completed 156 tonnes in a pilot project in 2021	Pledged to reach carbon peaking by 2025 and achieve carbon neutrality by 2060
Green Hydrogen Zero Carbon Fluidized Bed	H2-based fluidized bed pilot	Angang Steel	>10,000 tonnes per year	Plan to operate in 2023	Pledged to reach carbon peaking by 2025 and become one of the first companies to achieve carbon neutrality
Hydrogen Metallurgy Research Institute	H_2 metallurgical applications	Jiugang Steel	Research institution – production capacity not applicable not available	Established in September 2019	Not available
Low-Carbon Hydrogen Metallurgy Research Institute	R&D on hydrogen and low-carbon metallurgy	Baogang Steel		Established in July 2021	Pledged to reach carbon peaking by 2023 and achieve carbon neutrality by 2050

Rizhao Steel, a private steel company in Shandong Province, launched its hydrogen metallurgical project in 2020. Using industrial byproduct syngas (the process uses natural gas as feedstock to produce vinyl acetate), the project aims to produce 0.5 Mt/year of DRI (Zhong 2020).

Jianlong Steel, China's fifth largest private steel company, invested ¥1.09 billion RMB ($169 million USD) in developing a DRI project with a total capacity of 0.3 Mt/year. The source of hydrogen comes from coke oven gas. As of April 2021, Jianlong Steel has produced the first batch of 156 tonnes of DRI (CSteel News 2021).

In addition to pilot DRI projects, Chinese steel companies, such as Baowu Steel, Jiugang Steel, Angang Steel, and Baogang Steel, developed research institutes and/or joint agreements to focus on the research & development of hydrogen metallurgical innovations and technologies.

6.4.3. Injecting hydrogen-rich gases into the blast furnace

Globally, injecting hydrogen-rich gas in blast furnaces has been tested in Japan, Germany, Sweden, and China. In Japan, under the CO_2 Ultimate Reduction System for Cool Earth 50 (COURSE50) project, byproduct hydrogen (coke oven gas) was injected into an experimental blast furnace (The Japan Iron and Steel Federation 2021b). It is reported that in the experimental blast furnace, a 10% reduction of CO_2 emissions was achieved in 2021 (The Japan Iron and Steel Federation 2021a). In the Super COURSE50, initiated by the Japanese Iron and Steel Federation in 2020, the Japanese steel companies will further increase the use of hydrogen in blast furnaces by using purchased hydrogen from outside (The Japan Iron and Steel Federation 2021c).

The COURSE50 project also tested the use of coke oven gas (COG) and reformed COG in an experimental blast furnace (EBF) located in Lulea, Sweden. The EBF is owned by the Swedish mining company LKAB. The test results showed only a 3% reduction in CO_2 emissions, limited by the available COG production rate (Nishioka et al. 2016).

Thyssenkrupp finished its first stage of testing by injecting hydrogen in one of the 28 tuyeres of its “Blast Furnace 9” in Duisburg, Germany. The injected hydrogen, supplied by Air Liquide and delivered by truck, reached the designed volume of 1000 m^3 per hour. In the second stage of the project, which is expected to start in 2022, Thyssenkrupp plans to expand the test to all of the 28 tuyeres. It is also expected to receive hydrogen by pipeline (Thyssenkrupp 2021). Thyssenkrupp has more recently committed to replacing its blast furnaces with DRI plants combined with a submerged arc furnace (SAF) in 2025, allowing it to use blast-furnace grade iron ore in the process. The SAF will melt the sponge iron before it goes to ThyssenKrupp’s existing BOF for steelmaking. ArcelorMittal is also planning to implement a similar DRI-SAF combination (Nicholas and Basirat, 2022).

Chinese steel companies are also interested in applying hydrogen-rich gases in the BF to reduce coke consumption and mitigate emissions. Early in 2017, Xingtai Iron and Steel Company, located in Hebei Province, piloted hydrogen-rich ironmaking technology in collaboration with the China Iron and Steel Research Institute. The hydrogen-rich gas is from coke oven gas produced onsite (Xingtai Iron and Steel Company 2017).

Baowu Steel, the largest steel company in China and the world, launched its hydrogen-rich carbon circulation BF project in October 2020. It is reported that the project has completed the first and second stages of testing, reached the goal of utilizing hydrogen-rich gas (50% hydrogen in syngas), and achieved a 15% CO_2 intensity reduction target (Wang, 2022). The project is now in the third stage, which aims at reducing CO_2 intensity by 30% in the blast furnace process.

Shanxi Jinnan Steel, working with the China Iron and Steel Research Institute, implemented hydrogen injection on two of its blast furnaces in April 2021. Each blast furnace has a volume of 1860 m^3. The project is the first continuous industrial experiment on large blast furnaces in China. The project reported reducing coke use by 6.5 kg per tonne of iron and coal use by 29.5 kg per tonne of iron (China Baowu News 2022).

Table 6 provides a summary of completed and ongoing pilots related to injecting hydrogen-rich gas in blast furnaces in the world.

Table 6. Pilot projects of hydrogen application in blast furnaces

Project Name	H_2 Application	Steel Company/ Consortium	Country	Project Status
COURSE50	Coke oven gas (COG) injection in blast furnace	The Japan Iron and Steel Federation (JISF)	Japan	Tests completed in 2021; reached goal of 10% CO_2 emission reduction
COURSE50	COG injection in blast furnace	LKAB and JISF	Sweden	Tests completed in 2012; reduced CO_2 emissions by 3%
Super COURSE50	Outsourced H_2 injection in blast furnace	The Japan Iron and Steel Federation	Japan	Began in 2020
H2Stahl project	Outsourced H_2 (trucked) injection in blast furnace	thyssenkrupp	Germany	Testing began in 2019; the first stage was completed.
H2Stahl project	Outsourced H_2 (via pipeline) injection in blast furnace	thyssenkrupp	Germany	Plan to start in 2022
Low-carbon hydrogen-rich ironmaking	COG injection in blast furnace	Xingtai Steel	China	Began in 2017
Hydrogen-rich carbon circulation blast furnace	COG injection in blast furnace	Baowu Steel (Bayi Steel)	China	Began in 2020, achieved a 15% CO_2 emission reduction as of 2021
Blast furnace hydrogen injection	H_2-injection in blast furnace	Shanxi Jinnan Iron and Steel Group	China	Began in 2021, reduced CO_2 emissions by 10%

Sources: (The Japan Iron and Steel Federation 2021a, 50; 2021b; Nishioka et al. 2016; thyssenkrupp 2021; Xingtai Iron and Steel Company 2017; Wang 2022; China Baowu News 2022).

6.4.4. Hydrogen demand in China's steel industry

As discussed earlier, a substantial amount of hydrogen production is needed to supply hydrogen for iron and steel production processes by BF-BOF and H_2-DRI. Figure 25 shows the total hydrogen demand for the Chinese steel industry under different scenarios. In the Net-Zero scenario, 0.6 Mt of hydrogen is needed in the steel industry in China in 2030. The hydrogen demand will increase to around 5 Mt in 2040 and 6 Mt in 2050 under this scenario.

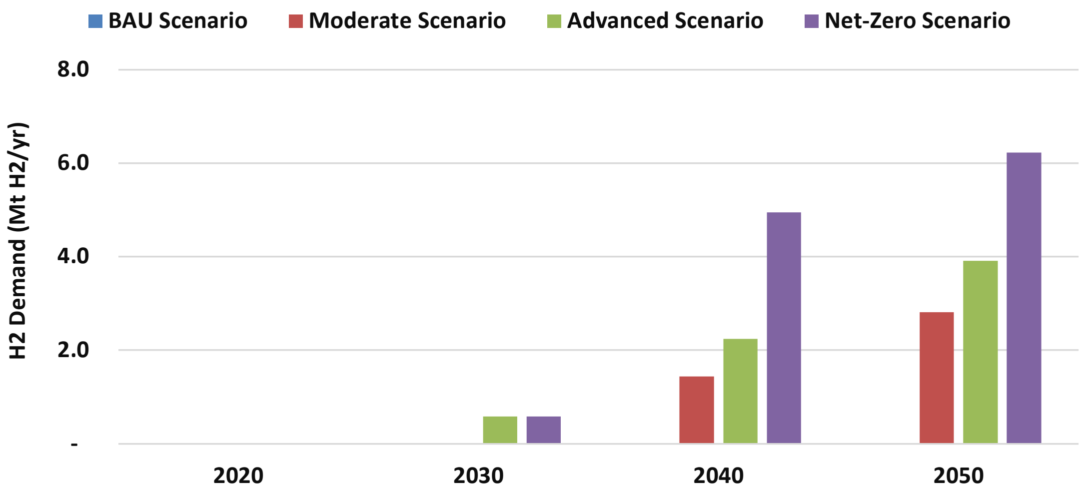


Figure 25. Total additional hydrogen demand for the Chinese steel industry under different scenarios (source: This study)

In our analysis, we assume that the hydrogen used in the Chinese steel industry will be green hydrogen. While the use of green hydrogen decreases CO_2 emissions, electricity demand increases. Figure 26 shows the additional annual electricity consumption for green hydrogen production for the Chinese steel industry under different scenarios. Hydrogen production to meet the steel industry's demand in China increases annual electricity consumption of 32, 272, and 342 TWh/year in 2030, 2040, and 2050, respectively, in the Net-Zero scenario. This translates into an increase in electricity load demand of 13, 113, and 143 GW in China in 2030, 2040, and 2050, respectively, under this scenario (Figure 27).

For comparison, in 2021, China had around 2,380 GW of power generation capacity. Also, the annual capacity of renewable power generation in China reached 1200 GW in 2021. China added 120 GW of new renewable capacity in 2021 alone (US EIA 2022). To estimate these additional loads, we assumed all of the additional load is coming from clean, renewable energy sources.

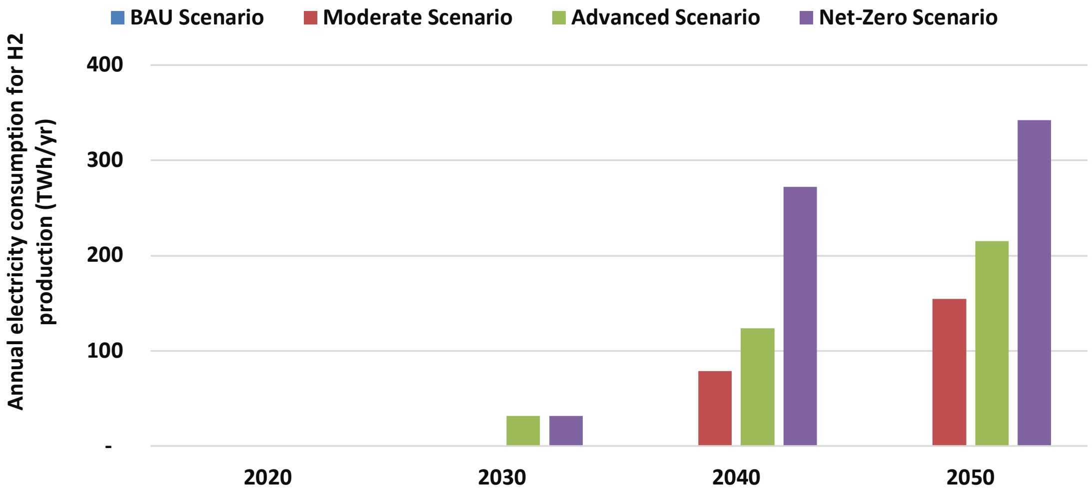


Figure 26. Additional annual electricity consumption for green hydrogen production for the Chinese steel industry under different scenarios (source: This study)

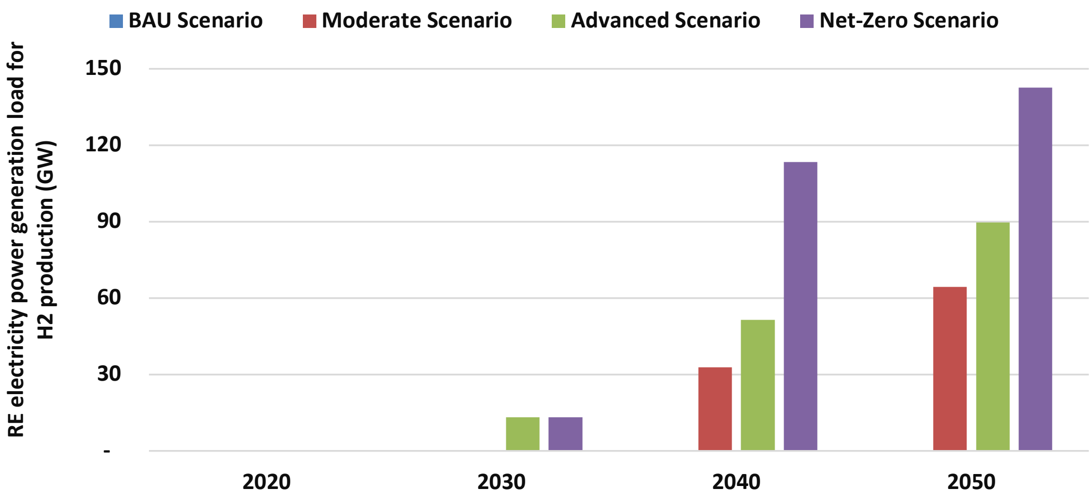


Figure 27. Additional RE power generation capacity is needed for green hydrogen production for the Chinese steel industry under different scenarios (source: This study)

In addition to investment in renewable power generation and distribution, substantial capital investment is needed to significantly increase hydrogen production capacity in China. Figure 28 shows our estimate for the number of 100 MW electrolyzers for hydrogen production for the Chinese steel industry under different scenarios. The status of hydrogen production and related policies and plans in China is discussed later in this report.

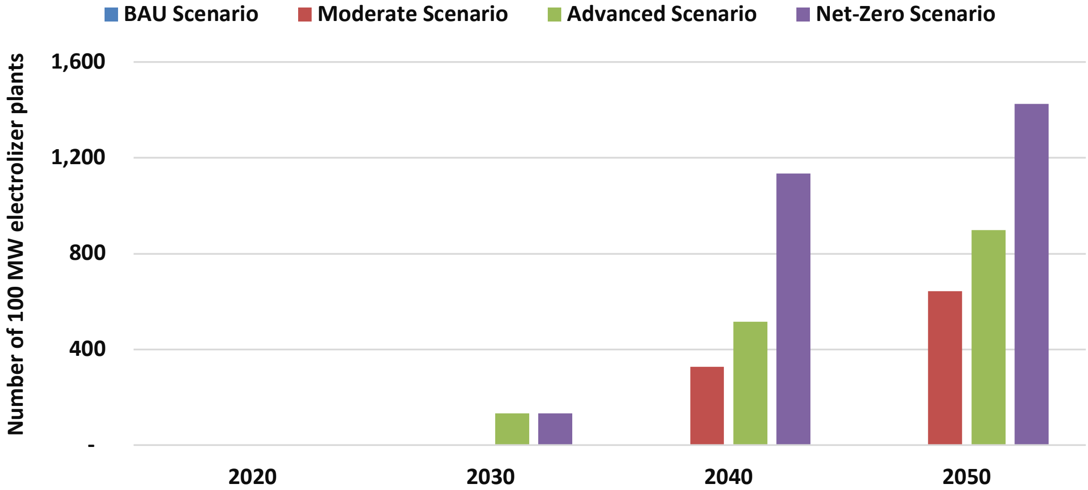


Figure 28. Number of 100 MW electrolyzers for hydrogen production for the Chinese steel industry under different scenarios (source: This study)

The use of green hydrogen in the steel industry has the potential to reduce CO_2 emissions when the electricity grid is decarbonized, but the infrastructure and competing demands for renewable electricity resources pose challenges to realizing these reductions in China. Investing in the electricity grid and increasing the share of renewable energy in the power sector energy mix will help accelerate the use of green hydrogen and contribute to a reduction in CO_2 emissions.

The electricity grid is a complex, interconnected system linking generation resources to customers with varying and variable electricity needs. Electricity generation from renewable resources has increased substantially over time in China, but China's electricity grid is very carbon-intensive.

Managing the grid's resources, infrastructure, and energy flows is a considerable undertaking that will continue to be complicated by trends toward more distributed generation resources and renewable resources. Additional pressure will be placed on China's already strained grid system as multiple sectors, such as transportation, buildings, and industry, move to electrify and access renewable resources in order to reduce their emissions. To deliver electrification at scale, investments will be needed to build or upgrade key infrastructure, including renewable electricity production, energy transmission, and distribution networks, and end-user infrastructure.

Developing a coherent power sector strategy is essential to accelerate the pace of power sector decarbonization which is a prerequisite to the use of green hydrogen in industry. Utilities, policymakers, industry, and other stakeholders should pay attention to this potential increase in demand for renewable electricity, and the associated need for more renewable electricity generation, additional energy storage, demand response programs, transmission and distribution system expansion, and grid modernization. Ensuring that sufficient renewable resources are brought online and connected to demand centers will be critical for a smooth energy transition and rapid multisector electrification and beneficial use of green hydrogen in Chinese industry.

6.4.4. Hydrogen production in China

The most important obstacle faced by H_2-DRI production is the production of low-carbon hydrogen at large quantities at an economical price. There is a need for increased effort in designing solutions for low-cost green hydrogen as well as safe hydrogen transport and storage.

Current Hydrogen Production in China
China currently produces about 33 Mt of hydrogen, the largest producer in the world (Bai 2022). According to China's national standard on hydrogen quality (GB/T 3634.1-2006), industrial grade (H_2 purity > 99%) H_2 production is about 12 Mt (CNIS 2020).

China's current hydrogen production relies significantly on fossil fuels, mainly coal. More than 62% of China's hydrogen is produced from coal or coal products, and renewable (or green) H_2 only accounts for 1-3% (H2weilai 2021). Natural gas-based hydrogen production accounts for 19%. This is very different from the fuel mix in global hydrogen production, where natural gas steam methane reforming accounted for 76% of total production in 2018 (IEA 2019).

The majority of China's current hydrogen producers are in the heavy industry and energy sectors. About 21 Mt of China's total hydrogen production is from dedicated hydrogen production processes in industrial sites, such as ammonia production, oil refining, methanol production, and other chemical and metal production processes (Figure 29). These processes require hydrogen with only small levels of other additives or contaminants. Another 12 Mt of China's total hydrogen production is generated as industrial byproducts, often a mixture of hydrogen and other gases (synthesis gases), and produced mainly from the steel industry, Chlor-alkali industry, and other chemical processes (Deng et al. 2010; Verheul 2019).

The coking process, where coal is heated in an oxygen-free condition to produce coke, is a key process in the primary steelmaking. The coking process not only produces the reducing agent for ironmaking in the blast furnace but also produces coke oven gas as a byproduct. Generally speaking, about 1 tonne of coke can produce 400-426 m^3 of coke oven gas, which contains mostly hydrogen (54-69%), methane (23-28%), carbon monoxide (5.5-7%), CO_2 (1.2-2.5%), and other unsaturated hydrocarbon (Deng et al. 2010; China EV100 2020). Based on the current level of coke production in China, we estimate that China's steel industry produces about 6-7 Mt of hydrogen from the coking process, as shown in Figure 30.

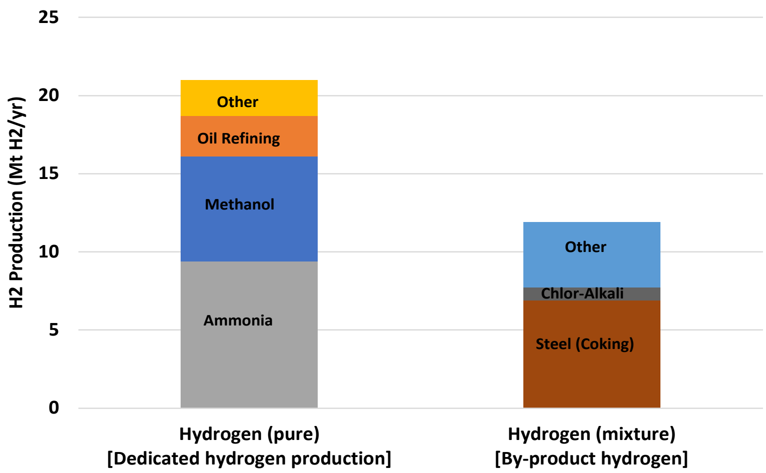


Figure 29. Hydrogen Production in China in 2018

Note 1: Coke-oven gas (COG), a byproduct of the coking process, has a relatively large fraction of hydrogen (H_2). However, most COG is combusted to produce heat and power. As the share of BF-BOF steelmaking, which requires coke, declines substantially in China in coming years and decades, the amount of COG will decline substantially too. Therefore, proposals to recover and purify H_2 from COG are less relevant.

Note 2: other sectors include: other chemical processing, metal production, electronics, food processing, pharmaceuticals, glass manufacturing, laboratory research, and aeronautics & astronautics

China's Hydrogen Industry Development Plan

In March 2022, China released its first *Hydrogen Industry Development Mid-Long Term Plan (2021-2035)*(NDRC and NEA 2022). The plan makes it clear that hydrogen will be a part of China's energy supply systems and emphasizes the coordinated "supply chain" development of hydrogen production, storage, transportation, and utilization, especially in the transportation and industrial sectors. The Chinese government not only views hydrogen playing a key role in providing clean and low-carbon energy, but also sees the hydrogen industry as a strategic industry for structural upgrades and economic growth. Under the plan, by 2025 China would have the core technologies and production processes of hydrogen production reach a total of 50,000 fuel cell vehicles, deploy hydrogen refueling stations, and produce renewable-based hydrogen to 100,000 to 200,000 tonnes per year. By 2030, the government aims to have a complete hydrogen industry technological innovation system, clean hydrogen production, and supply system to support China's carbon peaking goal. By 2035, the government envisions that hydrogen would have diverse applications and that the share of renewable-based hydrogen would increase significantly (NDRC and NEA 2022).

According to the industry group the China Hydrogen Alliance by 2030 China's hydrogen demand will reach 35 Mt, and it will require around 5% of China's final energy consumption to produce that amount of hydrogen (China Hydrogen Alliance 2019). The share will increase to 10% by 2050. By 2060, China's total hydrogen demand will increase to 60 Mt, with the industrial sector consuming 34 Mt, mostly in the iron and steel industry (China Hydrogen Alliance 2019).

China is building some of the largest hydrogen production facilities in the world. As of July 2022, we have identified a total of 40 hydrogen production projects (Figure 30) that either have been developed or are under development. Many of these projects began construction in 2020 or 2021, and are expected to start operation in late 2022 or 2023. The majority of the projects (34) produce hydrogen from solar PV, solar thermal, wind, or a combination of renewable sources. The other projects rely on hydropower for hydrogen production. Out of the 40 projects, 4 projects are producing hydrogen from either coke oven gas, natural gas, or as an industrial byproduct.

One of the largest hydrogen production projects in China is the PV-green hydrogen project in Kuqa, Xinjiang. The project was launched on November 30, 2021, with a total production capacity of 20,000 tonnes per year. With a total investment of 3 billion RMB ($465 million USD[5]), the project includes PV power generation, power transmission and distribution, water electrolysis for hydrogen production, hydrogen storage, and hydrogen transportation. Expecting to have the project in operation by June 2023, the green hydrogen produced will be used in Sinopec's Tahe Refining & Chemical Company to reduce the current natural gas consumption (Xinhua Net 2021).

5 Based on 2021 average exchange rate between US dollars and Chinese yuan (RMB), 1 USD = 6.45 RMB. https://www.macrotrends.net/2575/us-dollar-yuan-exchange-rate-historical-chart

Figure 30. Hydrogen Projects in China (various sources)

About 40% of planned and ongoing hydrogen production capacity is concentrated in Inner Mongolia, due to its rich solar and wind resources (Table 7). Another 30% of the announced hydrogen production capacity is located in Shanxi and Xinjiang. At this stage, coastal regions have a much small production capacity developed, as shown in Guangdong and Zhejiang provinces.

The locations of China's hydrogen development match quite well with China's plans to develop clean energy bases. In the 14th Five-Year Plan, the central government identified nine on-land clean energy bases, as shown in Figure 31, including Songliao Clean Energy Base (Heilongjiang, Jilin, and Liaoning), Jibei Clean Energy Base (Northern Hebei), Yellow River Jiziwan (n-shape bent) Clean Energy Base (Ningxia and Inner Mongolia), Hexi Corridor Clean Energy Base (Gansu), Upper Yellow River Clean Energy Base (Qinghai), Upper Jinsha River Clean Energy Base (Sichuan), Yalong River Clean Energy Base (Guizhou), and Lower Jinsha River Clean Energy Base (Yunnan). In addition, coastal regions' hydrogen development is also in line with the central government's plan to develop offshore wind energy bases in Guang-dong, Fujian, Zhejiang, Jiangsu, and Shandong.

Table 7. Announced hydrogen production capacity in China by provinces (various sources)

Province/ Autonomous Region	Announced Hydrogen Production Capacity (Nm^3/hour)	Share of Total (as of July 2022)
Inner Mongolia	139,625	40%
Shanxi	67,500	19%
Xinjiang	38,300	11%
Jilin	30,700	9%
Yunnan	23,500	7%
Ningxia	20,000	6%
Gansu	9,960	3%
Hebei	6,600	2%
Sichuan	6,000	2%
Shandong	5,600	2%
Guangdong	1,550	0.4%
Zhejiang	800	0.2%
Total	**350,000**	**100**

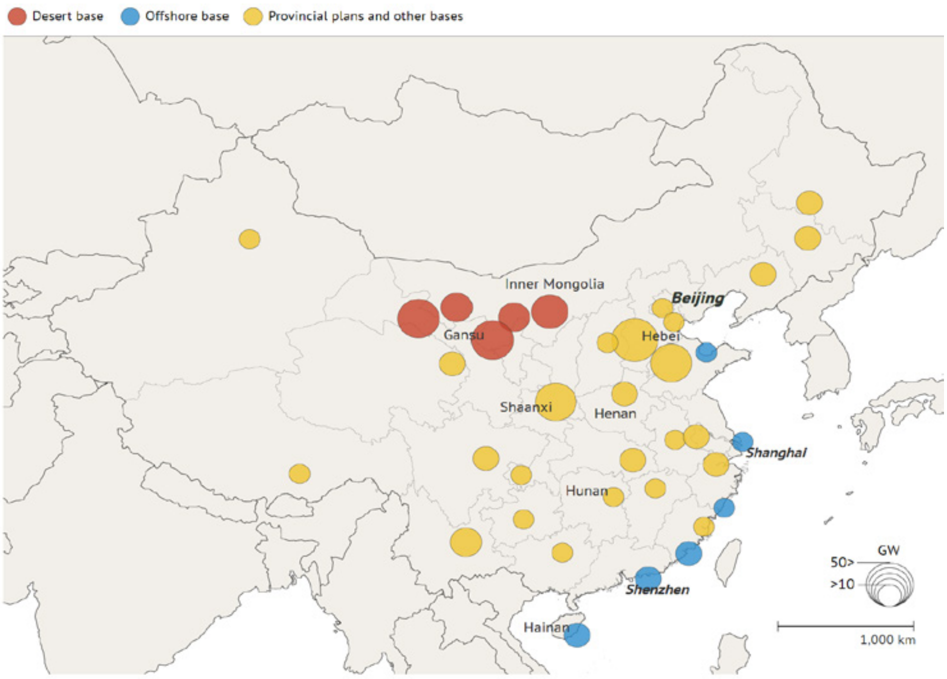


Figure 31. Clean energy production bases in China (Myllyvirta, Zhang, and Prater 2022)

China is also moving forward in investing and manufacturing electrolyzers. According to the International Energy Agency (IEA), China accounted for 8% of the global stock of electrolyzers (295 MW) and 35% of the total manufacturing capacity of electrolyzer equipment and components in the world (IEA 2021). The state-supported industry group, China Hydrogen Alliance called for reaching 100 GW of renewable hydrogen production by 2030 (Argus 2021). Figure 32 shows the location of steel plants and hydrogen production projects in China.

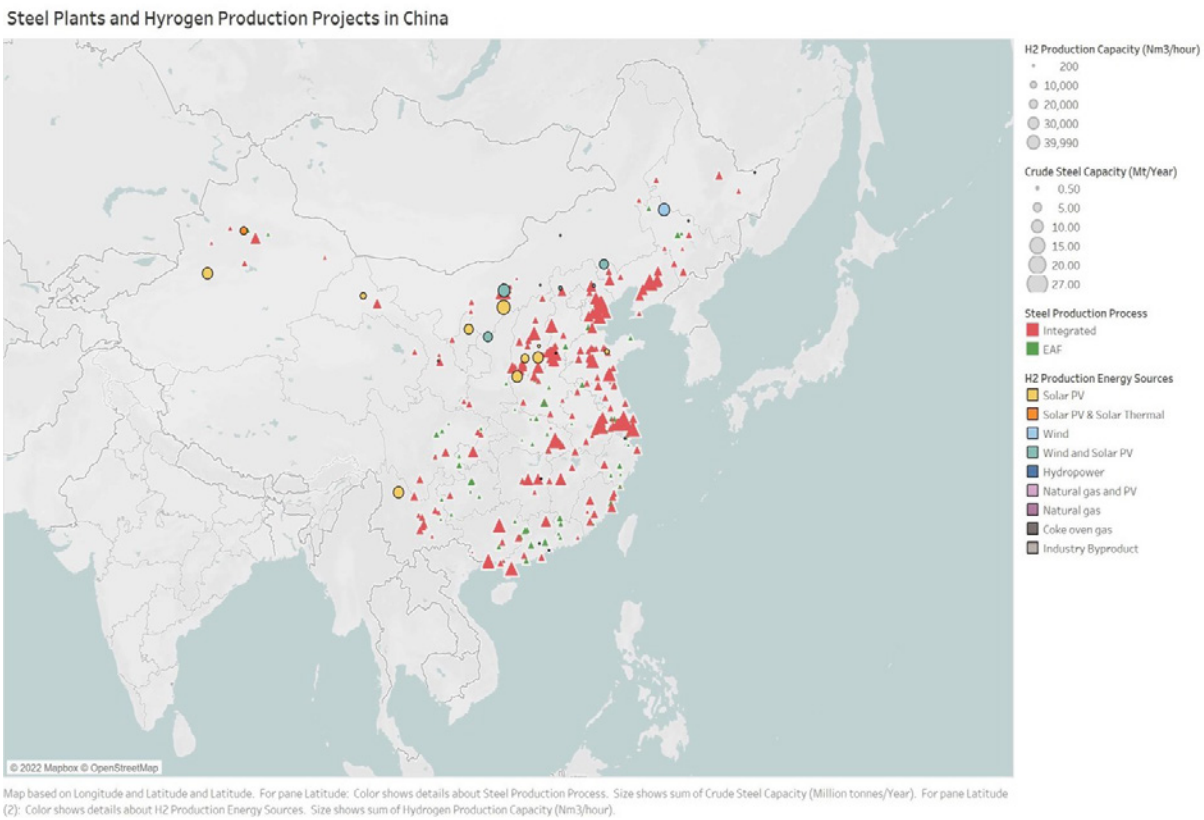


Figure 32. The location of steel plants and hydrogen production projects in China (Sources: Global Energy Monitor and author analysis.)

Cost of hydrogen production in China

As shown in Table 8, green hydrogen production cost in China is typically about ¥20-40 yuan ($3.1-6.2 USD) per kg, but can be higher, at around ¥48.5 yuan ($7.5 USD) per kg (X. Zhao 2022; China Hydrogen Alliance 2020; W. Chen 2021). Hydrogen produced from coal in China costs about ¥6-12 yuan ($1-1.9 USD) per kg (W. Chen 2021). The cost of hydrogen that is produced from industry byproduct is in the range of ¥10-27 yuan ($1.6-4.2 USD) per kg (China Hydrogen Alliance 2020; W. Chen 2021).

Various studies (see Table 8) from China expect green hydrogen cost to decrease, reaching ¥25 yuan ($3.9 USD) per kg by 2025 (China Hydrogen Alliance 2021). Green hydrogen cost is expected to be in the range of ¥15-22 yuan ($2.3-3.5 USD) per kg by 2030, and further declines to be less than ¥10 yuan ($1.5 USD) per kg (China Hydrogen Alliance 2021; W. Chen 2021).

Table 8. Hydrogen Production Cost in China

Year	Green H_2		Coal-based H_2		H_2 from industry byproduct		Source
	¥Yuan/kg	$USD/kg	¥Yuan/kg	$USD/kg	¥Yuan/kg	$USD/kg	
2020	¥20 - 30	$3.1 - 6.2	¥7 - 9	$1.1 - 1.4			(X. Zhao 2022)
2020	¥30 - 40	$4.7 - 6.2	¥8.85	$1.40	¥10 - 16	$1.6 - 2.5	(China Hydrogen Alliance 2020)
2020	¥9.2 - 48.5	$1.4 - 7.5	¥6 - 12	$0.9 - 1.9	¥14.6 - 26.9	$2.3 - 4.2	(W. Chen 2021)
2025	¥25	$3.90	-	-	-	-	(China Hydrogen Alliance 2021)
2030	¥15	$2.30	-	-	-	-	(China Hydrogen Alliance 2021)
2030	¥21.56	$3.30	¥13.33	$2.10	-	-	(W. Chen 2021)
2040	¥14.46	$2.20	¥15.63	$2.40	-	-	(W. Chen 2021)
2050	¥<10	$<1.6	-	-	-	-	(China Hydrogen Alliance 2020)
2050	¥9.7	$1.50	¥18.32	$2.80	-	-	(W. Chen 2021)

6.5. Carbon capture, utilization, and storage

Carbon capture, utilization, and storage (CCUS) can be used to decarbonize different steel production routes, such as top-gas recycling in blast furnaces with CCUS, DRI with post-combustion CCUS, and oxygen-rich smelt reduction with CCUS, etc. These CCUS technologies vary greatly in their commercialization status, with most of them currently at the pilot stage. The main challenges for CCUS technologies are achieving further reductions in costs and improving operational efficiencies as well as having suitable CO_2 transport systems and storage sites. The captured CO_2 emissions from iron and steel production can be permanently stored underground (depending on geology), or used to produce chemicals, fuels, construction materials, etc.

In our analysis, we assumed various adoption rates of CCUS technologies in China's steel industry across scenarios for both BF-BOF steelmaking and conventional DRI plants. It should be noted that post-combustion carbon capture technologies can reach up to 95% capture efficiency, but because of the structure of steel plants and different emissions point sources in production and the leakage that happens during carbon capture, it is hard to reach that high capture efficiency in steel plants. Figure 33 shows the CO_2 emissions captured by the adoption of CCUS in China's steel industry.

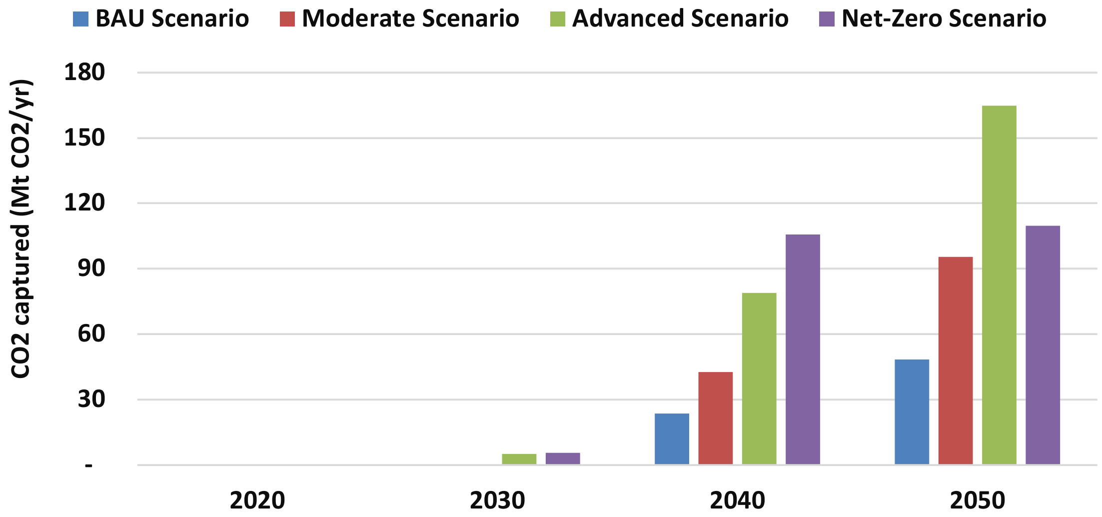


Figure 33. The CO_2 emissions captured by the adoption of CCUS in China's steel industry (CCUS is applied after the adoption of other decarbonization technologies) (Source: this study).

CCUS status in the global steel industry

Globally, the Al Reyadah project, located in the Emirates Steel complex at Mussafah, United Arab Emirates (UAE) is the only commercial steel industry carbon capture project. The project, with a seed capital of $15 billion USD, is a joint venture between Abu Dhabi Future Energy Company (Masdar) and Abu Dhabi National Oil Company (ANDOC) (MIT 2016). CO_2 emissions are captured from a DRI plant using a traditional monoethanolamine (MEA) absorption and recovery system (Zahra 2015). The CO_2-rich waste stream is then dehydrated, compressed, and piped 43 km for onshore enhanced oil recovery (EOR) (Scottish Carbon Capture & Storage 2022). The project has been operating since 2016 with the capacity to capture 800,000 tonnes of CO_2 per year (ADNOC 2017).

Pilots are being conducted to test technologies to capture CO_2 emissions from steel manufacturing processes. Companies in Japan (e.g., Nippon Steel) and Europe (e.g., ArcelorMittal and SSAB) are testing capturing CO_2 emissions from BFs. These carbon capture projects are in pilot stages with much smaller CO_2 capturing capacity, ranging from 6 tonnes per day to 14 tonnes per day.

In terms of CO_2 storage, Nippon Steel signed a joint study agreement with deepC Store to evaluate the commercial feasibility of capturing and transporting liquefied CO_2. The CO_2 will be supplied by Nippon Steel, shipped to a CO_2 Floating Storage and Injection (FSI) hub facility in offshore Australia, and then injected subsurface near the FSI facility (Nippon Steel 2022).

Steel companies are also exploring turning CO_2 into products, such as chemicals, plastics, and fuels. For example, ArcelorMittal is working with LanzaTech to demonstrate a CCU technology at an industrial scale. The project (called the Steelanol project) will produce ethanol from carbon-rich waste gases from the steel plant in Ghent, Belgium (ArcelorMittal 2021). The project is expected to be in operation by the end of 2022 and produce 80 million liters of ethanol, which will be blended with gasoline for transport fuel. ArcelorMittal expects the project to reduce CO_2 emissions by 125,000 tonnes per year (ArcelorMittal 2021).

In Germany, Thyssenkrupp has initiated the Carbon2Chem project involving 16 partners. The project, with funding support from the German Ministry of Education and Research, began in 2016. By 2018, it had utilized CO_2 from top gases to produce ammonia, methanol, and alcohols in its pilot plant (Thyssenkrupp 2020). The project is now in the second phase to include CO_2 emission sources from other sectors, such as cement and lime production and waste incineration plants (Thyssenkrupp 2020). Table 9 provides a list of current CCUS projects in the steel industry internationally (excluding China).

Table 9. Global Steel Industry CCUS Projects

Project Name	Type of Project	CO_2 Capturing Capacity	Steel Company	Country	Project Status
Al Reyadah	CO_2 Capturing and EOR	MEA absorption; 800,000 tonnes per year (21,918 tonnes per day)	Emirates Steel	UAE	Commercial (operation began in 2016)
CO_2 Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 50 (COURSE 50)	CO_2 capturing	Chemical absorption; 30 tonnes per day Physical absorption; 6 tonnes per day	Kimitsu Iron Works Fukuyama Iron Works	Japan	Testing and Pilot
DMX™ Demonstration	CO_2 capturing	12 tonnes per day	ArcelorMittal	Dunkirk, France	Pilot (operation began in 2022)
STEPWISE Pilot of SEWGS Technology	CO_2 capturing	Solid sorption; 14 tonnes per day	SSAB	Luleå, Sweden	Pilot (operation began in 2017)
Steelanol Project	CO_2 capturing and utilization	125,000 tonnes CO2 per year	ArcelorMittal (with LanzaTech)	Ghent, Belguim	Pilot (expected commission by end of 2022)
Carbon2Chem project	CO_2 capturing and utilization	Goal is to reduce 30% CO_2 by 2030	Thyssenkrupp	Duisburg, Germany	Pilot (began in 2016, received funding through 2024)
Offshore CO_2 storage	CO_2 transportation and storage	1-5 million tonnes of liquefied carbon	Nippon Steel	Japan/ Australia	Feasibility study

Sources: (Global CCS Institute 2022; Nippon Steel 2022; ArcelorMittal 2021; Thyssenkrupp 2020)

CCUS status in the Chinese steel industry

Based on personal communications with several China's steel experts, it seems that the Chinese steel industry is more interested in CO_2 utilization than CO_2 storage. In the steelmaking process, CO_2 can be used for stirring, temperature control, shielding, and dilution in blast furnaces, basic oxygen furnaces, electric arc furnaces, and continuous casting.

China's Shougang Jingtang Company has utilized CO_2 in the dephosphorization process of BOFs (top-blowing CO_2) to control the reaction temperature and create favorable conditions for the dephosphorization process (K. Dong and Wang 2019). Bottom-blowing CO_2 in converters has been found beneficial when compared to alternatives such as argon (higher cost) and nitrogen (potentially harmful). Shougang Jingtang will also be piloting this project as one of the CCUS pilot projects in Hebei Province (Hebei Government 2021). It is estimated that the project will capture a total of 50,000 tonnes of CO_2 per year.

Delong Steel will be piloting a CCU project with a total capacity of 140,000 tonnes per year. The project will capture waste gases from the hot stoves of the BFs and utilize CO_2 to produce nano-calcium carbonate (Hebei Government 2021).

Baotou Steel Group is working with Columbia University on steel slag utilization which has carbon sequestration capabilities. During the chemical process, steel slag is converted into valuable materials to be used in various industries while the process also utilizes CO_2 emissions. This project, which began in 2015, is one of six US-China EcoPartnership projects. The demonstration project can utilize 424,000 tonnes of steel slag per year and sequester 100,000 tonnes of CO_2 annually (Ministry of Science and Technology 2021).

Starting in June 2022, Baotou Steel began building a CCUS demonstration project at a total capacity of 2 million tonnes of CO_2. The first phase of the project captures 500,000 tonnes of CO_2 emissions from industrial waste gases. The captured CO_2 will partly be piped as an input for the steel slag utilization, and other CO_2 will be trucked for EOR in nearby oil/gas filed, after compressing and liquefication (Baotou Steel 2022).

China's steel industry has conducted one feasibility study on CO_2 capturing and storage. Shougang Jingtang Company, working with Toshiba, Tongfang Environment, and Global CCS Institute studied the feasibility of applying post-combustion CCS technology and using CO_2 for EOR at a nearby oilfield (Toshiba International Corp and Tongfang Environment 2015). Table 10 summarizes the CCUS projects in China's steel industry to date.

Table 10. CCUS Projects in China's Steel Industry

Project Name	Type of Project	CO_2 Capturing Capacity	Steel Company	Country	Project Status
Caofeidian Project	CO_2 capturing and EOR	300 CO_2 tonnes per day	Shougang Steel	China	Feasibility study in 2015
Top-blowing CO_2	CO_2 utilization	Not Available	Shougang Jingtang	China	Company pilot
Bottom-blowing CO_2	CO_2 capturing and utilization	50,000 tonnes CO_2 per year	Shougang Steel	China	Provincial pilot project in 2022
CO_2 Utilization	CO_2 capturing and utilization	140,000 tonnes CO_2 per year	Delong Steel	China	Provincial pilot project in 2022
Steel Slag Utilization and CO_2 EOR	CO_2 utilization	500,000 tonnes CO_2 per year (first phase), total capacity at 2 $MtCO_2$/year	Baotou Steel	China	Demonstration began in July 2022

Sources: (Ministry of Science and Technology 2021; Shougang Group 2022; K. Dong and Wang 2019; Toshiba International Corp and Tongfang Environment 2015)

CCUS potential in China's steel industry

China has significant theoretical CO_2 storage capacity. Dahowski et al. (2009) estimated that China has a potential CO_2 capacity of 2.3 trillion tonnes of CO_2 in onshore basins, and another 780 $GtCO_2$ in relatively close offshore basins. (Cai, Li, and Zhang 2022) estimated China's CO_2 storage capacity is in the range of 1.21 to 4.13 trillion tonnes.

More than 99% of the estimated storage capacity is in deep saline-filled sedimentary basins, including 16 onshore and 9 offshore basins, as shown in Figure 34. The largest three onshore storages, including Songliao Basin, Tarim Basin, Bohai Bay Basin, account for more than half of the total storage capacity. In addition, Subei Basin and Ordos Basin also have significant storage potential (Cai, Li, and Zhang 2022). A much smaller amount of CO_2 storage capacity is estimated in depleted gas fields, depleted oil fields, and coal seams.

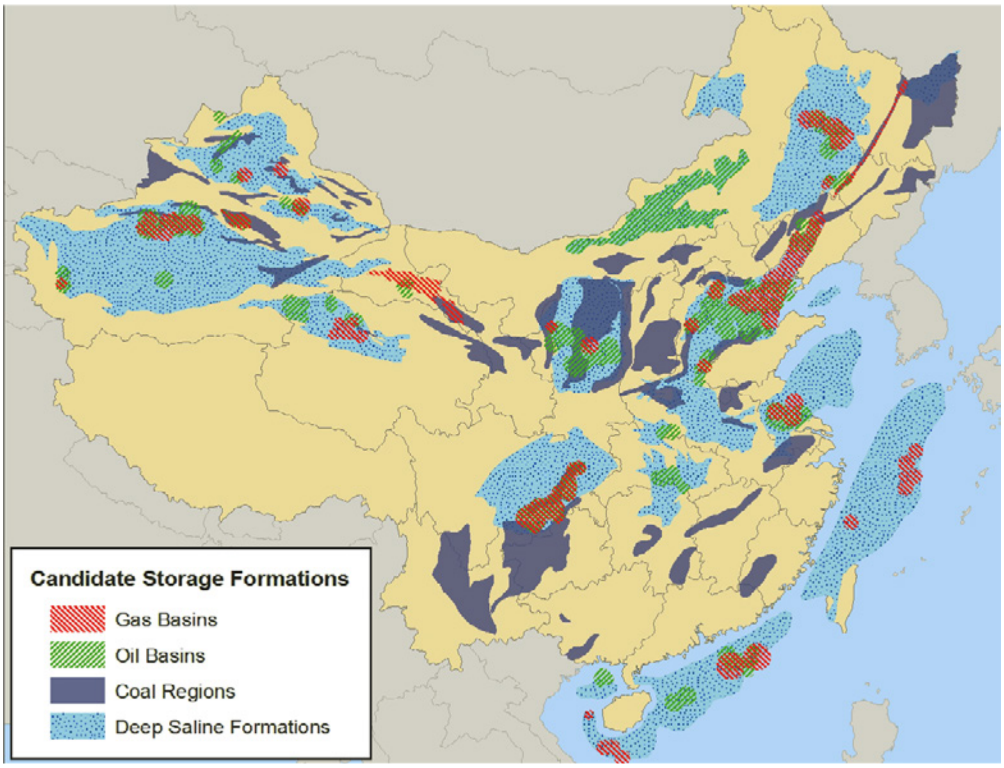


Figure 34. Geological CO_2 storage formations in China (Dahowski et al. 2009)

China's iron and steel plants are often located in provinces with rich iron ore and coal resources, such as Hebei, Liaoning, Shanxi, and Inner Mongolia, and also located in coastal regions which have a higher demand for steel products. One study shows that about 79% of China's iron and steel plants as of 2020 can find suitable geological locations (within a 250 km radius) (Cai, Li, and Zhang 2022).

As shown in Figure 35, steel plants located near Bohai Bay Basin, Junggar Basin, Jianghan Basin, and Ordos Basin have higher CO_2 emissions, are near feasible storage locations, and have a higher match with the storage sites. In contrast, steel plants in the south and coastal areas of China have a higher cost of geologic storage due to long transportation distances and relatively lower CO_2 emissions (Cai, Li, and Zhang 2021).

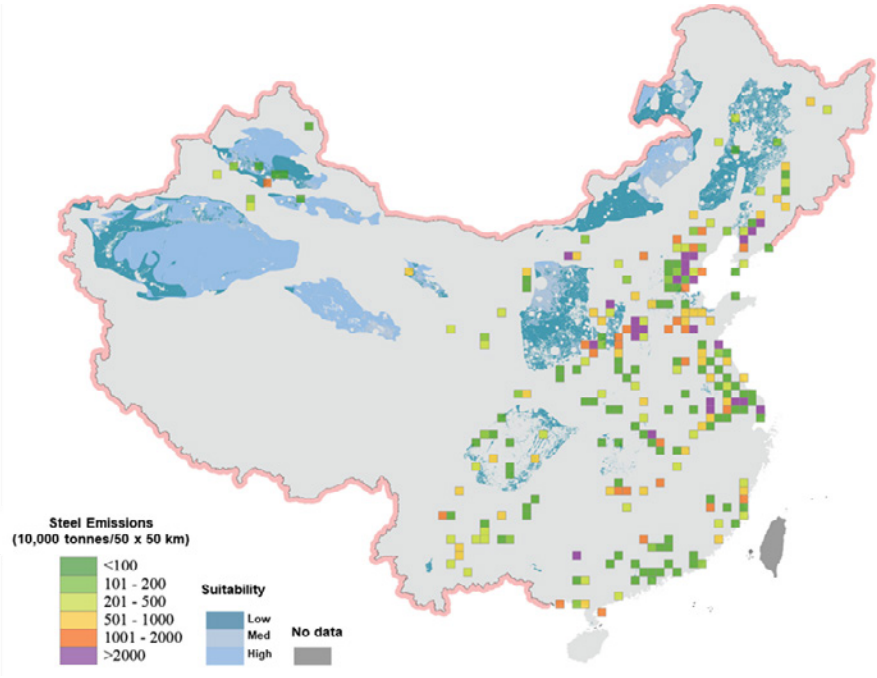


Figure 35. CO_2 emissions of China's Iron and Steel Facilities and Geological Storage Locations (Based on the graph from (Cai, Li, and Zhang 2022))

Due to limited storage capacity in CO_2-enhanced oil recovery (EOR) and competition with other industries (cement and chemical sectors), the steel industry cannot achieve deep mitigation by only relying on CO_2-EOR, but must consider other CCUS approaches.

Table 11 provides a summary of estimated CCS cost in China over time, including CO_2 capture, transportation, and storage. It shows that CO_2 capturing represented the majority of the cost compared to other components of the CCS system. The median CO_2 capturing cost by 2025 would be about $36-48 USD per tCO_2, using post-combustion capturing technologies, which are the most mature but not scaled commercially in the industry yet.

Table 11. Estimated CCS Cost in China (Cai, Li, and Zhang 2021)

CCS	Technology	2025	2030	2035	2040	2050	Unit
Capturing Cost	Pre-combustion	16-30	14-20	11-12	8-11	5-8	$USD/t
	Post-combustion	36-48	29-43	25-34	16-28	12-23	$USD/t
	Oxy-combustion	47-74	25-60	20-50	17-36	14-23	$USD/t
Transportation Cost	Truck	0.14-0.22	0.12-0.2	0.11-0.19	0.09-0.17	0.08-0.17	$USD/t-km
	Pipeline	0.12	0.11	0.09	0.08	0.07	$USD/t-km
Storage cost		7.8-9.3	6.2-7.8	5.4-6.2	4.7-5.4	3.9-4.7	$USD/t

CCUS challenges in China's steel industry
The development of CCUS in China's steel industry faces several challenges. While China has about 36 CCUS demonstration projects either in operation or under construction as of 2021 (Cai, Li, and Zhang 2021), most of the CCUS applications are in EOR, enhanced coal-bed methane recovery, and the power sector. Steel industry CCUS applications are limited in scope (i.e., focusing on utilization) and scale, as discussed earlier.

Technically, CCUS projects may require additional energy to operate the CO_2 capturing and compressing system. The increased energy demand can be a technical challenge to integrate the CCS system onsite as well as a financial challenge to procure or produce green energy. CCU processes that can turn CO_2 emissions into valuable products often require green hydrogen for chemical conversion. Securing green hydrogen (whether producing, transporting, or outsourcing it) can be difficult for some steel plants. In addition, some steel plants, especially the ones located in Southern China or central China, may face longer CO_2 transportation needs to find suitable geological storage sites.

Financially, both CCU and CCS projects currently have high costs. Without a clear market signal on carbon or mitigation efforts, steel companies are reluctant to invest in CCUS projects.

Significant investment and policy support need to be provided to accelerate the research and development of CCUS technologies, ranging from innovation, testing, validating, piloting to scaling up. Clear market incentives need to be provided and innovative business models need to be encouraged to reduce the risks and costs associated with CCUS projects in the steel industry. For CO_2 storage, site selection needs to be robust to minimize environmental risks, such as CO_2 leakage (Cai et al. 2017).

7 Action Plan and Recommendations

Decarbonization of heavy industries like the steel industry is a challenging task and can be capital intensive. To overcome barriers and avoid the misallocation of investments and capital lock-in in technologies that will not meet the needs of future climate, regulatory, and market environments, a clear action plan is needed. The following section presents suggested actions for governments, steel manufacturers, and other stakeholders to unlock investments in breakthrough production routes for low-carbon steel.

Suggested actions for the Chinese government
While the policy mix to support the transition towards net-zero carbon emissions in the steel industry may vary across countries and jurisdictions, the transition is unlikely to happen at the speed required without government intervention. The following subsection briefly discusses the possible actions the Chinese government can take to accelerate the transition toward a net-zero carbon steel industry.

Near-Term:

- **Discourage installation of any new blast furnaces (BFs) in China**. There will be a substantial increase in domestic steel scrap availability in China even in the near term (by 2030) that could replace the need for construction of new BFs. Instead, there will be a need to build new EAF steelmaking plants.
- **Discourage the relining of BFs as much as possible** and encourage installation of H_2-DRI or H_2-ready DRI plants to produce iron from iron ore.
- **Improving energy efficiency, coupled with reducing air pollution:** Government (NDRC and MEE) can develop policies to promote near-term investment in energy efficiency and ultra-low emissions retrofits, such as incentives for energy efficiency investment, requirements for retrofit ready built, and sunset clauses to strengthen energy efficiency in the steel industry (IEA, 2022).
- **Improving scrap quality and availability through a better recycling system**: Government (NDRC, MIIT, and MOF) can encourage and support the development of steel recycling through dissemination of recycling technology, developing scrap recycling standards, and providing tax benefits and incentives for scrap collection and sorting to recycling facilities.
- **Developing a hydrogen metallurgical action plan:** The government by working with the iron and steel industry association (CISA) and steel companies, can establish a clear hydrogen metallurgical action plan for the steel industry, including the development of an industry alliance or coalition on hydrogen's industrial applications to promote the development of hydrogen DRI, incentives for the steel industry to use hydrogen, and ensure the supply and transportation of hydrogen in the steel industry.
- **Establishing CO_2 or GHG emission standards**: Government (CNIS) can establish CO_2 or GHG emission standards for key steel products. Emission standards can be set as carbon (or CO_2 equivalent) intensity thresholds per unit of steel product. Such standards can provide a long-term signal to incentive technology breakthroughs to drive down emissions.
- **Accelerating tech-to-market in low-carbon steel technologies:** Government (NDRC, MIIT, and MOF) can enhance technological development by subsidizing low-carbon steel production.

- **Expanding Emissions Trading System:** Government (MEE and CNIS) can expand the current Emissions Trading System (ETS) to include the iron and steel industry, supported by the implementation of emission accounting, reporting, and verification systems (IEA,2022).
- **Building capacity for low-carbon iron and steelmaking technologies development and deployment**. Government should work closely with the steel industry in China and provide support for RD&D needed to develop domestic low-carbon iron and steelmaking technologies and deploy them at large scale. Currently DRI and H_2-DRI ironmaking technology is done by a few international companies. China needs to develop its domestic capacity needed for a large-scale deployment of these technologies at home.
- **Cross-sector policy alignment:** Government can consider cross-sector policy linkages and implications to support the steel industry's energy transition. Power sector decarbonization, hydrogen production and supply, as well as the design and use of steel products will have a significant impact on the steel industry. An integrated policy framework can be achieved by implementing supply-side policy instruments like Green Purchase Agreements (PPA) and demand-side technology options like energy storage and power-to-hydrogen, liquid fuels, or chemicals technologies (Wyns et al., 2019).

Mid-to-Long Term:

- **Relocating integrated steel mills:** The central government (NDRC, MEE, and MOF) can work with local governments to identify priority areas for the relocation of integrated mills, and provide incentives and financing support to attract integrated steel mills to regions with rich renewable resources.
- **Encouraging interprovincial waste circulation after 2030:** The central government (MEE) can also consider encouraging interprovincial waste circulation between eastern provinces and western provinces, as scrap availability increases in coastal regions after 2030-2040.
- **Guided phase out of blast furnaces:** Government (NDRC and MEE) can provide policy support to guide the transition of integrated steel mills in China, such as requirements and incentives on phasing out blast furnaces, job training and replacement support, and incentives to the local governments.
- **Creating a market for low-carbon steel:** The central government (NDRC and CNIS), working with the iron and steel industry association (CISA) can create a market for Near Zero emission steel using Near Zero mandates, regulations on carbon content, and programs like certification and product stewardship (IEA,2022). Programs such as green public procurement (GPP) of cleaner/low-carbon steel for government-funded infrastructure projects should be considered.
- **Increasing awareness of material efficiency:** Government (NDRC and MIIT) can increase the awareness of material efficiency strategies by collaborating with steel consumers, such as construction companies, engineering firms, and design companies to develop and disseminate guidebooks and best practice technologies.
- **Incentivizing material efficiency:** Government (MOF) can incentivize material efficiency through tax systems, i.e., increasing taxes on material extraction, use, or disposal (CLG Europe, 2017), or creating mandatory standards for material efficiency and recycled content (CLG Europe,2017).

- **Providing financial support on innovation and rollout of new zero-carbon technologies:** Government (NDRC, MOST, and MOF) can provide financial support for the building of pilot plants and demonstration of the implementation of innovative decarbonization technologies.
- **Piloting, testing, and validating industry-scale CCUS projects:** Government can play an important role in piloting and validating CCUS technologies in the iron and steel industry to showcase technologies, demonstrate performance, and provide examples for successful business cases.
- **Establishing tech-to-market partnerships:** Government can establish and/or facilitate partnerships between government, industry, research institutes, and academia to foster research in the field of low-carbon steel production technologies, as well as supporting stakeholder collaborations between final material users, technology suppliers, and trade unions to facilitate the rollout of the low-carbon technologies (IEA, 2022).
- **Stimulate investment in low-carbon technologies:** Government can stimulate investment in low-carbon technologies by providing direct public funding (IEA 2022); facilitating access to public and private sector funds aligned with innovations for energy decarbonization (CLG Europe, 2017); establishing mechanisms like low-interest loans or blended finances to encourage private sector spending in breakthrough production routes for low-carbon steel; providing sustainable investment schemes and taxonomies (IEA, 2022).

Suggested actions for steel companies

The steel manufacturing industry can complement government efforts to accelerate the decarbonization of steel production. There are various strategies industry stakeholders (suppliers and buyers) can adopt to facilitate the transition toward low-carbon steel production.

Near Term:

- **Continue to improve energy efficiency:** Steel companies can continue improving energy efficiency, through adoption of technologies such as waste heat recovery and smart manufacturing technologies, especially in the sintering/pelletizing, steel making, and steel casting and rolling processes.
- **Implement standards on life-cycle emissions for steel products:** Steel companies can work with the industry association (CISA) and standardization agencies (CNIS) to track and document the life-cycle emissions of key steel products, using China's national and/or industry standards. This will not only prepare the steel companies for future expansion of China's ETS, but will also provide experience and necessary inputs to refine and improve emission standards.
- **Consider adopting emission labels for key steel products:** Internationally recognized emissions labeling such as Environmental Product Declaration (EPDs) can be considered. In May 2022, China's *Iron and Steel Industry Environmental Product Declaration (EPD) Platform* was launched, organized by CISA and Baowu Steel. On the platform, several steel companies have published their product EPDs, including Baowu Steel, Shanxi TaiSteel, and Ma'anshan Steel. More steel companies can consider joining the platform in the near term. This platform can also facilitate downstream companies to understand the environmental impacts of purchased steel products and support public and private green procurement. Also, methane emissions from coal mining are important and should be seriously considered in Scope 3 emissions .

Mid-to-Long Term:

- **Establishing an industry hydrogen metallurgical alliance:** An industry alliance on hydrogen metallurgy can support the research and development (R&D), piloting, testing, and verification of key technologies to reduce risks, demonstrate technology performance, and accelerate the technology commercialization process.
- **Adopting smart manufacturing and digital technologies:** Steel companies can invest and adopt smart manufacturing and digital technologies, such as sensors and controls, to improve operational efficiency, upgrade production processes, improve production yields, and reduce material and energy losses.
- **Investing in product innovation and upgrades**: Steel companies can invest in developing low-carbon, high-strength steel products which can last longer with higher performance and improve material efficiency in end-use applications.
- **Developing pilot projects on carbon capture, utilization, and storage (CCUS)**: Steel companies can consider developing pilot CCUS projects, especially CCU, within the steel industry to identify potential applications, test technology performance, and better understand scalability and costs.
- **Initiating partnerships and collaborative research projects**: Steel companies can initiate partnerships with research institutes, academia, think tanks, and other stakeholders to develop business cases for decarbonization technologies (CLG Europe, 2017), explore the potential for cross-cutting decarbonization technologies for near-term options (Hasanbeigi et al.,2017), conduct techno-economic analyses of currently commercially available and emerging decarbonization technologies by collaborating with research institutes and academia, build pilot plants to demonstrate low-carbon technologies, and research the multiple benefits of decarbonization technologies (Hasanbeigi et al., 2017).
- **Tracking and monitoring emerging technologies:** Steel companies can closely track and monitor new technology developments, such as iron ore electrolysis, either through an aqueous process or molten oxide electrolysis.
- **Exploring business and technology cases on CCUS with other industries:** Steel companies can explore potential business and technology opportunities in the area of CCUS, especially working with other industries, such as exploring the synergies between the steel and chemical industry, steel industry and building materials industry, and others.

Suggested actions for steel consumers

A large share of steel produced in China is consumed for construction, automotive manufacturing, and electrical and optical equipment manufacturing (ADB, 2022). Steel consumers from these industry sectors can leverage their buying power to induce a low-carbon transition in the steel manufacturing industry.

The government is typically one of the leading consumers of iron and steel. Government can leverage its buying power to support the transition of steel manufacturing towards low-carbon steel by implementing green procurement policies (GPP) (Hasanbeigi et al. 2021, 2022).

Near-Term:

- Government can set clear targets, criteria, and timeframes for reducing embedded carbon in the steel procured for the infrastructure projects followed by an open or restricted tendering process identifying the suppliers.

- Government can mandate the submissions of Environmental Product Declarations (EPDs) to enter the tendering process for infrastructure projects.

Mid-to-Long Term:

- Government can encourage the publication of information on the life-cycle-costing of steel.
- The progress towards achieving targets can be assured by setting monitoring and reviewing mechanisms.

Companies that belong to the construction, automotive, and electronics and electrical equipment manufacturing sectors in the Chinese industry sector can significantly contribute to the low-carbon steel transition by fostering the market for low-carbon steel products. Companies can adopt green procurement policies and set demand signals to induce the transition towards low-carbon steel manufacturing.

Near-Term:

- Companies can set voluntary emissions reduction targets (industry targets, project targets, or product targets) to encourage industrywide carbon emissions monitoring.
- Steel consumers can track embodied carbon data and encourage compliance from the supplier using tools like EPDs.
- Direct demand signal – An agreement can be signed between a steel supplier and buyer which provides certainty needed for the supplier to invest in a breakthrough production route to produce low-carbon steel.

Mid-to-Long Term:

- Steel consumers can design financial or non-financial incentive programs to encourage low-carbon steel production.
- Future purchase commitment by buyers – Although this signal does not guarantee a purchase from a particular supplier, it indicates the willingness of the steel buyers to invest in low-carbon steel, thus, encouraging the suppliers to produce low-carbon steel. These commitments should, however, be made public and ideally aggregated with the commitments from producers.
- Indirect demand signals are indirect commitments to reduce carbon emissions sent by a broader pool of organizations such as investors, funds, or end-use markets (ETC 2021).

Suggested actions for other stakeholders

The low-carbon transition of steel manufacturing can also be supported by other stakeholders like technology/equipment suppliers and public utilities.

Near Term:

- Technology manufacturers can collaborate with government entities to disseminate techno-economic information to steel manufacturers
- Technology suppliers can collaborate with academia, think tanks, and steel manufacturers to develop energy-efficient and low-carbon technologies for steel production.

Mid-to-Long Term:

- Technology manufacturers can develop pilot plants for the demonstration of innovative low-carbon technologies and disseminate the results.

In conclusion, our analysis shows that China's iron and steel industry can significantly reduce its CO_2 emissions by mid-century, reducing 96% by 2050 compared to the 2020 level, under the Net-Zero Emissions Scenario. This scenario is technologically achievable with mostly commercialized technologies such as scrap-based EAF and DRI-EAF production, and near-commercialization technologies such as green H_2-DRI. Our results show that switching from BF-BOF production to scrap-EAF production route would have the largest contribution to CO_2 reduction, followed by demand reduction and fuel switching, electrification of heating, and electricity grid decarbonization.

Achieving the results shown in the Net-Zero Emissions scenario requires unprecedented uptake of low-carbon technologies, ranging from aggressive energy efficiency improvements to large-scale adoption of commercialized technologies, switching to secondary steel manufacturing, and significantly increase the use of lower-carbon fuel in China's iron and steel industry.

In the near term, we recommend that the Chinese government continue to strengthen energy efficiency through benchmarking, retrofits, and incentives; while improving steel products' recycling system to increase scrap quality and availability. The Chinese government should be ahead of the companies by providing standards and policy guidance, in terms of carbon emission standards for steel products and hydrogen applications in metallurgy. Steel companies, while continue pursuing energy efficiency, need to consider implementing life-cycle emission standards as well as emission labels for their steel products.

In the mid-term, the government should plan and guide the industry adjustments, especially in terms of phasing out blast furnaces and relocating steel mills to match local renewable resources. The Chinese government can also leverage market forces and set up green public procurement (GPP) programs for steel to incentivize low-carbon steel production. Steel companies in the mid-term will face even higher pressure and competition to adopt low-carbon technologies. We recommend steel companies join an industry group or a public-private partnership to have access to the latest development in technologies (H_2 DRI, CCUS, smart manufacturing, etc.) and policies. We recommend steel companies develop pilots and demonstration programs to use, test, and further improve low-carbon iron and steelmaking technologies.

We suggest that the Chinese government provide financial, regulatory, and policy support on technology innovation, in the areas of investing in high-risk and high-return breakthrough technologies, developing tech-to-market programs, and encouraging technology pilots, tests, and validation.

References

Abu Dhabi National Oil Company (ADNOC). 2017. "ADNOC and Masdar's Carbon Capture Facility Holds Key to Limiting Industrial CO_2 Emissions." 2017. https://www.adnoc.ae:443/en/news-and-media/press-releases/2017/adnoc-and-masdars-carbon-capture-facility-holds-key-to-limiting-industrial-co2-emissions.

Abdul Q., Shamsuddin A., DawalS.Z., Nukman Y. "Present needs, recent progress and future trends of energy-efficient Ultra-Low Carbon Dioxide (CO_2) Steelmaking (ULCOS) program". Renewable and Sustainable Energy Reviews., 2016.

ArcelorMittal, 2022. Low-carbon emissions steel standards.

ArcelorMittal. 2021. "ArcelorMittal Expands Partnership with Carbon Capture and Re-Use Specialist LanzaTech through US$30 Million Investment l." December 9, 2021. https://corporate.arcelormittal.com/media/press-releases/arcelormittal-expands-partnership-with-carbon-capture-and-re-use-specialist-lanzatech-through-us-30-million-investment/.

Argus. 2021. "China Hydrogen Alliance Seeks 100 GW Renewable Capacity." 2021. https://bit.ly/3mYhOfh.

Asian Development Bank (ADB), 2022. People's Republic of China: Input-Output Economic Indicators. https://data.adb.org/dataset/peoples-republic-china-input-output-economic-indicators

Bai, Yujie. 2022. "First National Hydrogen Development Plan Announced." Caixin. 2022. https://www.caixin.com/2022-03-23/101859866.html.

Bataille, C, Seton Stiebert, and Francis G.N. Li. 2021. "Global Facility Level Net-Zero Steel Pathways." The Institute for Sustainable Development and International Relations. http://netzerosteel.org/wp-content/uploads/pdf/net_zero_steel_report.pdf.

Cai, Bofeng, Qi Li, and Xian Zhang. 2021. "China Carbon Dioxide Capture, Utilization, and Storage (CCUS) Annual Report (2021)."

Cai, Bofeng, Qi Li, Guizhen Liu, Lancui Liu, Taotao Jin, and Hui Shi. 2017. "Environmental Concern-Based Site Screening of Carbon Dioxide Geological Storage in China." Scientific Reports 7 (1): 7598. https://doi.org/10.1038/s41598-017-07881-7.

Carruth, Mark A., Julian M. Allwood, and Muiris C. Moynihan. 2011. "The Technical Potential for Reducing Metal Requirements through Lightweight Product Design." *Resources, Conservation and Recycling* 57 (December): 48–60. https://doi.org/10.1016/j.resconrec.2011.09.018.

Chen, Ji, Shuyi Li, and Agnes Li. 2021. "Pursuing Zero-Carbon Steel in China." RMI. 2021. https://rmi.org/insight/pursuing-zero-carbon-steel-in-china/.

China Baowu News. 2022. "Breakthrough in Injecting Hydrogen in Blast Furnaces from China Iron and Steel Research Institute." February 8, 2022. https://i.xpaper.net/baowu/news/6763/41616/205441-1.shtml.

China EV100. 2020. "China Hydrogen Industry Development Report 2020."

China Government Website. 2021. "The 14th Five-Year Plan for Economic and Social Development and Long-Range Objectives through the Year 2035." March 13, 2021. http://www.gov.cn/xinwen/2021-03/13/content_5592681.htm.

China Government Website. 2022. "Industry Sector Carbon Peaking Action Plan." 2022. http://www.gov.cn/zhengce/zhengceku/2022-08/01/content_5703910.htm.

China Hydrogen Alliance. 2019. "China Hydrogen Energy and Fuel Cell Industry White Paper."

China Iron and Steel Association (CISA). 2022. China Iron and Steel Industry "Dual Carbon" Vision and Technological Roadmap. August 15.

China Metallurgical News. 2021. "Scrap Plays a Significant Role in Achieving "Dual Carbon" Goals." December 31, 2021. http://www.csteelnews.com/xwzx/djbd/202112/t20211231_58318.html.

China Steel News. 2020. "Representative Feng Shuling Suggested Reducing High Cost Is a First Priority for EAF Steel Development." June 2, 2020. http://www.csteelnews.com/xwzx/djbd/202006/t20200602_32784.html.

CLG Europe, Cambridge University. 2017. Forging a carbon-neutral heavy industry by 2050: How Europe can seize the opportunity.

China National Institute of Standardization (CNIS). 2020. "Overview of National Standards on Hydrogen Quality in China." 2020. https://www.cnis.ac.cn/bydt/kydt/202001/t20200102_49207.html.

COURSE50. 2021a. "Message | COURSE50." COURSE50 |. February 25, 2021. https://www.course50.com/en/message/.

COURSE50. 2021b. "Technologies to reduce CO_2 emissions. February 25, 2021. https://www.course50.com/en/technology/technology01/.

CSteel News. 2021. "Jianlong DRI Project." April 13, 2021. http://www.csteelnews.com/xwzx/hydt/202104/t20210413_49101.html.

Dahowski, R. T., X. Li, C. L. Davidson, N. Wei, J. J. Dooley, and R. H. Gentile. 2009. "A Preliminary Cost Curve Assessment of Carbon Dioxide Capture and Storage Potential in China." Energy Procedia 1 (1): 2849–56. https://doi.org/10.1016/j.egypro.2009.02.058.

Deng, Xue, Hewu Wang, Haiyan Huang, and Minggao Ouyang. 2010. "Hydrogen Flow Chart in China." International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2010.03.051.

Dong, Kai, and Xueliang Wang. 2019. "CO_2 Utilization in the Ironmaking and Steelmaking Process." Metals 9 (3): 273. https://doi.org/10.3390/met9030273.

Dong, Yu, Xue Cui, Xunzhi Yin, Yang Chen, and Haibo Guo. 2019. "Assessment of Energy Saving Potential by Replacing Conventional Materials by Cross Laminated Timber (CLT)—A Case Study of Office Buildings in China." *Applied Sciences* 9 (5): 858. https://doi.org/10.3390/app9050858.

Duncan Kushnir, Teis Hansen Valentin Vogl Max Åhman. "Adopting hydrogen direct reduction for the Swedish steel industry: A technological innovation system (TIS) study". Journal of Cleaner Production, 2020.

Durant, C.F., Skelton, A.C.H., Drewniok, M.P., Cullen, J.M., and Allwood, J.M. 2019. "A marginal abatement cost curve for material efficiency accounting for uncertainty". *Resources, Conservation & Recycling* 144: 39-47, https://doi.org/10.1016/j.resconrec.2019.01.020

Eberhardt, Leonora Charlotte Malabi, Harpa Birgisdóttir, and Morten Birkved. 2019. "Life Cycle Assessment of a Danish Office Building Designed for Disassembly." *Building Research & Information* 47 (6): 666–80. https://doi.org/10.1080/09613218.2018.1517458.

Editorial Board of China Iron and Steel Industry YearbookNational Bureau of Statistics (NBS). 2021. China Iron and Steel Yearbook 2021.

Energy Transition Commission (ETC). 2018. Reaching zero carbon emissions from steel.

Energy Transition Commission (ETC). 2021. Steeling Demand: Mobilizing buyers to bring net-zero steel to market before 2030.

European Commission, 2016. Buying Green! A handbook on green public procurement.

Global Steel Plant Tracker, Global Energy Monitor, March 2022 release.

Global CCS Institute. 2022. “Facilities - Global CCS Institute.” 2022. https://co2re.co/FacilityData.

Guo, Daqing, and Yao Zhang. 2021. “How to Solve Scrap Industry’s Taxation Challenge?” MySteel. December 16, 2021. https://news.mysteel.com/21/1216/07/22293A10F35B4B23.html.

Guo, Haibo, Ying Liu, Wen-Shao Chang, Yu Shao, and Cheng Sun. 2017. “Energy Saving and Carbon Reduction in the Operation Stage of Cross Laminated Timber Residential Buildings in China.” *Sustainability* 9 (2): 292. https://doi.org/10.3390/su9020292.

H2weilai. 2021. “2021 China Green Hydrogen Industry Current Status and Development Prospect.”

Hasanbeigi, Ali (2022). Steel Climate Impact - An International Benchmarking of Energy and CO_2 Intensities. Global Efficiency Intelligence, LLC.

Hasanbeigi, Ali; Shi, Dinah; Bhadbhade, Navdeep (2022). Advancing Buy Clean Policy in Canada. Global Efficiency Intelligence, LLC.

Hasanbeigi, Ali; Astrid Nilsson, Gökce Mete, Germain Fontenit; Shi, Dinah (2021). Fostering Industry Transition through Green Public Procurement: A “How to” Guide for the Cement & Steel Sectors.

Hasanbeigi A., Kirshbaum L.A., Collison B., Gardiner D. 2021. Electrifying U.S. Industry: A technology and process-based approach to decarbonization. Global Efficiency Intelligence. David Gardiner & Associates.

Hasanbeigi, A.; Arens, M.; Price, L. (2013). Emerging Energy Efficiency and CO_2 Emissions Reduction Technologies for the Iron and Steel Industry. Berkeley, CA: Lawrence Berkeley National Laboratory BNL-6106E.

Hebei Government. 2021. “The Notice on the First List of CCUS Pilot Projects in Hebei Province.” http://hbepb.hebei.gov.cn/hbhjt/zwgk/fdzdgknr/zdlyxxgk/ydqhbh/tan-shichang/101620801516065.html.

Hertwich, Edgar G., Saleem Ali, Luca Ciacci, Tomer Fishman, Niko Heeren, Eric Masanet, Farnaz Nojavan Asghari, et al. 2019. “Material Efficiency Strategies to Reducing Greenhouse Gas Emissions Associated with Buildings, Vehicles, and Electronics—a Review.” *Environmental Research Letters* 14 (4): 043004. https://doi.org/10.1088/1748-9326/ab0fe3.

International Energy Agency (IEA). 2019. “The Future of Hydrogen: Seizing Today’s Opportunities.” https://doi.org/10.1016/S1464-2859(12)70027-5.

International Energy Agency (IEA). 2020. “Iron and Steel Technology Roadmap.” October 2020. https://www.iea.org/reports/iron-and-steel-technology-roadmap.

International Energy Agency (IEA). 2020b. Energy technology Perspectives 2020.

International Energy Agency (IEA). 2020c. Global CO_2 emissions in 2019. Available at https://www.iea.org/articles/global-co2-emissions-in-2019

International Energy Agency (IEA). 2021. “Global Hydrogen Review 2021.” https://doi.org/10.1787/39351842-en.

International Energy Agency (IEA). 2022. Achieving Net Zero Heavy Industry Sectors in G7 Members.

Intergovernmental Panel on Climate Change (IPCC). 2022. “Summary for Policymakers. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.” https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/.

International Energy Net. 2021. “The First Hydrogen Metallurgy Demonstration Project in the World Began Construction.” May 14, 2021. https://www.in-en.com/article/html/energy-2304270.shtml.

Japan Iron and Steel. 2021c. “Vision | Carbon Neutrality.” Carbon Neutrality. March 2, 2021. https://www.zero-carbon-steel.com/en/vision/.

Japan Iron and Steel Federation (JISF). 2022a. Recommended technologies for energy-saving, environmental protection and recycling in Indian iron and steel industry- Part 1: BF-BOF.

Japan Iron and Steel Federation (JISF). 2022b. Recommended technologies for energy-saving, environmental protection and recycling in Indian iron and steel industry- Part 2: EAF

Katharina Rechberger, Andreas Spanlang, Amaia Sasiain Conde, Hermann Wolfmeir. “Green Hydrogen-Based Direct Reduction for Low-Carbon Steelmaking”. Steel Research International. 2020.

Kuramochi, Takeshi. 2016. “Assessment of Midterm CO_2 Emissions Reduction Potential in the Iron and Steel Industry: A Case of Japan.” Journal of Cleaner Production, Absolute Reductions in Material Throughput, Energy Use and Emissions, 132 (September): 81–97. https://doi.org/10.1016/j.jclepro.2015.02.055.

Massachusetts Institute of Technology (MIT). 2016. “Carbon Capture and Sequestration Technologies @ MIT.” 2016. https://sequestration.mit.edu/tools/projects/esi_ccs.html.

Material Economics. 2019. “Industrial Transformation 2050 - Pathways to Net-Zero Emissions from EU Heavy Industry.” https://materialeconomics.com/publications/industrial-transformation-2050.

McKinsey and Company, 2019. How should steelmakers adapt at the dawn of the EAF mini-mill era in China?

Midrex, 2017. Ultimate Low CO_2 Ironmaking and its place in the new Hydrogen Economy. https://www.midrex.com/tech-article/midrex-h2-ultimate-low-co2-ironmaking-and-its-place-in-the-new-hydrogen-economy/

Ministry of Industry and Information Technology. 2022. “Guiding Opinions on Promoting High Quality Development of China’s Steel Industry.” 2022. http://www.gov.cn/zhengce/zhengceku/2022-02/08/content_5672513.htm.

Ministry of Industry and Information Technology. 2022. “Guiding Opinions on Promoting High Quality Development of China’s Steel Industry.” 2022. http://www.gov.cn/zhengce/zhengceku/2022-02/08/content_5672513.htm.

Ministry of Science and Technology. 2021. "100,000 Tonnes Steel Slag Utilization and Carbon Sequestration Demonstration Project Implemented in Baotou." June 8, 2021. https://www.most.gov.cn/dfkj/nmg/zxdt/202106/t20210608_175104.html.

Mission Possible Partnership. 2021. "Net-Zero Steel Sector Transition Strategy." https://missionpossiblepartnership.org/wp-content/uploads/2021/10/MPP-Steel_Transition-Strategy-Oct19-2021.pdf.

Myllyvirta, Lauri, Xing Zhang, and Tom Prater. 2022. "Analysis: What Do China's Gigantic Wind and Solar Bases Mean for Its Climate Goals?" Carbon Brief. May 3, 2022. https://www.carbonbrief.org/analysis-what-do-chinas-gigantic-wind-and-solar-bases-mean-for-its-climate-goals/.

National Bureau of Statistics (NBS). 2022. China Energy Statistical Yearbook 2021. China Statistics Press. Beijing, China.

National Development and Reform Commission (NDRC) and National Energy Administration (NEA). 2022. "Hydrogen Industry Development Mid-Long Term Plan (2021-2035)."

NE21. 2022. "Baowu Steel Zhanjiang Steel Began Constructing the First Million Tonne-Level Hydrogen Shaft Furnace." February 18, 2022. https://www.ne21.com/news/show-168307.html.

Nicholas, S. and Basirat, S. 2022. Solving Iron Ore Quality Issues for Low-Carbon Steel- Technology Solutions Are Under Development.

Nippon Steel. 2022. "Execution of Joint Study Agreement Regarding Capturing and Transporting Liquefied Carbon Dioxide (CO_2) to Offshore Floating CO_2 Capture and Storage Hub Project." 2022. https://www.nipponsteel.com/en/news/20220214_100.html.

Nishioka, Koki, Yutaka Ujisawa, Shigeaki Tonomura, Natsuo Ishiwata, and Peter Sikstrom. 2016. "Sustainable Aspects of CO_2 Ultimate Reduction in the Steelmaking Process (COURSE Project), Part 1: Hydrogen Reduction in the Blast Furnace." Journal of Sustainable Metallurgy 2 (3): 200–208. https://doi.org/10.1007/s40831-016-0061-9.

Organisation for Economic Co-operation and Development (OECD) (2021), Government at a Glance 2021, OECD Publishing, Paris, https://doi.org/10.1787/1c258f55-en.

Rissman, J., C. Bataille, E. Masanet, N. Aden, W. Morrow, N. Zhou, N. Elliott, R. Dell, N. Heeren, B. Huckestein, J. Cresko, S. Miller, J. Roy, P. Fennel, B. Cremmins, T. Blank, D. Hone, E. Williams, S. de la Rue du Can, B. Sisson, M. Williams, J. Katzenberger, D. Burtraw, G. Sethi, H. Ping, D. Danielson, H.Y. Lu, T. Lorber, J. Dinkel, and J. Helseth. 2020. "Technologies and Policies to Decarbonize Global Industry". *Applied Energy*, Vol 26, May, https://doi.org/10.1016/j.apenergy.2020.114848

Scottish Carbon Capture & Storage. 2022. "Al Reyadah Details." 2022. https://www.geos.ed.ac.uk/sccs/project-info/622.

Shangguan, Fangqin, Xiuping Li, Jicheng Zhou, Fangjie Wang, Qingcai Bu, and Chunxia Zhang. 2020. "Strategic research on development of steel scrap resources in China." Iron and Steel 55 (6): 8–14. https://doi.org/10.13228/j.boyuan.issn0449-749x.20190427.

Shougang Group. 2022. "Overview of Green and Low-Carbon Development of Shougang Jingtang." June 27, 2022. https://www.shougang.com.cn/sgweb/wap/sgyw/20220627/8091.html.

Sina Finance. 2022. "The Development of Secondary Steelmaking Is Important for the Steel Industry to Achieve Carbon Peaking." August 9, 2022. https://finance.sina.com.cn/money/future/roll/2022-08-09/doc-imizmscv5496089.shtml.

Stockholm Environment Institute (SEI). 2022. Green Steel Tracker. https://www.sei.org/projects-and-tools/tools/green-steel-tracker/

Stockholm Environmental Institute (SEI). 2018. Hydrogen steelmaking for a low-carbon economy. https://cdn.sei.org/wp-content/uploads/2018/09/hydrogen-steelmaking-for-a-low-carbon-economy.pdf

Tan, L. 2022. "First year highlights of the national carbon market", Feb 18. https://chinadialogue.net/zh/3/75074/

Tenova. 2020. "First Hydrogen Based ENERGIRON DRI Plant for Tenova in China." 2020. https://tenova.com/newsroom/press-releases/first-hydrogen-based-energiron-dri-plant-tenova-china.

Thyssenkrupp. 2020. "Carbon2Chem®: First Project Phase Successfully Completed and Notice of Funding Received from Federal Government for Second Phase." Thyssenkrupp. 2020.

Thyssenkrupp. 2021. "Injection of Hydrogen into Blast Furnace: Thyssenkrupp Steel Concludes First Test Phase Successfully." Thyssenkrupp. February 3, 2021. https://www.thyssenkrupp-steel.com/en/newsroom/press-releases/thyssenkrupp-steel-concludes-first-test-phase-successfully.html.

Toshiba International Corp, and Tongfang Environment. 2015. "Applying Carbon Capture and Storage to a Chinese Steel Plant: Feasibility Study on a CCS Facility for Shougang Jingtang United Iron & Steel Company's Caofeidian Steel Plant, China." https://www.globalccsinstitute.com/archive/hub/publications/195933/Applying%20carbon%20capture%20and%20storage%20to%20a%20Chinese%20steel%20plant.pdf.

US Energy Information Administration (US EIA). 2022. Energy consumption in China. https://www.eia.gov/international/analysis/country/CHN

United Nations Environmental Program (UNEP). 2020. Emissions Gap Report 2020.

Verheul, Bente. 2019. "Overview of Hydrogen and Fuel Cell Developments in China." Holland Innovation Network in China, no. January.

Vog, V., Åhman, M. J.Nilsson, L.2018. "Assessment of hydrogen direct reduction for fossil-free steelmaking". Journal of Cleaner Production.

Wang, W. 2017. 2019 China Steel Association unit steelmaking Technical review

Wang, Y.Q. Zhao, A. Babich, D. Senk, X.Y. Fan. "Hydrogen direct reduction (H-DR) in steel industry—An overview of challenges and opportunities". Journal of Cleaner Production. 2021.

Wang, Zhenbang. 2022. "Initiating Ceremony of Hydrogen-Rich Carbon Circulation Blast Furnace Test Was Held in Bagang Steel." 2022. https://www.ts.cn/zxpd/zl/bygt/202207/t20220708_7878456.shtml.

Worldsteel Association. 2020. Steel production process.

World Steel Association (worldsteel). 2021. Steel statistical yearbook 2020. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://worldsteel.org/wp-content/uploads/Steel-Statistical-Yearbook-2020-concise-version.pdf

World Steel Association (worldsteel). 2022. World steel in figures. https://worldsteel.org/steel-topics/statistics/world-steel-in-figures/

Worrell, E. et al. 2010. Energy efficiency improvement and Cost Saving Opportunities for the U.S. Iron and Steel Industry. An ENERGY STAR. ®. Guide for Energy and Plant Managers.

Wübbeke, Jost, and Timo Heroth. 2014. "Challenges and Political Solutions for Steel Recycling in China." Resources, Conservation and Recycling 87 (June): 1–7. https://doi.org/10.1016/j.resconrec.2014.03.004.

Wyns et. al., (2019), Industrial Transformation 2050 – Towards an Industrial Strategy for a Climate Neutral Europe, IES. Available at ies.be.

Xingtai Iron and Steel Company. 2017. "Launching Low-Carbon Hydrogen-Rich Ironmaking Technology Retrofit Project." 2017. http://www.xingtai.gov.cn/ywdt/jrxt/xtyw/201705/t20170523_239531.html.

Xinhua Net. 2021. "The Largest PV-Green Hydrogen Project of the World Is in Kuqa, Xinjiang." November 30, 2021. http://www.xinhuanet.com/energy/20211130/7d7a74ef-f26a4641ad692f3e9a2e73a7/c.html

Xuan, Yanni, and Qiang Yue. 2016. "Forecast of Steel Demand and the Availability of Depreciated Steel Scrap in China." Resources, Conservation and Recycling 109 (May): 1–12. https://doi.org/10.1016/j.resconrec.2016.02.003.

Zahra, Dr Mohammad Abu. 2015. "Perspective from Emirates Steel Project/UAE."

Zhang, Shaohui, Ernst Worrell, Wina Crijns-Graus, Fabian Wagner, and Janusz Cofala. 2014. "Co-Benefits of Energy Efficiency Improvement and Air Pollution Abatement in the Chinese Iron and Steel Industry." Energy 78 (December): 333–45. https://doi.org/10.1016/j.energy.2014.10.018.

Zhao, Qinghua, and Ming Chen. 2011. "A Comparison of ELV Recycling System in China and Japan and China's Strategies." Resources, Conservation and Recycling 57 (December): 15–21. https://doi.org/10.1016/j.resconrec.2011.09.010.

Zhao, Xuan. 2022. "The Role of Hydrogen Energy Storage." Caixin. 2022. https://www.caixin.com/2022-04-20/101873665.html.

Zhong Shaoliang. 2020. "Hydrogen in China's Steel industry." worldsteel.org (blog). September 16, 2020. https://worldsteel.org/zh-hans/media-centre/blog/2020/hydrogen-technology-momentum-chinese-steel-industry/.

Zhou, Nan, Hongyou Lu, Nina Khanna, Xu Liu, David Fridley, Lynn Price, Bo Shen, et al. 2020. "China Energy Outlook: Understanding China's Energy and Emissions Trends."

Zhou, Nan, Lynn Price, Dai Yande, Jon Creyts, Nina Khanna, David Fridley, Hongyou Lu, et al. 2019. "A Roadmap for China to Peak Carbon Dioxide Emissions and Achieve a 20% Share of Non-Fossil Fuels in Primary Energy by 2030." Applied Energy 239 (April): 793–819. https://doi.org/10.1016/j.apenergy.2019.01.154.

Chen, Wenguang. 2021. "2021 Research on hydrogen Industry Chain in China", LeadLeo Research Institute, July.

Appendices

Appendix 1. List of acronyms

BF	blast furnace
BOF	basic oxygen furnace
CDQ	coke dry quenching
CISA	China Iron and Steel Association
CNIS	China National Institute of Standardization
CO_2	carbon dioxide
DRI	direct-reduced iron
EAF	electric arc furnace
EIA	Energy Information Administration (U.S. Department of Energy)
GHG	greenhouse gas
GJ	gigajoule
IEA	International Energy Agency
IPCC	Intergovernmental Panel Climate Change
kton	kilo tonne (1000 metric tonne)
MJ	megajoule
MEE	Ministry of Ecology and Environment
MIIT	Ministry of Industry and Information Technology
MOF	Ministry of Finance
MOST	Ministry of Science and Technology
Mt	million metric tonne
NDRC	National Development and Reform Commission
TRT	top-pressure recovery turbine