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Technical Development and Prospect for Collaborative Reduction of Pollution and Carbon Emissions from Iron and Steel Industry in China

Tingyu Zhu[a,b,*], Xiaolong Liu[a], Xindong Wang[d], Hong He[b,c]

[a] CAS Key Laboratory of Green Process and Engineering, Institute of Process Engineering, Innovation Academy for Green Manufacture, Chinese Academy of Sciences, Beijing 100190, China
[b] Center for Excellence in Regional Atmospheric Environment, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China
[c] State Key Joint Laboratory of Environment Simulation and Pollution Control, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China
[d] HBIS Group Co., Ltd., Shijiazhuang 050023, China

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ABSTRACT

As the largest steel-producing country, China's steel industry has experienced rapid development in terms of production level and quality. Owing to the high consumption of coal in the iron and steel industry, air pollutants and carbon dioxide (CO_2) show similar emission properties in flue gas. In view of the collaborative reduction of pollution and carbon emissions, the emission standards for pollutants and carbon were first analyzed, suggesting that carbon emission standards for the iron and steel industry should be accelerated. A collaborative technology system for the reduction of pollution and carbon emissions from the iron and steel industry in China is demonstrated, consisting of ① optimization of present ultra-low emission technology, ② low-carbon innovation for present production processes, ③ steel production process reengineering, and ④ carbon capture, utilization, and storage (CCUS). Finally, the technical prospect for collaborative reduction of pollution and carbon emissions from the iron and steel industry in China is suggested to support high-quality green development in this industry.

1. Introduction

The iron and steel industry plays an important role in the national economy, providing raw materials, energy, and technical equipment necessary for production, as well as a wide variety of consumer goods for daily life. In China, it is recognized as a significant contributor to the construction of a complete industrial system [1]. Industrial-scale iron and steel production first emerged in the United Kingdom in the 1620s and 1870s, respectively. The United States surpassed the United Kingdom with the highest steel production in 1890 and became the largest country in terms of gross domestic product (GDP) in 1894. The Soviet Union and Japan became the countries with the highest steel production in 1971 and 1993, respectively. Crude steel production in China overtook Japan in 1996, exceeding 1.000×10^8 t, and it is the primary steel producer in the world to date. In 2021, China's crude steel production reached 1.033×10^9 t, accounting for 53% of the global production (Fig. S1 in Appendix A) [2].

The resource endowment of more coal and less oil/gas in China determines its energy structure, which is dominated by coal [3], accounting for 57% of the primary energy structure in 2020. In view of controlling crude steel production and reducing energy consumption in China [4], coal consumption in the iron and steel industry has fluctuated but remained at a high level in recent years. As shown in Fig. S2 (a) in Appendix A, the coal consumption of the iron and steel industry reached 6.7×10^8 t in 2020. The massive consumption of coal fuels also results in the emission of large amounts of air pollutants, which cause serious harm to the environment by aggravating the destruction of the ozone layer and destroying the ecological balance [5]. Owing to the production characteristics of high coal consumption, pollution and CO_2 show similar emission properties in the flue gas from the iron and steel industry [6]. Considering the wide applications of flue gas pollution control [7], Fig. S2(b) in Appendix A shows that the total emission amounts of the three major conventional pollutants (particle matter (PM), sulfur dioxide (SO_2), and nitrogen oxides (NO_x)) from the

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* Corresponding author.
E-mail address: tyzhu@ipe.ac.cn (T. Zhu).

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iron and steel industry in China decreased from 4.19×10^6 t in 2016 to 1.54×10^6 t in 2020, achieving a significant reduction. However, the air quality still does not meet the interim targets-1 of the World Health Organization (WHO). Considering the serious harm to human health caused by air pollution, China has devoted significant efforts to reducing flue gas pollution [8]. In contrast, CO_2 emissions from China's steel industry have been increasing annually, reaching 1.81×10^9 t in 2020, accounting for approximately 15%–18% of the total carbon emissions in China [9].

Over the past 20 years, the development of the iron and steel industry in China can be divided into three stages: capacity expansion, focusing on pollution but ignoring carbon, and reducing pollution and carbon. ① Capacity expansion: In 2001–2011, crude steel production in China quadrupled. With the rapid development of the steel industry, flue gas pollution has become poorly controlled, resulting in an annual increase in air pollution emissions. ② Focusing on pollution but ignoring carbon: Before the implementation of the ultra-low emission policy, China's standards were formulated by referring to foreign standards and considering its own situation, while the ultra-low emission policy was independently formulated by China based on its own environmental needs. Aiming at the high pollution emission of the sintering and pelletizing processes [7], the former Ministry of Environmental Protection issued *Emission standard of air pollutants for sintering and pelletizing of iron and steel industry* (GB 28662–2012) [10] in 2012, and increasing attention started to be given to the flue gas pollution control in the iron and steel industry. Significant efforts have been devoted to dedusting and desulfurization [11], whereas denitrification has rarely been considered. In the Government Work Report of 2018, the then Premier Li Keqiang promised to "promote ultra-low emissions in steel and other industries." Henceforth, certain steel enterprises have begun to conduct ultra-low emission projects, and denitrification technologies have been developed [12]. In April 2019, five ministries and commissions jointly issued the *Opinions on promoting the implementation of ultra-low emissions in the iron and steel industry*, leading to the beginning of ultra-low emissions for industrial flue gas. China's steel industry has been slow to reduce its carbon emissions [13]. In comparison, developed countries such as those in Europe and the United States started their carbon reduction work earlier, showing the technological tendency of "Focusing on carbon rather than pollution" [14]. Short-process steelmaking by electric furnaces accounts for 43.9% in Europe and 69.2% in the United States, and carbon emissions have been significantly reduced compared to long-process steelmaking [15]. However, their pollutant emission standards are significantly more lenient than those of China. High concentrations of steel production in particular areas of China lead to high regional emission intensity and apparent environmental problems. Hence, the Chinese government is more concerned with the reduction of flue gas pollutants such as PM, SO_2, and NO_x. After the implementation of ultra-low emissions, the pollutant emission intensity in China's steel industry was greatly reduced, which was significantly lower than that of the European Union (EU). However, two tonnes of CO_2 are emitted during one tonne of steel production from blast furnace-converter long process in China (2.0 t/t-steel), which is similar to that of EU. In contrast, CO_2 emission from short process in China is approximately 0.9 t/t-steel, which is significantly higher than that of EU (~0.6 t/t-steel). This is mainly because of the widespread use of molten iron in the electric furnace process in China [16]. China has the largest scale iron and steel industry, whereas the amount of steel scrap is still far from sufficient to support the development of the short-process industry. Under the strictest ultra-low emission limits, China has shown a typical tendency of "Focusing on pollution but ignoring carbon" over time. ③ Reducing pollution and carbon: In September 2020, during the general debate of the 75th session of the UN General Assembly, President Xi Jinping proposed that China would strive to minimize carbon dioxide emission and achieve carbon neutrality. In March 2021, the China's State Council mentioned that they collaboratively promote the "reduction of pollution and carbon emissions" in *The outline of the 14th Five-Year Plan for national economic and social development and long-rang objectives through the year of 2025*. The Ministry of Ecology and Environment of the People's Republic of China also proposed "taking ultra-low emissions as the key point and collaboratively promoting the reduction of pollution and carbon emissions." This is the first time China and even the world have placed "pollution" and "carbon" on a comparable level, and it is of great significance for the construction of the ecological environment in China.

From the perspective of collaborative reduction of pollution and carbon emissions, emission standards for air pollution and carbon from the iron and steel industry in China were analyzed. Technical progress in the reduction of pollution and carbon emissions was demonstrated, and future development prospects were suggested to promote high-quality green development of the iron and steel industry in China.

2. Emission standards for pollution and carbon from the iron and steel industry in China

The iron and steel industry is a multi-process metallurgical system consisting of sintering, pelletizing, coking, blast furnaces, converters, steel rolling, and so forth. The emission characteristics and standards vary for different processes and are summarized in Fig. 1. For sintering and pelletizing processes, which account for the highest proportion of pollution emissions in the steel industry, the former Ministry of Environmental Protection issued *Emission standard of air pollutants for sintering and pelletizing of iron and steel industry* (GB 28662–2012) [10] in 2012, with special emission limits (referred to as "SELs") for PM, SO_2, and NO_x of 40, 180, and 300 $mg{\cdot}m^{-3}$, respectively. In 2018, the Government Work Report set a goal to "promote the ultra-low emission in steel and other industries," and then Hebei Province took the lead in publishing *Ultra-low emission standards for air pollutants in iron and steel industry* (DB 13/2169–2018) [17]. The Ultra-Low-Hebei (referred to as "ULH") limits for PM, SO_2, and NO_x are 10, 35, and 50 $mg{\cdot}m^{-3}$, respectively. In April 2019, five ministries jointly issued the *Opinions on promoting the implementation of ultra-low emissions in the iron and steel industry* (referred to as "National Opinions"), in which the Ultra-Low-National (referred to as "ULN") limits for PM, SO_2, and NO_x were 10, 35, and 50 $mg{\cdot}m^{-3}$, respectively. In the local standard of Hebei Province, the emission limits were calculated based on 16% O_2 for the sintering and pelletizing processes, which differed from those in the National Opinions, where the emission limits for the chain grate-rotary kiln and belt roaster pelletizing plants were calculated based on 18% O_2. For the sintering process, the ultra-low emission limits for SO_2 and NO_x in China are significantly stricter than those in the EU and Japan [18,19].

For the coking process, the SELs for PM, SO_2, and NO_x in coke oven flue gas were 15, 30, and 150 $mg{\cdot}m^{-3}$ in the *Emission standard of pollutants for coking chemical industry* (GB 16171–2012) [20], and the ULN limits for PM, SO_2, and NO_x were 10, 30, and 150 $mg{\cdot}m^{-3}$ respectively. In September 2018, Hebei Province published the first ultra-low emission standard for coking processes in China, issued as *Local standards for ultra-low emission of air pollutants from the coking chemical industry* (DB 13/2863–2018) [21], in which the ULH limits for PM, SO_2, and NO_x were 10, 30, and 130 $mg{\cdot}m^{-3}$, respectively, and the emission limit for NO_x was further decreased.

For the blast furnace ironmaking process, the SELs for PM, SO_2, and NO_x in the hot blast furnace flue gas were 15, 100, and 300 $mg{\cdot}m^{-3}$, respectively, while the ULN limits were reduced to

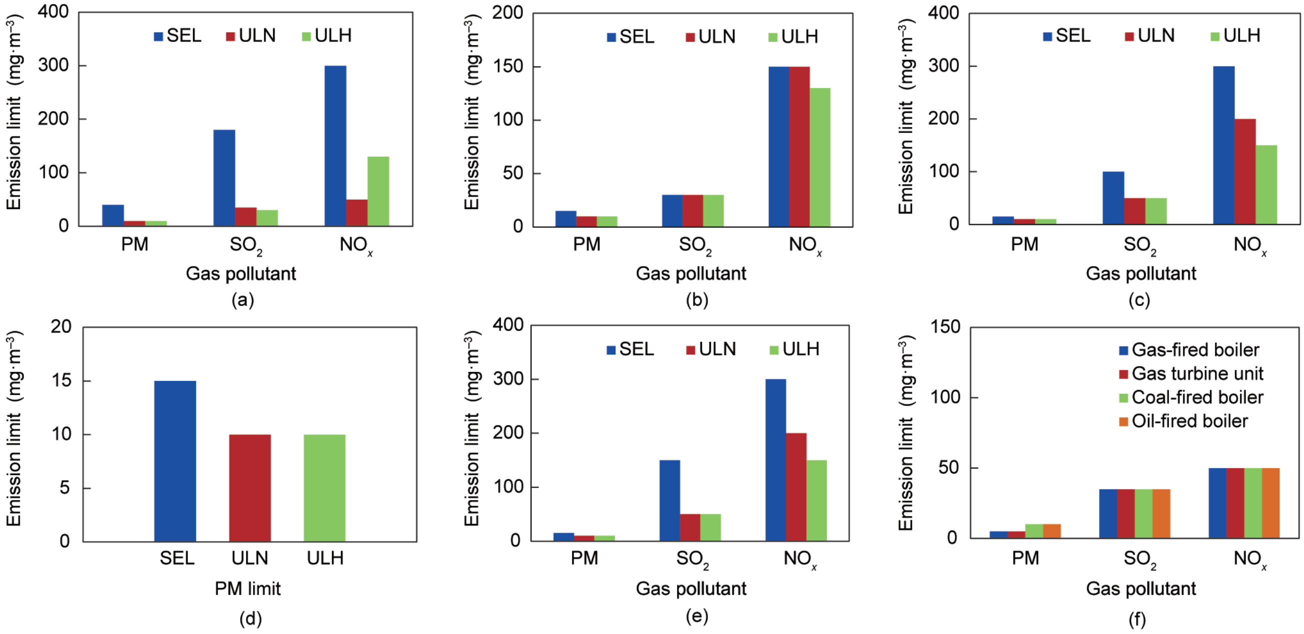


Fig. 1. Emission limits for PM, SO_2, and NO_x from the main processes in the iron and steel industry: (a) sintering/pelletizing; (b) coke oven; (c) hot air furnace for blast furnace; (d) secondary flue gas from converter; (e) heat treatment furnace for steel rolling; and (f) different types of captive power plants (unlike the other processes, only the ULN limits are shown in this figure). SEL: special emission limit; ULN: Ultra-Low-National; ULH: Ultra-Low-Hebei.

10, 50, and 200 mg·m^{-3}, respectively. The ULH limits were 10, 50, and 150 mg·m^{-3}, respectively, and the NO_x limit was stricter.

In addition, SO_2 and NO_x were absent from the secondary flue gas of the converter steelmaking industry, with PM as the main pollutant. The SEL for PM in the *Emission standard of air pollutants for steel smelt industry* (GB 28664–2012) [22] was 15 mg·m^{-3}, while the later published ULN and ULH limits both decreased to 10 mg·m^{-3}.

For steel rolling heat treatment furnaces, the SELs for PM, SO_2, and NO_x in the *Emission standard of air pollutants for steel rolling industry* (GB 28665–2012) [23] were 15, 150, and 300 mg·m^{-3}, respectively, while the ULN limits decreased to 10, 50, and 200 mg·m^{-3}, respectively. The ULH limits were the most stringent at 10, 50, and 150 mg·m^{-3}.

For different types of captive power plants in the steel industry, National opinions also set the requirements separately; the ULN for flue gas PM, SO_2, and NO_x were 5, 35, and 50 mg·m^{-3} for gas-fired boilers and gas turbine units, respectively, and 10, 35, and 50 mg·m^{-3} for coal-fired boilers and oil-fired boiler flue gas, respectively. In addition, there were differences in the discounted oxygen for different types of boiler/wheel units.

It is noteworthy that the National Opinions did not state clear requirements for non-conventional pollutants, such as dioxins, fluoride, volatile organic compounds (VOCs), and heavy metals. According to *Emission standard of air pollutants for sintering and pelletizing of iron and steel industry* (GB 28662-2012) and the *Emission standard of air pollutants for steel smelt industry* (GB 28664–2012), the SEL for dioxins in sintering and electric furnace flue gas adopts a value of 0.5 ng toxic equivalent quantity per cubic meter (TEQ·m^{-3}), which is the same as before. The *Emission standard of air pollutants for steel rolling industry* (GB 28665–2012) also proposed specific special emission limits for various pollutants such as fluoride, VOCs, and heavy metals in the heat treatment furnace, pickling unit, and waste acid regeneration, respectively.

In terms of establishing carbon emission standards, China has significantly lagged behind developed countries, such as Europe and the United States. Government departments from 12 countries, including the United Kingdom, the United States, Japan, and the Republic of Korea, are actively developing product carbon labelling systems [24]. China has released two batches of low-carbon product certification catalogues involving seven products each. However, steel products were not included in either of these batches. The steel industry in China is still in the early stages of developing low-carbon product certification and establishing a carbon labelling system. The International Organization for Standardization (ISO) published a number of standards in the field of carbon emissions. For example, the ISO/TC207/SC7 Committee published ISO 14067:2018 *Greenhouse gases—carbon footprint of products—requirements and guidelines for quantification.* ISO/TC17 published ISO 14404-1 *Calculation method of carbon dioxide emission intensity from iron and steel production—Part 1: converter steelmaking* and other standards. China has published a series of standards, such as *Requirements of the greenhouse gas emission accounting and reporting—Part 5: iron and steel production enterprise* (GB/T 32151.5–2015) [25], *Technical specification at the project level for assessment of greenhouse gas emission reductions—utilization of waste energy in iron and steel industry* (GB/T 33755–2017) [26], and *Technical specification for green house gas emission verification of iron and steel production enterprises* (RB/T 251–2018) [27]. However, problems such as poor systematization and imperfect systems make it difficult to effectively support the implementation of carbon emission reduction in the iron and steel industry. Hence, the development of carbon emission standards should be accelerated to support the high-quality green development of the iron and steel industry in China.

3. Collaborative technology system for reduction of pollution and carbon emissions from iron and steel industry in China

Steel production is a multiscale, heterogeneous, and long process system. In the material flow, 65% is exported in the form of steel products, and the remaining 35% is exported in the form of wastewater, flue gas, solid waste, and chemical by-products. The migration of energy and mass is very complicated, with a large amount of unused waste heat. In technical development, the traditional idea of "single process and single component control" should be replaced by "overall optimization" [7]: ① whole flow control: the processes, including sintering, pelletizing, coke oven, blast furnace, and converter, should be fully covered; ② whole process control: with the gradual increase in the pressure of terminal control, source and process emission reduction technology with the deep integration of environmental protection and production has attracted increasing attention [28]; and ③ whole component control: the steel industry emits conventional pollutants such as PM, SO_2, and NO_x; unconventional pollutants such as VOCs, dioxins, and Hg; and greenhouse gases such as CO_2 [29,30]. It is difficult to satisfy the increasing requirements of single-component control [31].

As shown in Fig. 2, four paths are proposed for the collaborative reduction of pollution and carbon emissions from the iron and steel industry in China: ① optimization of the present ultra-low emission technology; ② low-carbon innovation in present production processes; ③ steel production process re-engineering; and ④ carbon capture, utilization, and storage (CCUS).

3.1. Optimization of present ultra-low emission technology

During the 13th Five-Year Plan period, the steel industry in China implemented a wide range of ultra-low emission technologies [32,33]. To meet the increasingly strict emission limits, present ultra-low emission technologies have greatly broadened the technical boundary value with extensive energy and material consumption [34]. Throughout the entire life cycle technology evaluation, the carbon incremental effect has gradually become prominent [35,36]. It is estimated that the full implementation of ultra-low emissions in the steel industry will cause a carbon increment of nearly $8.0 \times 10^7\ \text{t}\cdot\text{a}^{-1}$, among which reheating in medium–low temperature selective catalytic reduction (SCR) denitrification results in $5.0 \times 10^7\ \text{t}\cdot\text{a}^{-1}$, accounting for more than 60% of the total carbon increment (carbon increment refers to the increase in CO_2 emissions caused by energy consumption and other indirect CO_2 emissions from purification devices). The drawback of the carbon increase for traditional pollution control technology is that it is difficult to meet the requirements of collaborative control [37].

In view of the carbon increment caused by the implementation of ultra-low emissions, three novel technologies have been proposed, including blast furnace gas desulfurization, CO oxidation coupled with medium–low temperature SCR denitrification for sintering flue gas, and embedded denitrification for pelletizing flue gas [38,39].

3.1.1. Blast furnace gas desulfurization

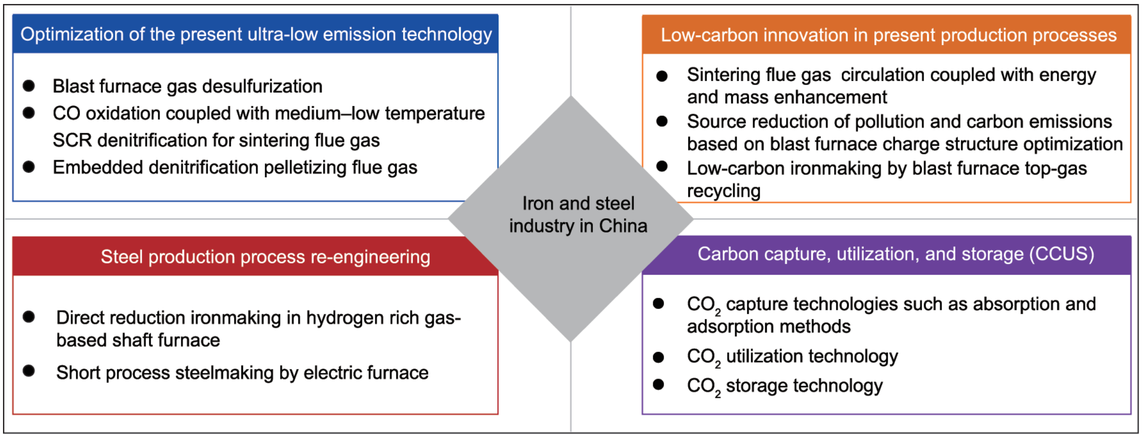
The total sulfur concentration of blast furnace gas is 100–200 $\text{mg}\cdot\text{m}^{-3}$, organic sulfur is mainly carbonyl sulfide (COS) with a small amount of carbon disulfide (CS_2), and inorganic sulfur is mainly hydrogen sulfide (H_2S) [40–42]. COS accounts for more than 70% of the total sulfur content in blast furnace gas, but its chemical properties are relatively stable [43]. Purified blast furnace gas is used as fuel for hot air, heat treatment, and self-provided power furnace combustion without desulfurization to achieve source emission reduction in the steel industry. As shown in Fig. S3 in Appendix A, blast furnace gas desulfurization can be divided into two sections: catalytic hydrolysis of COS and absorption of H_2S [44]. The hydrolysis catalyst is the core component of the desulfurization process [45]. There are nearly 1000 blast furnaces in China, of which less than 5% have undergone desulfurization, and the inactivation of hydrolysis catalysts is the biggest problem. The inactivation mechanism is extremely complicated and includes sulfate deposition caused by O_2 oxidation and chlorine (Cl) poisoning [46,47]. Currently, the entire industry is at a critical stage. After catalytic hydrolysis, various dry or wet methods can be used for H_2S purification, which is relatively mature [48,49].

In 2022, the Institute of Process Engineering, Chinese Academy of Sciences built a pilot plant with a gas flow of 2000 $\text{m}^3\cdot\text{h}^{-1}$ in a 2922 m^3 blast furnace in HBIS Group Tangsteel Company. The catalytic hydrolysis tower was equipped with wet and dry desulfurization processes. The COS hydrolysis efficiency was greater than 99.8%, with H_2S removal efficiency above 90.0% and total sulfur emission below 15.0 $\text{mg}\cdot\text{m}^{-3}$. To date, the pilot operation has been stable, and the demonstration project design for the 2922 m^3 blast furnace has been promoted.

Additionally, adsorption methods have received increasing attention. Molecular sieves have been regarded as promising adsorbents owing to their large specific surface areas, excellent thermal stabilities, and outstanding regeneration cycles. In the adsorption process, COS and H_2S were first adsorbed onto the molecular sieves. After adsorption saturation, the adsorbed sulfur species were dissociated from the adsorbent surface and transformed into sulfur during the regeneration process, realizing the desulfurization of blast furnace gas [50].

3.1.2. CO oxidation coupled with medium–low temperature SCR denitrification for sintering flue gas

The purification technologies for sintering flue gas include the activated carbon method [51], low temperature oxidation-absorption [52,53], and semi-dry desulfurization with medium–low temperature SCR denitrification [54,55]. Among them, semi-dry desulfurization with medium–low temperature SCR denitrification has gradually become the most successful technology for sintering flue gas purification owing to its high purification efficiency, excellent system stability, and synergistic removal of


Optimization of the present ultra-low emission technology
- Blast furnace gas desulfurization
- CO oxidation coupled with medium–low temperature SCR denitrification for sintering flue gas
- Embedded denitrification pelletizing flue gas

Low-carbon innovation in present production processes
- Sintering flue gas circulation coupled with energy and mass enhancement
- Source reduction of pollution and carbon emissions based on blast furnace charge structure optimization
- Low-carbon ironmaking by blast furnace top-gas recycling

Iron and steel industry in China

Steel production process re-engineering
- Direct reduction ironmaking in hydrogen rich gas-based shaft furnace
- Short process steelmaking by electric furnace

Carbon capture, utilization, and storage (CCUS)
- CO_2 capture technologies such as absorption and adsorption methods
- CO_2 utilization technology
- CO_2 storage technology

Fig. 2. Collaborative technology system for reduction of pollution and carbon emissions from the iron and steel industry in China.

dioxins, accounting for more than 70% of practical applications [10]. During medium–low temperature SCR denitrification operation, a hot blast stove must be used to raise the temperature of the flue gas by 30–60 °C through heat exchange, which consumes a large amount of blast furnace gas [56]. However, there are still significant issues that need to be addressed.

- A large amount of blast furnace gas is consumed during denitrification.
- High concentrations of CO (~8000 mg·m^{-3}) in flue gas are emitted without purification [57].

The above drawbacks lead to a technical contradiction by requiring the consumption of a large amount of CO-rich blast furnace gas and meanwhile emitting abundant CO pollutants. The high heat consumption value of CO makes it a potential source for energy reuse [58]. The consumption heat of CO is 283 kJ·mol^{-1}. Taking a 360 m^2 sintering machine as an example, the flue gas flow was approximately 1.4 × 10^6 Nm^3·h^{-1}. When the CO concentration was 8000 mg·m^{-3}, the annual CO emissions were approximately 90 000 t. Based on the heat consumption of CO, it can be converted into 2.40 × 10^8 m^3 blast furnace gas. The heat released from CO oxidation to CO_2 can lead to a temperature increase in the flue gas of approximately 60 °C, which is consistent with the requirement of the heat supplement by the hot blast stove. Therefore, when a CO reactor is installed in front of the SCR denitrification reactor (Fig. 3), the consumption of blast furnace gas can be replaced by the catalytic oxidation of CO from the flue gas for the heat supplementation of medium–low temperature SCR denitrification, resulting in saving of energy. However, existing CO catalysts are rapidly deactivated in sintering flue gas. Therefore, this technology has not yet been applied in practice and remains under investigation.

A CO oxidation catalyst is the core of this technology. Catalysts are divided into transition/rare earth metal oxide catalysts and noble metal catalysts [59,60]. Transition/rare earth metal oxide catalysts (Co, Cu, Mn, Ce, etc.) [61–63] are greatly affected by their physical and chemical properties, such as the active components, microstructure, and exposed crystal plane. There are still several limitations to the thermal stability, sulfur, and water resistance. Compared to other active species, Pt-based catalysts exhibit excellent CO oxidation activity and sulfur resistance [64,65]. Thus, they have been widely used in diesel vehicle exhaust diesel oxidation catalyst (DOC) sections [66]. Despite considering the side reactions of SO_2 oxidation and the scale of catalyst application [67], the development of Pt-based catalysts with ultra-low loading capacity (≤ 0.1 wt%) remains promising. V_2O_5-based catalysts are the most widely used commercial catalysts for SCR denitrification and simultaneous removal of dioxins [68]. By adjusting the contents of V_2O_5 and WO_3, the temperature window of the V_2O_5–WO_3/TiO_2 catalyst can be shifted to a lower temperature region [69,70]. At present, the V_2O_5 content of medium–low-temperature SCR catalysts for sintering flue gases is above 2% [54], and the denitrification efficiency is usually above 85% [71].

3.1.3. Embedded denitrification for pelletizing flue gas

The pellet production process in China consists of three main types: shaft furnace, grate-kiln, and belt roaster [72]. Among them, grate-kilns accounted for more than 60% of the production capacity. Therefore, it is important to develop a low energy consumption and ultra-low emission technology that fits the technical characteristics of the grate-kiln.

In the grate-kiln process, the NO_x-containing flue gas is first emitted from the rotary kiln and then passes through the chain grate preheating (PH) section and the following down-draught drying (DDD) section. Subsequently, it is mixed with the flue gas from the transitional preheating (TPH) section and finally enters the flue gas purification system. The flow amount of flue gas between the PH and DDD was significantly lower than that of the end flue gas, accounting for approximately 60% of the total flue gas emissions. In addition, based on the unique temperature distribution characteristics of the grate-kiln process, the flue gas temperature above the pellet bed in PH is 950–1100 °C, matching the reaction temperature window of selective non-catalytic reduction (SNCR) [73]. The temperature of the flue gas in the bellows of PH is 350–500 °C, which is consistent with the temperature range of SCR denitrification [74].

Based on the temperature distribution characteristics of the grate and the migration tendency of NO_x in the flue gas, an embedded SNCR coupled with SCR denitrification technology for pelleting flue gas is proposed in Fig. 4. Because of the consistency of the flue gas temperature with SNCR and SCR, the embedded denitrification technology does not require a gas–gas heater (GGH) for additional flue gas heating, which is necessary in the conventional medium–low SCR technology. The investment, energy consumption, and operation costs were greatly reduced. Accordingly, carbon emissions from energy consumption also decreased significantly.

In HBIS Xuansteel, two grate-kiln plants with 1.0 × 10^6 and 1.2 × 10^6 t·a^{-1}adopted the technology of embedded SNCR coupled with SCR to achieve a denitrification efficiency above 90%, with NO_x emission below 30 mg·m^{-3}. During operation, additional fuel consumption for heating is no longer required. The denitrification operation cost for one tonne of pellet is approximately 3 CNY, which is significantly lower than that of 10–12 CNY in medium–low temperature SCR denitrification.

3.2. Low-carbon innovation for present production processes

Steel production in China has increased rapidly over the last two decades [2]. The average service life of a blast furnace is only

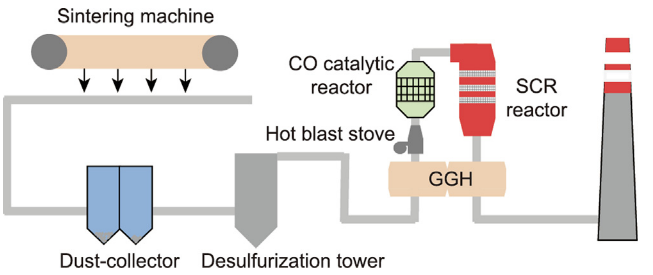


Fig. 3. Process flow chart of CO oxidation coupled with medium–low temperature SCR denitrification for sintering flue gas. GGH: gas–gas heater.

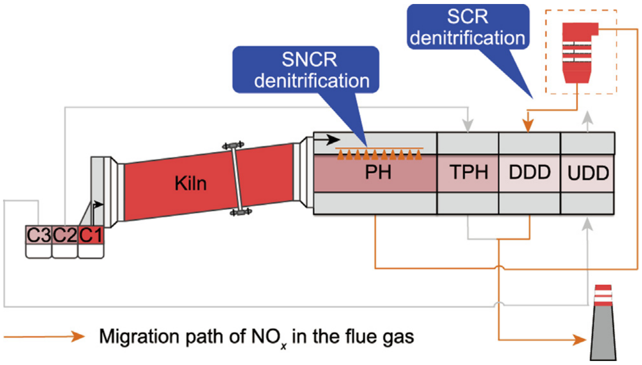


Fig. 4. Process flow chart of embedded denitrification for pelletizing flue gas. C1/C2/C3: the 1st/2nd/3rd section of annular cooler; UDD: up-draught drying.

12–15 years, which is far shorter than the average service life of 40 years [2]. This means that most blast furnaces in China still have 25 years of service until 2050. Moreover, considering the current shortage of steel scrap in China [75], short-process electric arc furnace (EAF) steelmaking will not be widely developed in the near future. The long process of blast-converter will remain dominant for the next 25–30 years.

Assuming a steel production capacity with little change, even if the converter steel was reduced from 90% to 70%, the locked carbon emissions by the long process would still be as high as 1.2×10^9 $t \cdot a^{-1}$. Accordingly, three key technologies have been proposed for the present production processes [76].

3.2.1. Sintering flue gas circulation coupled with energy and mass enhancement

With the wide implementation of ultra-low emissions of sintering flue gas, the pollution reduction capacity has greatly decreased. Traditional "concentration control" is unable to meet the technical needs for deep reduction of flue gas pollution [77], and determining how to continuously achieve the goal of "total amount control" has become a top priority. Considering the problems of large flue gas emissions and low waste heat utilization in sintering production, flue gas circulation coupled with energy and mass enhancement has become the primary technology for realizing flue gas reduction and waste heat utilization [78]. This technology reduces carbon emissions by increasing sintering production and energy efficiency by reducing solid fuel consumption.

In inner circulation technology, bellows with different characteristics, such as high temperature, oxygen-rich, or high concentrations of pollutants, can be selected for optimization [79]. For example, Nippon Steel in Japan developed regional exhaust gas circulation technology, HKM in Germany developed low emission and energy optimized sinter production (LEEP) technology, and Voest-Alpine developed environmental process optimized sintering (Eposint) technology [80]. For these technologies, a portion of the heat-carrying flue gas from the different bellows is selectively collected and returned to the sintering machine, thus recovering a portion of the waste heat of the sintering and reducing the solid fuels. The circulating flue gas also contains NO_x, CO, and dioxins, which can be partially purified [81].

Recently, with the support of the National Key Research and Development Plan Project "Key technologies of whole process control of multiple pollutants from the flue gas in iron and steel industry," the Institute of Process Engineering, Chinese Academy of Sciences and HBIS Group jointly developed technology for sintering flue gas circulation coupled with energy and mass enhancement, as illustrated in Fig. 5. It has been applied in more than ten sintering plants, such as 2×360 and 2×435 m^2 in Hansteel and 3×360 m^2 in Chengsteel. The pollutants of $PM/SO_2/NO_x$ have been further reduced by more than 30% compared to ultra-low emissions. The CO and dioxin emissions were reduced by more than 30%. The CO_2 emissions from fuel consumption can be reduced by more than 15%.

3.2.2. Source reduction of pollution and carbon emissions based on blast furnace charge structure optimization

Compared with the sinter, the pellet exhibits advantages such as smaller flue gas amount, as well as lower pollution and carbon emission intensities [82]. The SO_2, NO_x, and CO_2 emission intensities of the pellets are 1/3–1/2 of those of the sinter (Table S1 in Appendix A). Thus, increasing the proportion of pellets in the blast furnace charge can achieve source reduction of pollution and carbon. The pellet ratios of blast furnaces in European and American countries are above 90%, and those of Swedish Steel AB (SSAB) in Sweden, Ashland steel plant in the United States, and Monclova steel plant in Mexico are 100%, 90%, and 93%, respectively. The pellet ratios in Asian countries are lower, at 12% for Posco Gwangyang in the Republic of Korea, 10% for Nippon Steel in Japan, and an average value of approximately 10% in China.

The energy consumption for one tonne of pellet production is approximately 25 kg coal equivalent (kgce), which is significantly lower than that of sinter production (50 kgce). Therefore, increasing the proportion of pellets in the blast furnace can significantly reduce the pollution—carbon emissions caused by fuel consumption from the iron and steel industry. In the iron-making process, two factors limit the increase of the pellet proportion in the blast furnace. First, the iron concentrates produced in China are commonly SiO_2-rich, and the produced flux pellets show the drawback of low mechanical strength, which must be optimized through doping with MgO additives. In addition, an increase in the pellet proportion in the blast furnace leads to an unstable material surface shape, unbalanced air flow, and high fuel ratio, which should be dealt with in a pellet-majored structure. To ensure stable iron-making, the whole basicity in the blast furnace is commonly stabilized at 1.05–1.20. Hence, conventional acid pellets cannot be used with a high proportion of pellet-major blast furnaces. To meet the basicity requirements in a blast furnace, it is important to develop flux pellets (basicity of 0.8–1.0) and optimize the blast furnace charge structure.

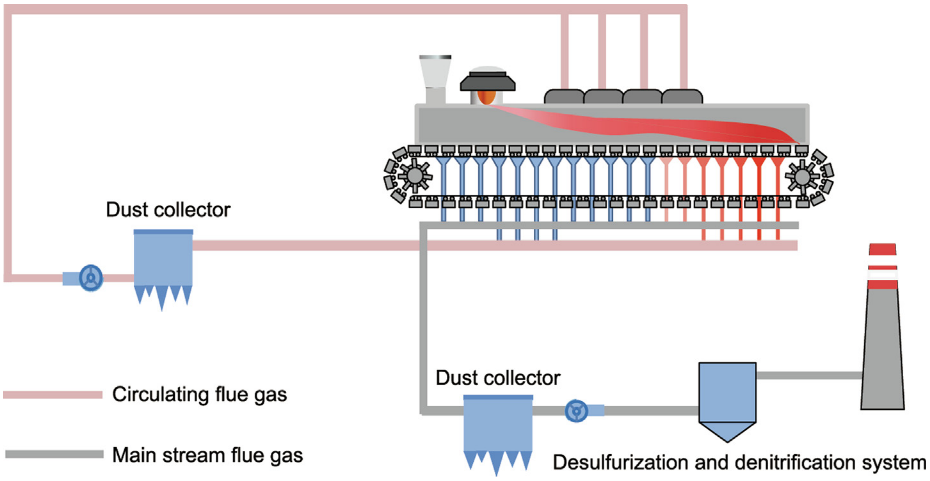


Fig. 5. Process flow chart of sintering flue gas circulation coupled with energy and mass enhancement.

Relying on the National Key Research and Development Plan subject "Technology and demonstration of the source reduction of sulfur and nitrate emission based on the optimization of blast furnace charge structure," HBIS Group has developed key technologies, such as flux pellet production and high-proportion pellets for blast furnace ironmaking, and established a demonstration project on a 450 m^3 blast furnace in Tangsteel. As shown in Fig. S4 in Appendix A, the pellet proportion in the blast furnace increased from approximately 10%–80%, and the emissions of SO_2, NO_x, and CO_2 decreased by 52%, 26%, and 10%, respectively. This has been applied to newly built 2922 m^3 large-scale blast furnaces in Tangsteel.

3.2.3. Low-carbon ironmaking by blast furnace top-gas recycling

As illustrated in Fig. S5 in Appendix A, blast furnace top-gas recycling is a novel strategy that applies vacuum pressure swing adsorption (VPSA) to the blast furnace top gas, thereby removing CO_2, and the purified blast furnace is then circulated for reuse [83,84]. This process consists of three parts: ① CO_2 is isolated and utilized or stored using CCUS technology; ② recycled CO acts as a reducing agent to reduce coke use; and ③ O_2 is used instead of preheated air to avoid the cyclic accumulation of N_2 [85,86].

Many theoretical studies on blast furnace top-gas recycling have been reported [87], but few practical applications have been discussed [88,89]. China Baowu Steel Group Co., Ltd. built a green low-carbon metallurgy experimental platform on a 430 m^3 blast furnace in Bayi Steel, and it exhibits the functions of top-gas recycling, CO_2 separation, and hydrogen-rich metallurgy. Industrial experiments were performed in four steps to achieve a carbon reduction of 30%.

The project has been in operation since 2020, successfully achieving the goals of 35% oxygen-rich smelting in the first period and 50% oxygen-rich smelting in the second period. An industrial test of decarbonized gas circulation and coke oven gas injection was also conducted. When 50% oxygen injection and 200–250 $m^3 \cdot t^{-1}$ coke oven gas were used, the base coke ratio decreased by 30–40 $kg \cdot t^{-1}$, and the fuel ratio decreased by 85–95 $kg \cdot t^{-1}$.

3.3. Steel production process reengineering

In the existing blast furnace ironmaking process, Fe_2O_3 reacts with CO to form Fe and CO_2, which is the most important chemical reaction [90], leading to significant CO_2 emissions [91]. To realize a significant reduction in CO_2, the iron and steel production processes must be reconstructed [92]. Among them, hydrogen metallurgy and short-process electric furnace steelmaking are the two most important technologies in future steel process reengineering systems.

3.3.1. Direct reduction ironmaking in hydrogen rich gas-based shaft furnace

Hydrogen metallurgy is a promising strategy for reducing pollution and carbon emissions in the steel industry [93]. Compared with traditional carbon-based reducing agents, hydrogen has a smaller molecular radius, a stronger diffusion osmotic force, and a reduction rate—5–10 times that of CO, and the reducing product is water [94]. At present, hydrogen metallurgy processes include hydrogen-rich metallurgy in blast furnaces, all-hydrogen metallurgy, and hydrogen-rich gas-based shaft furnaces [87].

For hydrogen-rich metallurgy in blast furnaces, coke furnace and natural gases are injected into the blast furnace to reduce the consumption of coal/coke, other carbon-based reductants, and CO_2 emissions [95]. Although hydrogen-rich metallurgy in blast furnaces can reduce carbon emissions to a certain extent, it can only achieve part of the reductant replacement, and the nature of its carbon metallurgy does not change. It is believed that the CO_2 emission reduction rate cannot easily exceed 20% [96]. The COURSE50 plan in Japan proposes to achieve the target of 30% CO_2 emission reduction in blast furnaces by 2030, in which blast furnace injection and coke oven gas can achieve a 10% CO_2 emission reduction, and the remaining 20% should be achieved through waste heat utilization and CO_2 capture. Hydrogen metallurgy is based on pure H_2 as a reducing agent, such as HYBRIT, all hydrogen-based shaft furnaces in Sweden, and AISI hydrogen flash melting in the United States. Hydrogen metallurgy using circulating fluidized beds (CFBs) is also being explored in China. However, all-hydrogen metallurgy has drawbacks, such as the high cost of pure hydrogen and the strong heat absorption effect of all-hydrogen metallurgy. At present, the proportion of green electricity in China is relatively low, and carbon emissions remain high throughout the process.

For hydrogen rich gas-based shaft furnace, H_2–CO hydrogen-rich gas is used as the reducing agent. Compared with hydrogen-rich metallurgy in blast furnaces, it can eliminate the constraints of coke. Compared to all-hydrogen metallurgy, it can significantly reduce the demand for thermal hydrogen compensation. The EU ultra-low CO_2 steelmaking (ULCOS) [97], Republic of Korea COOLSTAR, Germany SALCOS [98], Austria Steel Union H2FUTURE, and other projects have all adopted the hydrogen-rich gas-based shaft furnace process, which is combined with the short process of the electric furnace, and carbon emission reduction can reach more than 50% [98]. Therefore, direct reduction ironmaking in hydrogen-rich gas-based shaft furnaces has been recognized as the most feasible path for hydrogen metallurgy [99]. At present, the direct reduction of hydrogen-rich gas-based shaft furnaces use natural gas as the gas source, such as the MIDREX and HYL technologies. However, the resource endowment of coal-rich coal, poor oil, and less gas in China has limited their application [100]. In 2021, coke production in China was 4.64×10^8 t, with the by-product coke oven gas reaching 2.00×10^{11} $m^3 \cdot a^{-1}$. Coke oven gas contains 60% H_2 and 25% CH_4 and is suitable as a hydrogen-rich reducing gas. Therefore, the direct reduction process of a hydrogen-rich coke oven gas vertical furnace is expected to become mainstream hydrogen metallurgy technology in China [99].

In May 2021, HBIS began to build a demonstrative project of 1.2×10^6 $t \cdot a^{-1}$ for hydrogen metallurgy in Xuansteel, and it will be put into operation in 2023. This is the first project to use coke oven gas as the hydrogen-rich gas for a shaft furnace (Fig. S6 in Appendix A). Purified coke oven gas was introduced into the shaft furnace to reduce pellets, generating a direct reduction iron (DRI) for the electric furnace to produce high-quality steel.

3.3.2. Short process steelmaking by electric furnace

Electric furnace-based steelmaking is a short process that uses steel scrap as the main raw material for steelmaking, and its CO_2 emissions are only 20%–25% of those from the blast furnace-converter long process (CO_2 emissions from electric furnace are approximately 0.4–0.5 t per tonne of steel, while CO_2 emissions from blast furnace-converter long process are approximately 1.9–2.0 t per tonne of steel) [101]. The development of electric furnace steelmaking can significantly reduce the CO_2 emissions. It is noteworthy that adequate steel scrap resources and low-cost green electricity are crucial for the development of electric furnace steelmaking to gain a competitive advantage over the long process using a blast furnace converter [8].

In 2020, the total steel scrap consumption in China was 220 million tonnes, of which only 30% was used for electric furnaces with 655 kg per tonne of steel consumption. The remaining 70% was used in converters with 156 kg per tonne of steel consumption. Dramatic competition from converters greatly limits the applications of steel scrap in electric furnaces, and there will be a serious shortage of steel scrap for electric furnaces in the near future. In 2020, the crude steel produced by electric furnaces was only 9.6×10^7 t, accounting for 9.1% of the total domestic crude steel production, which was below the world average value of 28% and far lower than that of the United States (70%).

In the last few years, a unique production mode has been developed by adding hot-molten iron to electric furnaces, effectively alleviating the shortage of scrap steel, reducing the consumption of electric energy, shortening the smelting cycle, and improving the production capacity of the electric furnace. However, the addition of hot-molten iron leads to an obvious de-carbon effect and an increase in O_2 consumption, increasing the energy consumption and pollutants of the smelting system. The proportion of molten iron did not exceed 40%. Furthermore, the addition of hot-molten iron significantly increased carbon emissions. Hence, this production mode will likely be gradually abandoned with an increase in the amount of raw materials for electric furnaces.

In recent years, the cumulative stock of crude steel in China has grown by 1×10^9 $t{\cdot}a^{-1}$, and steel scrap production is expected to increase further, reaching 3.3×10^8 t by 2025. In 2021, China opened the import of recycled steel raw materials, which can reduce the demand for steel scrap to a certain extent. In addition, DRI production in China will continue to grow rapidly with the development of non-blast furnace DRI, which can be used as a high-quality raw material for electric furnaces. The gradual increase in steel scrap and DRI will strongly promote the development of electric furnaces (Fig. S7 in Appendix A). In addition, with the wide construction of green and low-carbon power facilities, such as hydro, wind, photovoltaic, and nuclear power, as well as the development of electricity transmission technologies, the green power shortage will be greatly modified.

In January 2022, three ministries and commissions jointly published the *Guidance of promoting high-quality development of the steel industry*, proposing that the crude steel proportion of electric furnaces will increase to more than 15% by 2025. Against the background of "double carbon," the electric furnace steelmaking industry is rapidly developing in China.

In recent years, electric furnaces have continuously been developed. There are approximately 400 electric furnaces in production or under construction in China, of which Consteel accounts has the highest proportion. The horizontal charging structure was used in a Consteel electric furnace with a limited preheating capacity for steel scrap. The steel scrap can only be preheated to 200–300 °C, which is a suitable temperature range for dioxin production [102].

In recent years, new electric furnace technologies, such as Quantum, Ecoarc, and Sharc technology, have been developed with a vertical shaft configuration to improve preheating efficiency [103]. The Quantum furnace has a siphon-type slag-free steel discharge system with elevated preheating temperatures and low hazardous emissions. To date, more than ten plants have been in operation or are under construction worldwide. The steel scrap preheating shaft furnace of an Ecoarc electric furnace is composed of a vertical preheating shaft and directly connected melting chamber. The combination of furnace sealing and scrap preheating allows the scrap to be preheated at temperatures of 800 °C, avoiding dioxin generation with the emission below 0.1 ng $TEQ{\cdot}m^{-3}$. The Sharc electric furnace adopts a direct current, it is designed to use exhaust gas to preheat steel scrap, and the dioxin is below 0.1 ng $TEQ{\cdot}m^{-3}$. At present, in China, only HBIS Shisteel has adopted this technology, and two 130 t electric furnaces were put into operation in 2022.

3.4. Carbon capture, utilization, and storage

CCUS is currently considered a promising option for achieving zero emissions from fossil energy on a large scale [104]. The International Energy Agency (IEA) published a technology roadmap for the iron and steel industry in 2020, predicting that the steel industry will still have 34% of carbon emissions by 2050, after process improvement, efficiency improvement, and raw/fuel substitution [105]. Even if DRI technology is completed, 8% of the carbon emissions remain. CCUS is the most important technology for deep decarbonization in the steel industry [106].

Absorption and adsorption are recognized as the most promising technologies for CO_2 capture [107]. In absorption, organic amines or ammonia are typically employed as absorbents [108]. The first CCUS project for the steel industry in the world was constructed by Emirates Steel in partnership with the Abu Dhabi National Oil Company and Masdar Carbon at a cost of 1.22×10^8 USD, with a CO_2 capture capacity of 8.00×10^5 $t{\cdot}a^{-1}$. A DRI process combined with an electric furnace was applied in this project. The CO_2 generated from the DRI process is first captured by the monoethanolamine (MEA) absorption system and is subsequently transported to a storage site for compression and dehydration. Highly concentrated CO_2 with 98% purity is transported via a 43 km pipeline to the Rumaitha and BAB oil fields in United Arab Emirates, where it is used to improve oil recovery while the injected CO_2 is stored underground. Nippon Steel in Japan has developed the Energy-Saving CO_2 Absorption Process (ESCAP®) low-energy CO_2 separation process, which reduces the energy consumption required to separate and recycle CO_2 by more than 40%. POSCO in the Republic of Korea uses a low concentration of ammonia (less than 10%) as a chemical absorbent to separate CO_2 from blast furnace gas, while recovering the ineffective medium- and low-temperature waste heat from the steel plant as energy for CO_2 regeneration. The desorption temperature of ammonia is approximately 80 °C, which is significantly lower than that of organic amines at 120 °C. Sinosteel in China uses 30% MEA as the absorbent, with a CO_2 recovery rate of more than 95% and an average energy consumption of 5.4 $GJ{\cdot}t^{-1}$ CO_2. In the adsorption method, molecular sieves are typically used as adsorbents to remove CO_2 by VPSA [109]. At present, Pohang in Republic of Korea and JFE in Japan have conducted research on VPSA-based CO_2 separation technology for blast furnace gas. VPSA-based CO_2 adsorption and separation processes are also used in blast furnace top-gas recycling in the EU ULCOS project [110]. To pursue the carbon capture potential, HBIS, Baowu, and Shougang in China have initiated related technology research, but they are still in the preliminary stage.

CO_2 utilization technology refers to the resource utilization of captured CO_2 through chemical and biological processes [111]. The coking industry in China produces a large amount of coke oven gas by-products with the main components of hydrogen (~58%), methane (~24%), and a small amount of carbon monoxide (~6%) [112], which can be used to achieve the goal of "steel-chemical co-production" through the collaborative use of hydrogen resources and CO_2 to prepare a variety of important chemicals such as methanol. In addition, this biological method is expected to be applied to carbon sequestration and utilization in the steel industry. Microalgae carbon [113] sequestration requires a low concentration of CO_2, which can be cultivated by using a large amount of wastewater from the steel smelting process, while removing CO_2 from the flue gas of hot blast furnaces and other processes. The resulting microalgae products can be further transformed into high-value products such as oils, chemicals, soil conditioners, and biofertilizers through downstream processes [114].

CO_2 storage technology refers to the injection of captured CO_2 into deep geological reservoirs for storage [115], which has an enormous reduction capacity. This is recognized as the main strategy for achieving large-scale emission reduction in the CCUS system [116]. China has already conducted demonstration projects at different scales for CO_2 enhanced oil recovery and deep saline water extraction. During the 14th Five-Year Plan period, with the improvement of carbon emission reduction related policies and systems and the formation of business models, the steel and oil/gas industries are expected to jointly complete the first million-tonnes CO_2 enhanced oil recovery demonstration project.

Accordingly, a CCUS system for the iron and steel industry in China is illustrated in Fig. 6. The blast furnace process has the highest proportion of carbon emissions, and CO_2 is separated and purified using adsorption methods such as VPSA. CO_2 in sintering, pelletizing, and coke oven flue gas was separated and purified through absorption, using organic amines as absorbents. Alkaline steel slag can be used for CO_2 mineralization to capture and eliminate CO_2. Highly concentrated CO_2 and H_2 from coke oven gas were used for chemical synthesis. Part of the CO_2 is injected into the converter as a weak oxidant for dephosphorization. The remaining unconsumed CO_2 can be geologically sequestered.

Based on this, a roadmap for the development of CCUS technology in the iron and steel industry in China is shown in Fig. 7. Technology validation will occur by 2025 through breakthroughs in several key technologies. By 2030, based on the advanced maturity and low cost of first-generation capture technologies, more than 1×10^5 t of carbon-capture projects will have been established. By 2035, the scale of carbon capture will have significantly increased to millions of tonnes, and wide applications will be achieved. Projects will be completed for most CO_2 utilization technologies, and a number of geological utilization technologies will become commercially available. By 2040, CO_2 capture technologies will be completely commercial, whereas most CO_2 utilization and storage technologies will be commercially available. By 2050, the CCUS will be fully covered by the steel industry, with the steel industry approaching carbon neutrality. By 2060, the deep

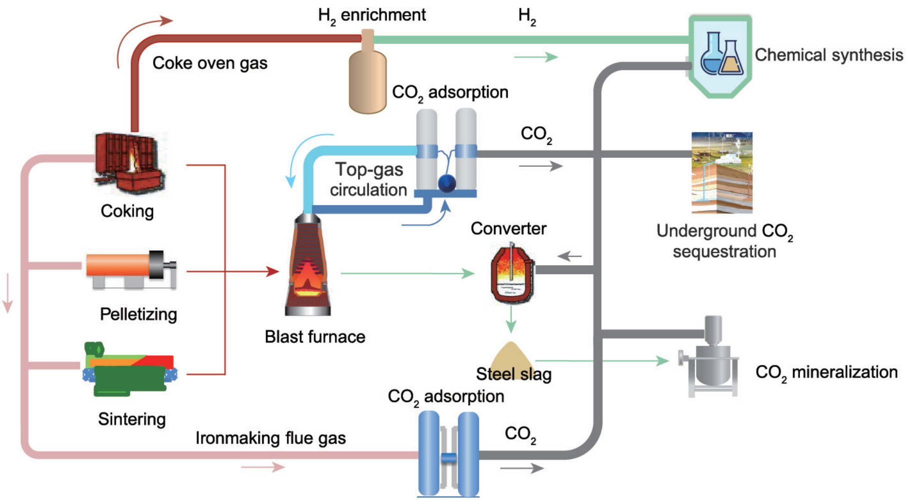
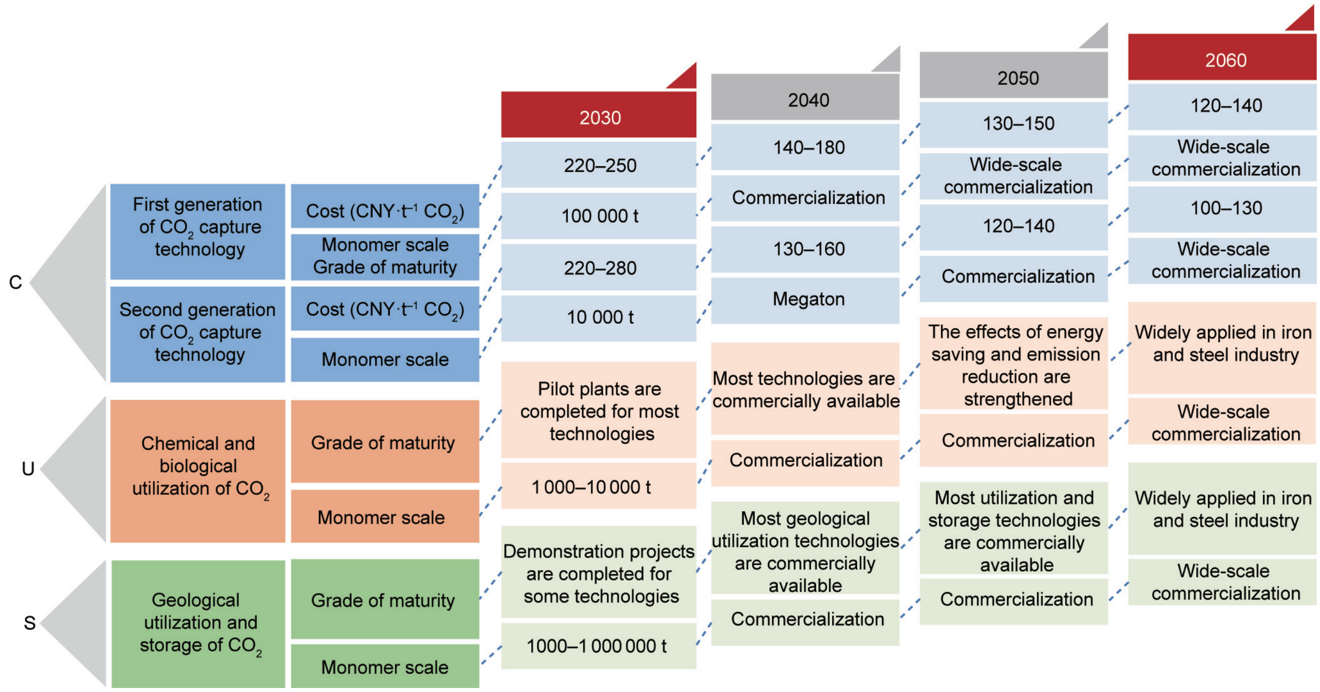


Fig. 6. CCUS technology system for the iron and steel industry in China.



			2030	2040	2050	2060
C	First generation of CO_2 capture technology	Cost ($CNY \cdot t^{-1}$ CO_2)	220–250	140–180	130–150	120–140
		Monomer scale Grade of maturity	100 000 t	Commercialization	Wide-scale commercialization	Wide-scale commercialization
	Second generation of CO_2 capture technology	Cost ($CNY \cdot t^{-1}$ CO_2)	220–280	130–160	120–140	100–130
		Monomer scale	10 000 t	Megaton	Commercialization	Wide-scale commercialization
U	Chemical and biological utilization of CO_2	Grade of maturity	Pilot plants are completed for most technologies	Most technologies are commercially available	The effects of energy saving and emission reduction are strengthened	Widely applied in iron and steel industry
		Monomer scale	1 000–10 000 t	Commercialization	Commercialization	Wide-scale commercialization
S	Geological utilization and storage of CO_2	Grade of maturity	Demonstration projects are completed for some technologies	Most geological utilization technologies are commercially available	Most utilization and storage technologies are commercially available	Widely applied in iron and steel industry
		Monomer scale	1000–1 000 000 t	Commercialization	Commercialization	Wide-scale commercialization

Fig. 7. Roadmap of CCUS technology development for the iron and steel industry in China. C: capture; U: utilization; S: storage.

integration of CCUS and other low-carbon smelting technologies will be completed, and wide-scale applications will be realized for most CCUS technologies, achieving carbon neutrality or even carbon negativity.

4. Technical prospect for collaborative reduction of pollution and carbon emissions from iron and steel industry in China

As the iron and steel industry enters the post-ultra-low and carbon reduction era, flue gas control from the steel industry has become increasingly important. With the widespread implementation of ultra-low emissions, the total amount of flue gas pollution from the iron and steel industry has been greatly reduced. However, in the context of collaborative reduction of pollution and carbon emissions, several issues remain, such as the overall optimization of the production structure, rationality of pollutant calculation, energy consumption from ultra-low emissions, feasibility of CCUS technologies, and total reduction of pollution and carbon emissions. As summarized in Fig. 8, technical prospects are suggested to promote the green development of the iron and steel industry in China.

(1) **Green production**. China produces the largest amount of steel worldwide. Based on the development plan of the iron and steel industry in China, the newly green smelting technology cannot easily achieve large-scale applications in a short time. Therefore, national departments and industry groups should devote increasing efforts to promote the research and applications of various green technologies, such as high-proportion pellets in blast furnaces, short-process steelmaking, and hydrogen metallurgy, to support the overall reduction of pollution and carbon emissions.

(2) **Reasonable calculation for pollutants**. The calculation of emissions for every process and pollutant is adopted in the iron and steel industry, leading to great pressure on steel enterprises. Therefore, the calculation method of "total amount assessment based on the whole process" should be used to replace the "single pollutant calculation in every single process." The equal or reduced displacement of pollutants between different production processes and different pollutants should be allowed in appropriate scenarios, making it more reasonable for the management and control of pollution.

(3) **Energy-saving ultra-low emission**. Pollution has been greatly reduced owing to the wide implementation of ultra-low emissions, whereas the incremental effect of carbon emissions is significant. Therefore, the technologies of high proportion of flue gas circulation coupled with energy and mass enhancement, embedded environmental protection, multi-pollutant collaborative catalysis, and pollutant purification with chemical energy recycling should be developed to achieve energy saving pollution reduction.

(4) **Applicable CCUS technology**. At present, CCUS terminal decarbonization technologies exhibit the drawback of high operating costs, and it is difficult to realize wide applications in the steel industry. A low-cost CCUS technology that fits the characteristics of the iron and steel industry should be developed. Key materials, such as adsorbents, absorbents, and catalysts, should be explored, making deep decarbonization applicable.

(5) **Total reduction of pollution and carbon emission**. The present ultra-low emissions of the iron and steel industry primarily focus on conventional pollutants, such as PM, SO_2, and NO_x. Unconventional pollutants, including dioxins, VOCs, and heavy metals, are less concerning. In addition, carbon emission standards are still unpublished. It is necessary to promote the development of technology and the construction of standards to realize a comprehensive emission reduction of pollution-carbon components.

5. Conclusions

This study first demonstrated that China's iron and steel industry has achieved rapid growth in recent years. The development of this industry over the past 20 years has been divided into three stages: capacity expansion, focusing on pollution but ignoring carbon, and reducing pollution and carbon. At present, China has entered the third stage, facing the challenge of collaborative reduction in pollution and carbon emissions. The emission standards for pollution and carbon for the iron and steel industry in China have been summarized, clearly illustrating the emission limit variation and proposing that publishing and implementing carbon emission standards can be accelerated. Subsequently, a collaborative technology system for reducing pollution and carbon emissions from the iron and steel industry in China was developed, consisting of four strategies based on present and future steel production processes. Among them, the degree of completion of CCUS techniques in China is systematically demonstrated. Various technologies and their corresponding applications have been described in detail. Finally, the technical prospect is proposed, including five specific advice simplified as "GREAT": ① green production; ② reasonable calculation for pollutants; ③ energy-saving ultra-low emission; ④ applicable CCUS technology; and ⑤ total reduction of pollution and carbon emission. It is believed that these technical prospects will support high-quality green development of the iron and steel industry in China.

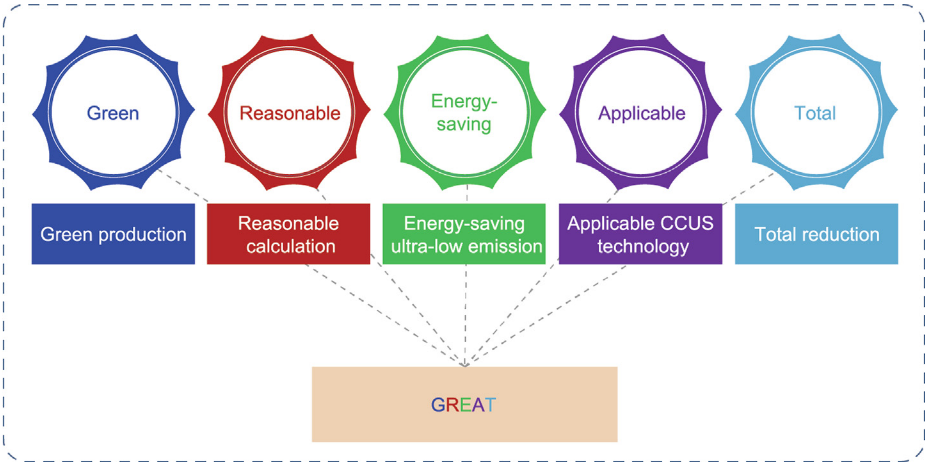


Fig. 8. Technical prospect for collaborative reduction of pollution and carbon emissions from the iron and steel industry in China.

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Compliance with ethics guidelines

Tingyu Zhu, Xiaolong Liu, Xindong Wang, and Hong He declare that they have no conflict of interest or financial conflicts to disclose.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2023.02.014.

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