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Key Technologies and Strategic Thinking for the Coal–Coking–Hydrogen–Steel Industry Chain in China

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Abstract: Energy resource-consuming industries, such as coal, coking, and steel, are crucial for socioeconomic development; however, they are associated with high energy consumption and environmental pollution. As carbon peak and carbon neutral goals are proposed, it is becoming increasingly urgent to accelerate the revolution of energy production and consumption in China. To this end, we investigated the status of coal-based hydrogen production technologies and proposed a coal–coking–hydrogen–steel industrial chain, which is a green, low-carbon, secure, and highly efficient industrial chain, based on the resource endowment, environmental capacity, and industry foundation of China. Subsequently, we compared and evaluated five technological paths for this industry chain from the aspects of economy, energy consumption, and carbon emissions and analyzed the potentials and path choices for coupling hydrogen production with direct reduced iron. Moreover, we identified the strategic goals and the entire layout of the coal–coking–hydrogen–steel industry chain using Shanxi Province as a case study. Furthermore, a clean and low-carbon development concept should be established to promote energy transformation in China. An overall development plan should be formulated for the industry chain, and policies, science, technologies, personnel, and market should be further integrated.

Keywords: direct reduced iron; industry chain; energy transition; coking; hydrogen energy

1 Introduction

The iron and steel industry is a fossil energy-intensive industry, whose greenhouse gas emissions account for ~7% of the world's total emissions [1]. Nearly 75% of the world's iron and steel is produced by the blast furnace (ironmaking) and converter (steelmaking) processes, and large amounts of CO_2, sulfide, nitrogen oxides, sewage, and so on are discharged into the environment. Therefore, global countries are actively seeking ironmaking and steelmaking processes with low energy consumption, low emission, and high efficiency. As the largest energy producer and consumer in the world, China has large-scale energy consumption industries (such as coal, coking, and steel). Related industries have made positive contributions to economic and social development. However, environmental, ecological,

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and energy security issues have been reported. It is important to comprehensively promote the revolution of energy production and consumption and the construction of ecological civilization to realize the green and harmonious development of energy and environment.

Direct reduced iron (DRI) process is characterized by low sulfur and phosphorus contents, high density, high heat energy, and regular size, among others. With this environment-friendly process, clean production can be realized. Compared with the blast furnace–converter process, the gas-based DRI–electric arc furnace (EAF) steelmaking process reduces the CO_2 emission per ton of steel by approximately 0.83 t [2]. However, the main method for iron and steel production (accounting for ~90%) in China is the long-process steelmaking using blast furnace–converter with high energy consumption and high emission, while the proportion of EAF steelmaking is noticeably low. Accordingly, the energy sources of China’s iron and steel industry is mainly coal and coke (accounting for ~92%), with the coal consumption of the iron and steel industry accounting for ~18% of China’s total coal consumption and the carbon emission accounting for ~15% of the national total consumption [3]. The long-term development of China’s coal, coking, steel, and other industries is bounded by the constraints of resources, environment, and ecology. Given the goals of carbon peak and carbon neutralization, it is difficult for the steel industry to maintain the current market stock scale of the furnace–converter steelmaking process. DRI is an important direction for the transformation of China’s iron and steel industry, and it is necessary to accelerate the development of DRI–EAF short-process steelmaking. DRI products boast low content of harmful elements and high purity of iron, which can significantly reduce impurity in molten steel during EAF steelmaking. Therefore, DRI products are ideal pure iron materials for smelting high-quality steel and special steel. There is need to broaden the production scale of clean and high-quality steel, improve the structure of steel products, and provide main raw materials for high-end casting, ferroalloy, powder metallurgy, and other industrial processes.

DRI is generally produced with refined iron ore as raw material and hydrogen-rich gas as a reducing agent. It has obvious advantages in Russia, Iran, Venezuela, and other natural gas-rich countries with low production costs. In China, based on the resource endowment characteristics of “rich coal, lean gas, and little oil,” using coal-based gas source instead of natural gas as the reducing agent of DRI can improve the energy supply mix of the iron and steel industry, overcome the shortage of coking coal resources, and achieve a streamlined steelmaking process (scrap–EAF steelmaking process), thus promoting the clean production and sustainable development of the iron and steel industry. The continuous reduction of scrap steel quality is the main factor restricting the development of EAF steelmaking. The steel produced through DRI has less impurities and high-quality scrap steel, and it will be the necessary iron source for smelting pure steel by EAF. For example, the related raw materials are generally scrapped steel of 50%–70% and DRI of 30%–50%. In 2019, the crude steel output in China was 9.96×10^{8} t, accounting for ~53.12% of total world output [4]. As the main raw material for short process or streamlined process steelmaking, the output of DRI is only 1×10^{6} t, accounting for ~0.9% of the world’s total output. This shows that it is imperative to develop DRI in China [5].

For high-quality development of China’s iron and steel industry, we should continuously promote high-end, intelligent, green, clustering, and standardized production. China is rich in hydrogen-rich sources like coke oven gas and coal-formed gas and has great potential in hydrogen production from renewable energy. Renewable energy provides reliable and economic hydrogen sources for DRI and guarantees the upgrading and transformation of the coal, coking, and steel industries. Some of the suggestions are as follows: actively develop gas-based DRI technology, increase new steel varieties (high-quality steel and special steel), and enhance the core competitiveness of the high-end smelting industry. Moreover, it is important to build new green metallurgy and other emerging industrial clusters and industrial chains, and reduce energy consumption and carbon emissions of related industries, to promote China's demonstration of the global green steel industry. Herein we systematically summarize the development status of DRI technology and industry in China and other countries and analyze the key technological path and development potential involved in China’s coal–coke–hydrogen–iron industry chain. Taking Shanxi, a resource-rich province, as an example, we analyze the technological path selection for the development of coal–coke–hydrogen–iron industry chain and then put forward some countermeasures and suggestions for the high-quality development of the industry in China, to provide a basic reference for the development of the coal, coking, and steel industries in China and other countries.

2 Development status of DRI technology

2.1 Development trend of DRI

According to different reducing agents, the DRI process can be divided into two categories: gas-based DRI and coal-based DRI (solid-solid). The comparisons of corresponding techno-economic performances are summarized in Table 1. Compared with the traditional blast furnace ironmaking method, DRI process has less pollution and consumption and is not affected by the shortage of coking coal. Compared with those of coal-based DRI, gas-based DRI has more substantial advantages in energy consumption, single equipment output, and carbon emission. In recent years, the output of DRI worldwide has increased rapidly. Fig. 1. shows the DRI output of major countries. India's DRI output ranks first in the world. Due to the lack of natural gas and minimization of its dependence on natural gas, India has been actively developing DRI with coal-based gas sources (such as coke oven gas, coal-based gas, and shale gas) as reducing agents (the output accounts for nearly one-third of India's total DRI outputs).

Table 1. Comparison of design capacity, energy consumption, and carbon emission of DRI processes [6–12].

Technology	Reducing agent	Reactor	Energy consumption (GJ·t^{-1})	Carbon emission (t CO_2·t^{-1})	Economy ($\times 10^4$ CNY·t^{-1})	Single furnace capacity ($\times 10^4$ t·a^{-1})	Product form
MIDREX process	Natural gas	Shaft furnace	10	0.65	0.27	180	≥90% DRI
HYL/Energiron	Natural gas	Shaft furnace	10	0.53	0.28	190	≥90% DRI
Direct reduction of coal-to-gas shaft furnace	Coal-to-synthesis gas	Shaft furnace	12	1.00*	0.18	190	≥90% DRI
COREX melting reduction	Lump coal/coke	Pre-reduction furnace–melting gasifier	16.5	1.15*	0.32	120	≥93% hot molten iron
Rotary kiln process method	Coal	Rotary kiln	20	-	-	15	≥93% DRI
Tunnel kiln process method	Coal	Tunnel kiln	20–30	-	-	1–4	≥80% DRI
Blast furnace ironmaking	Coke	Blast furnace	15.5–18.1	1.5	0.26	200–400	≥93% hot molten iron

Note: Data with * are estimated based on production unit DRI consumption of syngas/lump coal/coke.

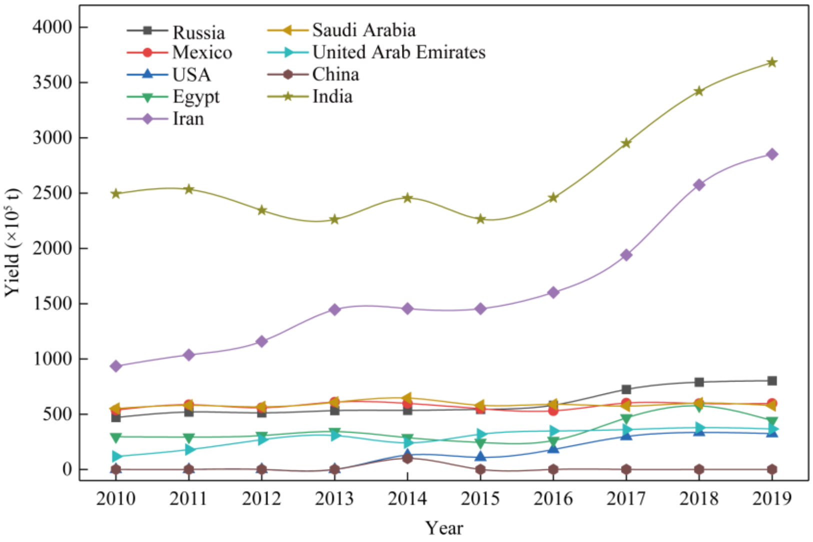

Fig. 1. Distribution of DRI output in major countries.

The research on DRI technology in China began in the 1950s, and DRI technology was put into production in 1992. In 2010, the DRI production capacity reached the highest in history (1.08×10^6 t), accounting for ~0.15% of the world's total output in that year. The production scale of DRI was small and the process was not advanced enough, so the coal-based direct reduction process of the rotary kiln was used. Since 2010, to speed up the transformation and upgrading and to promote the green and sustainable development of the steel industry, DRI factories with high energy consumption and alarming pollution levels were shut down consecutively, and the national DRI output has dropped significantly. In 2019, the output of EAF steel in China was 1.032×10^8 t [5], accounting for ~10% of the total output of steel in China (the corresponding proportion of the world was 27.9%).

In the long run, the continuous accumulation of scrap steel resources (increasing supply), the expansion and application of short-process new technology, low-carbon metallurgy, and clean energy in China will promote energy saving and low carbon use in the steel industry. To improve the production structure and energy consumption structure of iron and steel products and remove the restriction of coking coal resources on the development of iron and steel production, improving the DRI technology is an important direction for the transformation and upgrading of China's iron and steel industry. According to the national industry plan, the demand for DRI in China is as high as 9×10^7 t/a, but at present, the low proportion of EAF steel output leads to the shortage and low quality of scrap steel. Hence, DRI depends on imports: the import volume of 2019 was 2.73×10^6 t, which may be detrimental to high-end casting and industrial security.

2.2 Specific progress of China's DRI industry

China has successively built Tianjin Steel Pipe Manufacturing Co., Ltd. (3×10^5 t/a), Beijing Miyun Metallurgical Mining Company (6.2×10^4 t/a), and so on. There are six rotary kiln DRI production lines, and the total production capacity is nearly 6.0×10^5 t, but many enterprises have stopped production due to market competitiveness, production costs, environmental protection, and other problems. The rotary kiln DRI method has strict requirements of raw fuel, high energy consumption (coal consumption is ~950 kg/t), high investment and operational cost, difficulty in maintaining stable operation, and difficulty in the expansion of production scale (1.5×10^5 t/set). Therefore, it may be adequate for medium- and small-scale DRI production in areas with suitable resource conditions, but it may not be suitable as the main technology for DRI development. The DRI development in the Middle East and India shows that using gas-based shaft furnace to produce DRI is an effective way to rapidly expand production capacity. With the development of natural gas resources and the transformation and integration of the coke industry in China, some areas in China are able to develop gas-based DRI. Coal-to-gas (including coke oven gas, coal-to-gas with industrial oxygen and steam as oxidant, and underground coal gasification) technology provides necessary conditions for the development of coal-to-gas-shaft furnace DRI, and gas-based shaft furnace DRI will be an important direction for China's industrial development.

In recent years, because of the lack of natural gas resources, China has experienced breakthroughs in the research and development of DRI technology from coal-based gas sources. Shanxi Zhongjin Taihang Mining Co., Ltd., used synthesis gas from coke oven gas as reducing agent, built DRI test device (capacity of 3×10^5 t/a) and its supporting devices (oxidation pellet device, coke oven gas-to-synthesis gas device, and shaft furnace device), and started operation smoothly at the end of 2020. The device is based on the China-Shanxi DRI technical scheme, covering the self-developed coke oven gas-to-reduction gas process and PERED process from MME Company of Germany. It is the first gas-based shaft furnace reduction iron device in China and the first gas-based reduction iron device with coke oven gas as gas source worldwide. Thus, a breakthrough has been achieved in DRI production in gas-based shaft furnace in China and a new way has been explored for adjusting product structure and improving steel quality in the iron and steel industry.

3 Comparative analysis of the development technological paths of coal-coke-hydrogen-iron industry chain

Hydrogen can be divided into blue hydrogen (derived from fossil energy), gray hydrogen (derived from industrial by-products), and green hydrogen (derived from renewable energy). Considering the differences in the hydrogen-rich sources, combined with China's energy supply and consumption structure, resource endowment, and coal/coke/hydrogen/iron industry base, there are five main technological paths of coal–coke–hydrogen–iron industrial chain: (1) DRI coupled with hydrogen production by coal gasification; (2) DRI coupled with hydrogen production by

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coke oven gas; (3) DRI coupled with hydrogen production by multi-energy compensation; (4) DRI coupled with hydrogen production by unconventional natural gas; and (5) DRI coupled with integrated hydrogen-rich fuel gas produced by low-rank coal-derived modified coking gasification.

3.1 Characteristics of different key technological paths

3.1.1 DRI coupled with hydrogen production by coal gasification

Coal gasification is the main technical direction of clean and efficient utilization of coal, and hydrogen production from coal gasification is the most important method in China [13]. Hydrogen produced from coal gasification can be used as a reducing agent for shaft furnace ironmaking. This process flow generally includes coal gasification, gas purification, CO conversion, hydrogen purification, shaft furnace ironmaking (DRI), and other production links (Fig. 2). Because of the advantageous resource endowment, the path of developing this kind of technology in China is mature in process and low in cost, but it has a great impact on the environment, including serious carbon emission problems.

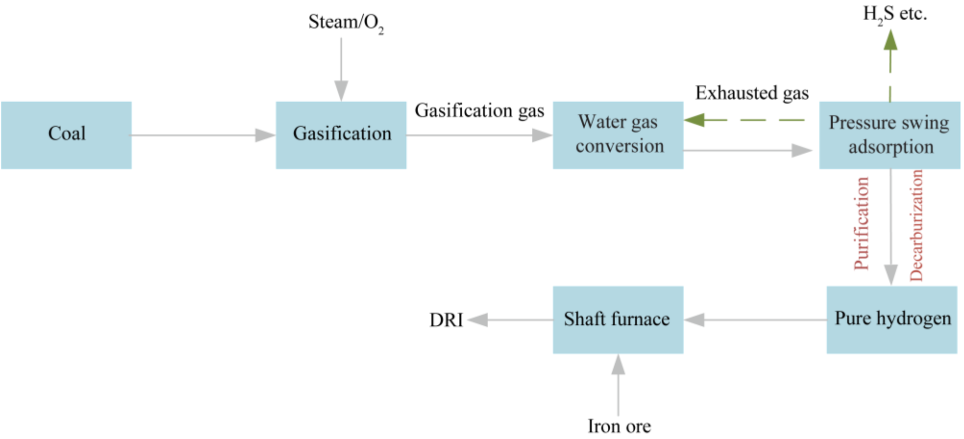


Fig. 2. Process roadmap of DRI coupled with hydrogen production by coal gasification.

3.1.2 DRI coupled with hydrogen production by coke oven gas

The coke oven gas is a volatile gas produced during the dry distillation of coal in the coke oven, and its main components are hydrogen (55%–60% by volume) and methane (23%–25% by volume). Hydrogen is extracted from the coke oven gas and used as a reducing gas to reduce iron ore in the shaft furnace [14]. The process flow generally includes processes such as coke oven gas purification, hydrogen purification, and shaft furnace ironmaking (DRI) (Fig. 3). This technological path makes full use of the advantages of hydrogen-rich resources of the coke oven gas, which is a by-product of the coking industry, and enables the high-value utilization of the coke oven gas. The hydrogen production process is simple and mature. In the short and medium terms, the co-production of coke oven gas and DRI will effectively improve the overall energy utilization efficiency and reduce carbon emissions. However, in the long-term carbon neutralization goal, coke oven gas still has carbon emission problems, and coking capacity will be gradually reduced, which makes the coke oven gas–gray hydrogen DRI path gradually transition to renewable energy–green hydrogen DRI path.

3.1.3 DRI coupled with hydrogen production by multi-energy compensation

Hydrogen production by multi-energy compensation refers to the high-efficiency and low-carbon production of hydrogen energy through mutual matching and cascade utilization of various energy sources. Specifically, hydrogen enters the shaft furnace as a reducing gas to reduce iron ore (Fig. 4). The instability of renewable energy and the limitation of power transmission and distribution cause the phenomenon of abandoned energy. By coupling gray hydrogen or blue hydrogen with stable source and low cost, the local conversion and utilization of abandoned energy can be realized, and a low-carbon, efficient, stable, and low-cost hydrogen source supply can be formed. This kind of technology will be the main pathway to produce hydrogen in low-carbon life in the future, as it can effectively reduce the carbon emission intensity and has great developmental potential. However, there is a mismatch in the spatial distribution of various regional energy resources, and the energy storage and multi-energy integration technology are still immature. Moreover, it is necessary to carry out technical research and implement engineering demonstrations.

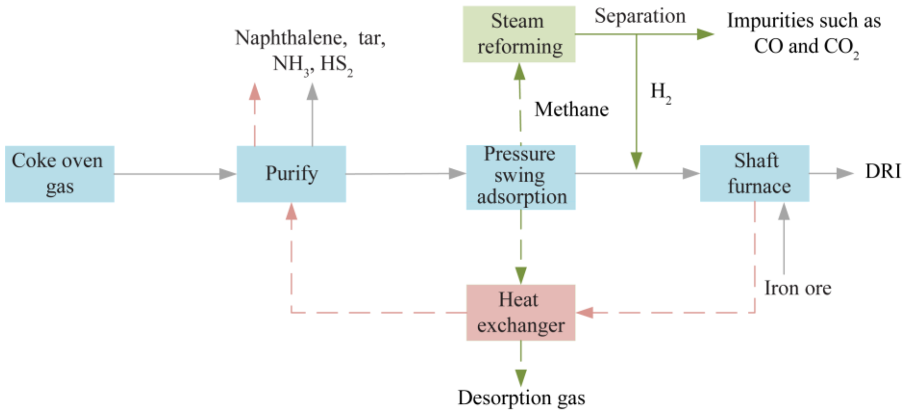


Fig. 3. Process roadmap of DRI coupled with hydrogen production by coke oven gas.

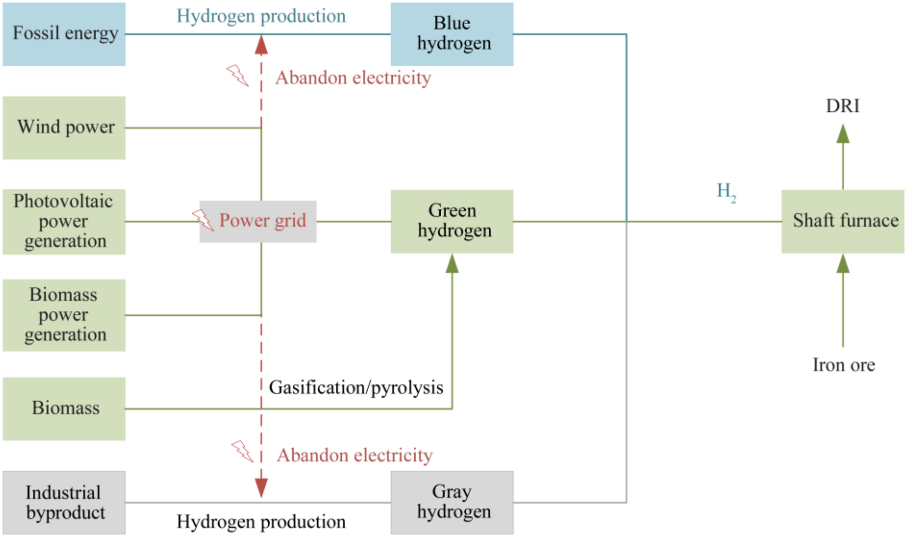


Fig. 4. Process roadmap of DRI coupled with hydrogen production by multi-energy compensation.

3.1.4 DRI coupled with hydrogen production by unconventional natural gas

Unconventional natural gas resources mainly include coalbed methane, shale gas, and sandstone gas [15]. The corresponding technological paths are subdivided into two types: (1)hydrogen and benzene by-products are produced from unconventional natural gas by molybdenum-based catalysis [16], and hydrogen directly enters the shaft furnace after purification and other processes to produce DRI; (2) hydrogen is obtained by steam reforming, pressure swing adsorption, and other processes, and then enters the shaft furnace to produce DRI (Fig. 5). In China, large amounts of unconventional natural gas are produced in the process of coal mining. The separation and enrichment technology for low concentration gas is an important prerequisite for the utilization of unconventional natural gas. However, it consumes high energy and costs. Although this kind of technological path helps to reduce greenhouse gas emissions, unconventional natural gas is a carbon-based energy. Under the constraint of carbon neutrality, it is necessary to consider the overall layout optimization of the unconventional natural gas energy utilization industry.

3.1.5 DRI coupled with integrated hydrogen-rich fuel gas produced by low-rank coal-derived modified coking gasification

Low-rank coal is used for power generation, which has low efficiency and large pollutant emission. Developing the integrated technology of modified coking and gasification of low-rank coal is an effective way to meet the coke demand of metallurgy, machinery, chemical industry, and other industries and reduce environmental pollution. This technological path is the extension of modified coking of low-rank coal (Fig. 6): Clean coal is obtained by washing low-rank coal, and coal blending modification is carried out between unbonded clean coal and caking coal to prepare modified coal with certain caking properties. Coal is blended with raw clean coal for high-temperature pyrolysis to generate modified pyrolytic carbon and volatile gas. Gasification gas produced by the gasification of modified pyrolytic carbon is coupled with hydrogen-rich volatile gas to form hydrogen-rich gas, which enters a gas-based shaft furnace to reduce the iron ore. Another part of the gasified gas is used for power generation or hydrogen reduction-based iron production through water gas shift. China is rich in low-rank coal resources, and adopting relevant technologies can reduce the consumption of high-quality coal resources and alleviate the shortage of high-quality coking coal, while the carbon emission coefficient remains high. At present, this kind of technological path is in the transitional stage from technology R&D to engineering demonstration, and the integration and development of coking–steel industry will be rapidly promoted after the technology matures.

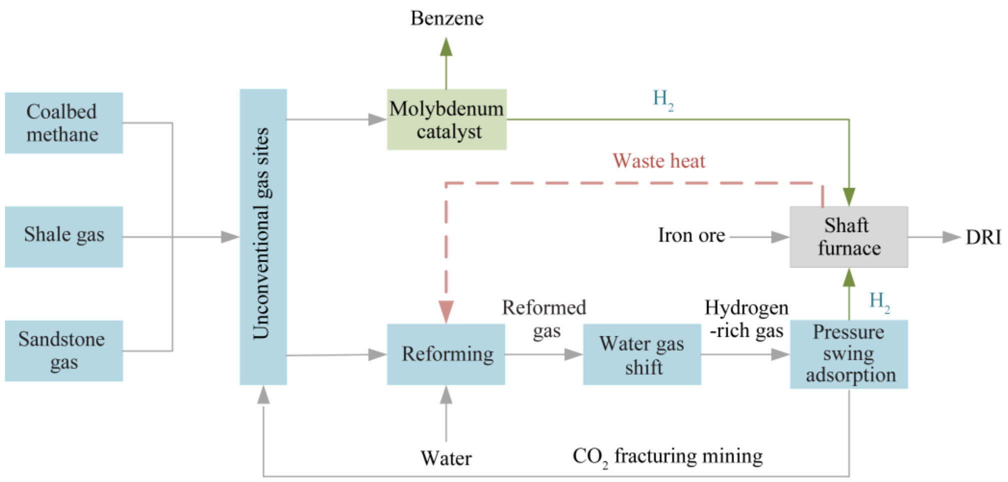


Fig. 5. Process roadmap of DRI coupled with hydrogen production by unconventional natural gas.

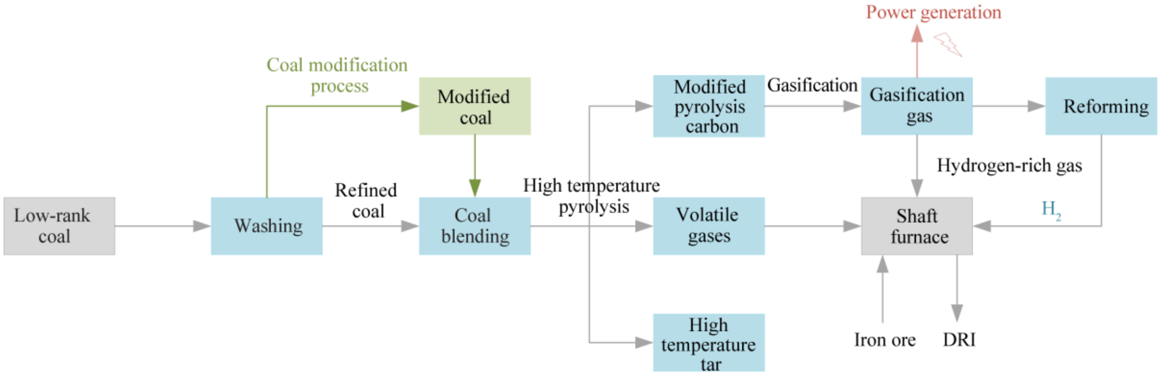


Fig. 6. Process roadmap of DRI coupled with integrated hydrogen-rich fuel gas produced by low-rank coal-derived modified coking gasification.

3.2 Comparative analysis of technological path performance of coal-coke-hydrogen-iron industry chain

In the whole production process of hydrogen reduction iron, the price of iron ore is the main factor affecting the production cost. The biggest difference between the above five technological paths lies in the difference of hydrogen production methods. (1) From the perspective of energy consumption level, the raw materials for multi-energy synergistic complementary hydrogen production come from renewable energy sources such as wind, light, and biomass. Moreover, hydrogen is produced through the electrolysis of water or biomass pyrolysis/gasification, and the energy consumption (16.2–19.8 MJ/kg H_2) is the lowest among several paths. The production process of hydrogen production from coke oven gas is simple, and the energy consumption (34.3–139.7 MJ/kg H_2) is slightly higher than that of multi-energy synergistic complementary hydrogen production. The energy consumption of hydrogen production from coal gasification (200–240 MJ/kg H_2) is the highest. (2) From the economic point of view, the cost of raw materials or the price of local basic energy determines the cost of hydrogen production by fossil energy/electrolytic process. The lowest cost of hydrogen production from coke oven gas is (0.3–1.5 CNY/m^3). The cost of multi-cooperative complementary hydrogen production is 0.4–5.0 CNY /m^3), which fluctuates greatly, as it is caused by the instability of hydrogen production from renewable energy. (3) From the perspective of greenhouse gas emission reduction, the carbon emission of multi-energy synergistic hydrogen production is the smallest (1.2–2.0 kg CO_2eq/kg H_2) [17], followed by coke oven gas hydrogen production [18] (11.68–15.8 kg CO_2eq/kg H_2), unconventional natural gas hydrogen production [19] (8.9–12.9 kg CO_2eq/kg H_2), and coal gasification hydrogen production [18] (18.8–29.0 kg CO_2eq/kg H_2).

Table 2 summarizes the characteristic analysis of the technological paths of coal–coke–hydrogen–iron industry chain. In the near future, given the urgency of China's energy transformation and development, the adoption of the technology of hydrogen production and DRI by coal gasification is not recommended. However, the popularization of the coke oven gas scheme with mature technology and good economy is recommended. DRI coupled with hydrogen production by unconventional natural gas is suitable for local promotion in resource gathering areas, and low-quality unconventional natural gas is mainly used. The advantages and disadvantages of DRI coupled with integrated hydrogen-rich fuel gas produced by low-rank coal-derived modified coking gasification is outstanding, as it can be used as an important reserve technology for research and demonstration. In the long run, the hydrogen production capacity of the coke oven gas is limited by the production capacity of coke coal/coke, which will inevitably face the bottleneck problem of raw material production capacity. The environmental friendly characteristics of DRI coupled with multi-synergistic complementary hydrogen production are outstanding, and it is expected to become the main source of hydrogen supply for DRI after the technological breakthrough (Table 3).

According to the consumption of 0.4 t DRI per ton of steel, 240 N·m^3 (21.36 kg) hydrogen is consumed. Combined with the EAF steelmaking process, the comprehensive performance (energy consumption, carbon emission, and economy) of DRI–EAF steel production with different hydrogen production technologies is evaluated (Table 4) [20–24]. In view of energy consumption, the energy consumption of converter steelmaking is generally higher than that of DRI–EAF steelmaking. From the perspective of carbon emission, the carbon emission of converter steelmaking is higher than that of DRI–EAF steelmaking. In view of cost effectiveness, the cost of DRI–EAF steelmaking is higher than that of converter steelmaking. Overall, DRI–EAF steelmaking has more advantages.

4 Case analysis of the development technological path of coal–coke–hydrogen–iron industry Chain

Shanxi Province is the first pilot area for the comprehensive reform of the energy revolution in China. Its resource endowment and industrial base have great potential for the development of the coal–coke–hydrogen–iron industry. The deep combination of the three traditional industries of coal, coking, and steel with hydrogen energy, will actively drive the green and low-carbon transformation of Shanxi Province and simultaneously provide a path reference for the high-quality development of resource-based areas in China.

4.1 Energy resources endowment and industrial development feasibility of Shanxi Province

Shanxi Province is rich in hydrogen production sources (Table 5), and the available coke oven gas is ~1.94 ×10^{10} N·m^3 [25], mainly distributed in Lvliang, Linfen, Yuncheng, Taiyuan, Jinzhong, and Changzhi in southern Shanxi Province; Datong, Shuozhou, and Xinzhou in northern Shanxi Province; and Yuncheng in southern Shanxi Province have obvious advantages in wind power, hydropower and photoelectric energy storage. The total coal-formed gas resources in the province are ~8.31×10^{12} m^3 (accounting for 27.7% in China), and Jincheng, Linfen, and Xinzhou are rich in resources.

According to the consumption of 618 N·m^3 coke oven gas to produce 1 t DRI [26], it is estimated that the coke oven gas in Shanxi Province can produce 3.138×10^7 t/a DRI. Renewable electricity (running time of 6000 h/a) is used to produce hydrogen through the electrolysis of water, and 3.5–5 kWh electricity is consumed for every 1 N·m^3 hydrogen, and 600 N·m^3 hydrogen is consumed for every 1 t DRI. It is estimated that renewable energy in Shanxi Province can produce 5.124×10^7 t/a DRI. Because 320 N·m^3 coal-formed gas (95% CH_4) is consumed for every 1 t DRI production, it is estimated that the coal-formed gas production available for DRI production in Shanxi Province is 4×10^9 m^3, that is, the DRI production potential is ~1.25×10^7 t/a.

Table 2. Characteristic analysis of different technological paths of DRI coupled with hydrogen production technologies.

Technological path	Strengths	Weaknesses	Opportunities	Threats
DRI coupled with hydrogen production by coal gasification	Rich coal resources Mature technology of hydrogen production by coal gasification Low cost of hydrogen production by large-scale coal gasification	Hydrogen production by coal gasification has high carbon emission, high water consumption, great environmental impact, long process flow, and high investment	Combing hydrogen production by coal gasification with CCS/CCUS can realize low-carbon emission. Low-cost hydrogen source is urgently needed to produce DRI.	This path has a higher carbon emission than others and is restricted by carbon peaking and carbon neutrality goals. CCS technology remains immature.
DRI coupled with hydrogen production by coke oven gas	Coke oven gas resources are abundant. Hydrogen production from coke oven gas is mature and low in cost.	Carbon emission exists in hydrogen production from coke oven gas. Waste gas, wastewater, and waste residues in the coking industry are prominent.	The high matching degree of steel–coking enterprises provides important support for this path. This path is the most economical and reliable technical scheme in the short and medium term.	Coking capacity is gradually reduced and coke oven gas output is decreasing. This path is restricted by the carbon peaking and carbon neutrality goals.
DRI coupled with hydrogen production by multi-energy compensation	Fossil energy conversion and utilization technology is mature. Renewable energy resources are abundant. Water electrolysis for hydrogen production is mature and has high purity.	The cost of Water electrolysis for hydrogen production is high. Key common technologies for energy storage and multi-energy integration are immature and have.high technical barriers. Insufficient development and demonstration of multi-energy coupled application	It solves the problem of "abandoning wind, light, and water." The green hydrogen industry chain is initially formed with a broad space for green hydrogen development, and the cost has a downside.	There is a mismatch between renewable energy and fossil energy in spatial distribution. This path contributes little to national energy security and carbon emission reduction in the short and medium terms.
DRI coupled with hydrogen production by unconventional natural gas	Unconventional natural gas resources are abundant. The scale effect of hydrogen production by unconventional natural gas is significant, which can realize large-scale hydrogen production.	Recovery rate of unconventional natural gas is low. Safe, low-cost, and high-efficiency mining technology needs to be developed. Separation and concentration technology of low-concentration unconventional natural gas has high cost and high energy consumption.	Compared with hydrogen production by fossil energy, hydrogen production by unconventional natural gas has relatively low carbon emissions. This path can Effectively help China's energy consumption structure adjustment, and promote the upgrading of energy consumption mode and industrial transformation in the energy industry.	It poses chanllenges to optimized layout and planning of unconventional natural gas resources and iron and steel industry Unconventional natural gas still belongs to carbon-based energy and is restricted by the carbon peaking and carbon neutrality goals.
DRI coupled with integrated hydrogen-rich fuel gas produced by low-rank coal-derived modified coking gasification	Low-rank coal resources are abundant. An important way for high-value utilization of low-rank coal. It promotes cross-industry integration and development and improves the overall energy efficiency of the industry	It is still in the transitional stage from technology research and development to engineering demonstration. High carbon emission.	It broadens the comprehensive utilization mode of low-rank coal and solves the shortage problem of high-quality coking coal. The deep correlation between coking and iron & steel industries provides a technical foundation, which is conducive to the efficient utilization of energy resources in the industry as a whole.	Industry barriers restrict large-scale application and promotion. Carbon-based ironmaking faces the constraint of the carbon peaking and carbon neutrality goals.

Note: CCS, carbon capture and storage; CCUS, carbon capture, utilization, and storage.

Table 3. Development potential and strategic choice of DRI coupled with different technologies of hydrogen production

Technological path	Energy category	Development trend	Development potential	Relevance to other strategic plans	Technical maturity	Pollutant emission
DRI coupled with hydrogen production by coal gasification	Coal	Not encouraged	☆	☆	☆☆☆☆☆	☆
DRI coupled with hydrogen production by coke oven gas	Coke oven gas	Main application modes in the short and medium terms	☆☆☆☆☆	☆☆☆☆☆	☆☆☆☆☆	☆☆☆
DRI coupled with hydrogen production by multi-energy compensation	Renewable energy and fossil energy	Main application modes in the medium and long terms	☆☆☆☆☆	☆☆☆☆☆	☆☆☆☆	☆☆☆☆☆
DRI coupled with hydrogen production by unconventional natural gas	Unconventional natural gas	Local promotion in short and medium terms	☆☆☆☆	☆☆☆☆	☆☆☆	☆☆☆☆
DRI coupled with integrated hydrogen-rich fuel gas produced by low-rank coal-derived modified coking gasification	Coal	Gradually promotion in iron and steel plants with supported coking devices.	☆☆☆☆	☆☆☆☆	☆☆☆	☆☆

Table 4. Comparative analysis of blast furnace–converter technology and EAF steelmaking technology.

Technological path	Energy consumption (GJ·t^{-1})	Carbon emission per ton of steel (t CO_2·t^{-1})	Cost (10^4 CNY·t^{-1})
Blast furnace–converter	19.63–35.41	1.86–2.53	0.28–0.32
DRI coupled with hydrogen production by coal gasification–EAF	5.72–6.57	0.48–0.70	0.38–0.39
DRI coupled with hydrogen production by unconventional natural gas–EAF	2.73–4.86	0.27–0.36	0.38–0.40
DRI coupled with hydrogen production by coke oven gas–EAF	1.49–1.54	0.33–0.42	0.37–0.40
DRI coupled with hydrogen production by multi-energy compensation–EAF	1.79–1.87	0.11–0.12	0.37–0.48
DRI coupled with integrated hydrogen-rich fuel gas produced by low-rank coal-derived modified coking gasification–EAF	1.87–3.15	0.24–0.95	0.36–0.38

In 2019, the total output of crude steel in Shanxi Province was 6.028×10^7 t, and the capacity utilization rate was 81.7%, concentrated in the Jinzhong and Jinnan areas (Table 6). Specifically, the output of Yuncheng, Taiyuan, and Linfen exceeded 1×10^7 t, and the output of Jinzhong, Lvliang, Jincheng, and Changzhi was 3×10^6–6×10^6 t. The coke output of Shanxi Province was 9.696×10^7 t, of which the output of Lvliang was 2.575×10^7 t, while the output of Linfen, Changzhi, Jinzhong, and Yuncheng exceeded 1×10^7 t. The output of coke oven gas was directly proportional to the output of coke. At present, coke oven gas in Shanxi Province is mainly used to produce methanol, but there is overcapacity in the methanol market. The surplus coke oven gas is used to produce hydrogen, which can alleviate the overcapacity and broaden the way of resource utilization for coke oven gas.

Based on the energy development plan of Shanxi Province, coke oven gas can produce hydrogen for DRI in the short term and can be used to develop hydrogen energy in the future.

Table 5. Installed capacity of coke oven gas, coal-formed gas, and renewable energy in Shanxi Province (2019).

Urban area	Coke oven gas ($\times 10^8$ N·m^3)	Coal-formed gas ($\times 10^8$ N·m^3)	Installed capacity of renewable energy ($\times$ 10^4 kW)
Taiyuan	22.46	0.85	59.63
Datong	0.00	0.00	475.57
Shuozhou	0.00	0.00	462.80
Xinzhou	4.38	5.40	528.95
Yangquan	1.64	0.50	153.68
Jinzhong	24.36	4.23	158.90
Changzhi	29.72	0.59	150.73
Jincheng	2.34	31.45	84.94
Lvliang	51.50	8.59	159.03
Linfen	33.74	19.35	73.95
Yuncheng	23.78	0.00	254.05

Source: Statistical bureaus of various cities in Shanxi Province and the *Three-year Action Plan for Increasing Coal-formed Gas Reserves and Production in Shanxi Province (2020–2022)*.

Table 6. Calculation of crude steel output and various DRI production potential in Shanxi Province.

Urban area	Crude steel output ($\times 10^4$ t)	Coke oven gas DRI ($\times 10^4$ t)	Coal-formed gas DRI ($\times 10^4$ t)	Renewable energy DRI ($\times 10^4$t)
Taiyuan	1307	363.64	14.97	119.26
Datong	111	0.00	0.00	954.11
Shuozhou	0	0.00	0.00	925.60
Xinzhou	64	70.87	95.12	1057.90
Yangquan	0	26.50	8.81	307.36
Jinzhong	305	394.17	74.51	317.80
Changzhi	608	480.91	10.39	301.46
Jincheng	475	37.86	554.01	169.88
Lvliang	347	833.33	151.32	318.06
Linfen	1206	545.95	340.86	147.90
Yuncheng	1605	384.79	0.00	508.10

Source: Statistical bureaus of various cities in Shanxi Province and the calculation results of raw material consumption of different technological paths.

DRI coupled with hydrogen production by coke oven gas in Shanxi Province and iron and steel enterprises have the best spatial layout, concentrating in Jinzhong and Jinnan. Coal-formed gas coupled with DRI production is basically consistent with the spatial layout of iron and steel enterprises. DRI coupled with hydrogen production from renewable energy production is inversely distributed with iron and steel enterprises, and a hydrogen transportation network needs to be built to meet future high utilization needs and to match the existing pattern of iron and steel enterprises. Approximately 40% DRI per ton of steel is produced by EAFs (generally 50%–70% scrap steel, 30%–50% DRI [7]). It is estimated that the total crude steel produced by the technological path of DRI coupled with hydrogen production from coke oven gas is 7.845×10^7 t, which meets the demand for DRI in Shanxi Province at present (the crude steel production capacity is planned to be 7.38×10^7 t). The technological path of DRI coupled with hydrogen production from coal-formed gas can produce 3.334×10^7 t of crude steel; so it can be the supplementary path in areas with relatively insufficient coke oven gas resources such as Linfen and Jincheng. A total of 1.281×10^8 t of crude steel can be produced through DRI coupled with hydrogen production by renewable energies. Therefore, in the short term, the technological path of DRI coupled with hydrogen production by coke oven gas is suitable for developing coal–coke–hydrogen–iron industrial chain in Shanxi Province. DRI coupled with hydrogen production by renewable energies can be used in the medium and long terms.

4.2 Choice of industrial technological path in Shanxi Province

The hydrogen production potentials of different paths in major cities of Shanxi Province are presented in Fig. 7. The hydrogen production potential of renewable energy in northern Shanxi (Datong, Shuozhou, and Xinzhou City) is huge, and the renewable energy is mainly photoelectric and wind power. The central and southern Shanxi Province (Jincheng, Linfen, and Changzhi) have the potential of producing hydrogen from coal-formed gas. Lvliang, Jinzhong, Linfen, Changzhi, and Yuncheng have potential for hydrogen production from coke oven gas. In the context of green and low-carbon development of metallurgical industry and control of fossil energy consumption in iron and steel industry, owing to the high energy consumption and carbon emission of hydrogen production from coal gasification, DRI coupled with hydrogen production by coal gasification is not recommended as the main production path. Shanxi Province is rich in unconventional natural gas resources, and its corresponding distribution is consistent with that of the iron and steel industry. In addition, the economy, energy consumption, and carbon emission of hydrogen production by unconventional natural gas are better than those of hydrogen production by coal gasification, so DRI coupled with hydrogen production by unconventional natural gas is an available promotion scheme in Shanxi Province in the near future. The coking capacity of Shanxi Province is as high as 9×10^7 t, and the output of coke oven gas is abundant, which is consistent with the layout of iron and steel production capacity. Therefore, the technological path of DRI coupled with hydrogen production by coke oven gas can effectively solve the problem of low-value utilization of coke oven gas, and it is the main path of DRI production in Shanxi Province in the near future.

The installed capacity of renewable energy in Shanxi Province has obvious advantages, but it does not match the distribution of the steel production capacity. There are technical bottlenecks in cost, hydrogen storage, and hydrogen transportation, and large-scale application is still far from being achieved. The technological path of DRI coupled with integrated hydrogen-rich fuel gas produced by low-rank coal-derived modified coking gasification scientifically connects the coking and steel industries in series, can solve the problem of coking coal resource shortage, realize the transformation and development of coking enterprises, and achieve the overall effect of energy saving and emission reduction. It should be first popularized and demonstrated in some areas or enterprises in the Shanxi Province.

4.3 Industrial development goals and layout of Shanxi Province

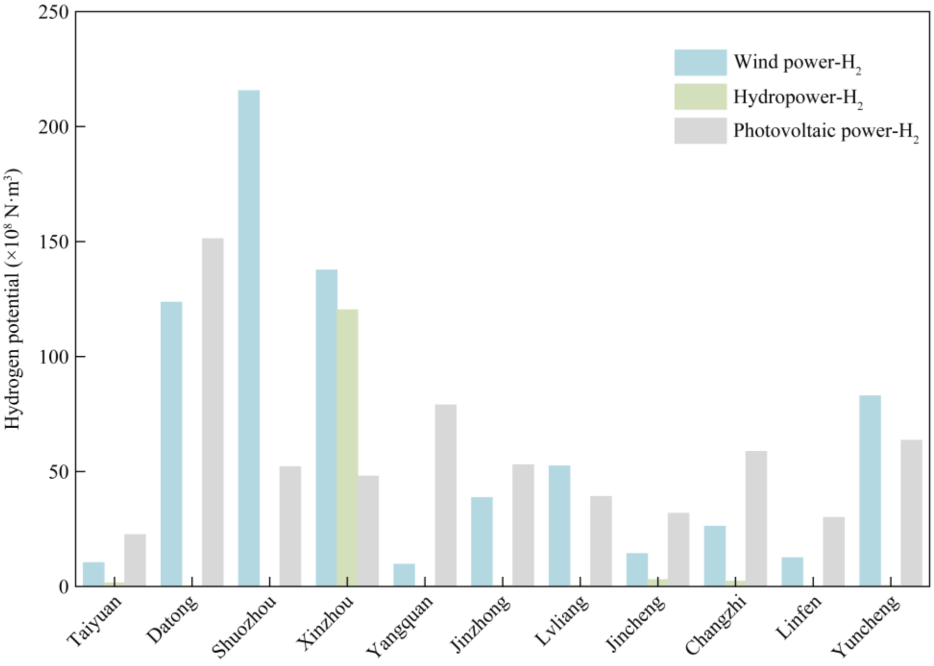
4.3.1 Development goals

For carbon peaking and carbon neutrality, the transformation of energy structure and industrial upgrading in Shanxi Province need to be accelerated. The coal-coke-hydrogen-iron industry chain can deeply integrate three traditional industries of coal, coking, and steel with hydrogen energy in Shanxi Province, and efficiently drive the coordinated development and green and low-carbon transformation of strategic emerging industries in Shanxi Province.

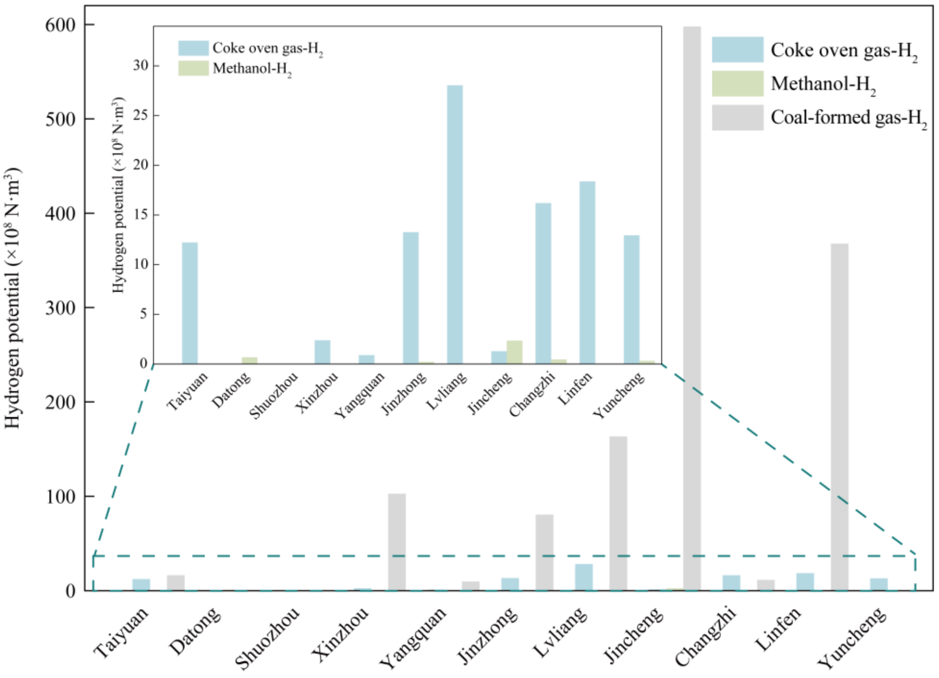
Currently (2021–2035), gray hydrogen steelmaking is the main method for DRI production. DRI coupled with hydrogen production by coke oven gas should be actively promoted in coking cluster areas and steel–coke joint enterprises or parks. In non-coking areas (such as northern Shanxi), priority should be given to promoting DRI coupled with hydrogen production by coupling fossil energy with renewable energy. Other regions should steadily promote DRI coupled with hydrogen production by unconventional natural gas. Based on the industrial development trend of steel-coke combination, DRI coupled with hydrogen production by coke oven gas in steel–coke combination park is the main project recently, and hydrogen steelmaking coupling blue and green hydrogen should be gradually implemented as a demonstration project.

In the middle stage (2035–2050), gray hydrogen steelmaking is expected to be transformed into green hydrogen steelmaking. With the deepening of energy structure transformation, the coke output in Shanxi Province is gradually decreasing, while the proportion of renewable energy power generation is increasing. The coal–coke–hydrogen–iron industry will form an industrial pattern dominated by (1) DRI coupled with hydrogen production by complementary energies and (2) DRI coupled with hydrogen production by unconventional natural gas. Among them, the former one is the main pattern in northern Shanxi, while the latter one and DRI coupled with hydrogen production by coke oven gas coexist in southern Shanxi, gradually realizing the conversion from gray hydrogen steelmaking to green hydrogen steelmaking.

In the long term (after 2050), green hydrogen steelmaking will be the main method. Shanxi Province accelerates the development of gray hydrogen and blue hydrogen (unconventional natural gas) steelmaking to green hydrogen steelmaking. By 2060, the path of coal–coke–hydrogen–iron will be mainly renewable energy, supplemented by unconventional natural gas hydrogen production technology with CCUS, forming an industrial chain pattern of coal–coke–hydrogen–iron with green hydrogen as the main factor.



(a) Distribution of industrial by-product gas and coal-formed gas



(b) Distribution of hydrogen production potentials

Fig. 7. Distribution of renewable energy in Shanxi Province.

4.3.2 Industrial layout

The proposed layout of the Shanxi coal–coke–hydrogen–iron industry chain is as follows: the strategic reserve base in northern Shanxi with Shuozhou as the core area and the industrial agglomeration areas with Taiyuan, Changzhi, and Yuncheng as the core areas; the triangular development layout of Taiyuan–Changzhi–Yuncheng should be promoted and a top-level development pattern of “1+3” created. (1) In northern Shanxi, multi-energy-based DRI coupled with hydrogen production is the main method, supplemented with DRI coupled with integrated hydrogen-rich fuel gas produced by low-rank coal-derived modified coking gasification, and relevant demonstration projects should be conducted to improve the application level of advanced technology and equipment. (2) DRI coupled with hydrogen production by coke oven gas should be promoted in coking gathering areas and steel-coke joint enterprises or parks. (3) DRI coupled with hydrogen production by unconventional natural gas should be promoted in gas extraction and utilization parks, Changzhi, Jincheng, Linfen, and Yuncheng, exploring DRI for coal mine gas. (4) There are few iron and steel enterprises in the three cities of northern Shanxi (Xinzhou, Shuozhou, and Datong) and Yangquan, which can carry out advanced technology research and development demonstration and reserve according to local industrial advantages, instead of being the main area of coal–coke–hydrogen–iron industry layout.

The important content of the coordinated development of the surrounding areas of Beijing–Tianjin–Hebei is to build an excellent clean, efficient, green and low-carbon high-end manufacturing industrial cluster, and high-end manufacturing is the core driving force for the transformation and upgrading of the steel industry. The development of the Shanxi coal–coke–hydrogen–iron industrial chain will provide high-quality and high-end special steel raw materials for high-end manufacturing industrial clusters around Beijing–Tianjin–Hebei. Meanwhile, it is also an important measure for the promotion of the coordinated development of energy, economy, and environment around Beijing–Tianjin–Hebei.

The development of coal-coke-hydrogen-iron industry chain in Shanxi Province is mainly divided into the three stages described further.

In the construction stage of demonstration projects, Jincheng gives priority to the demonstration project of DRI coupled with hydrogen production by unconventional natural gas, while Yuncheng focuses on the project of DRI coupled with renewable energy multi-energy hydrogen production. Taiyuan, Linfen, and Lvliang can prioritize the demonstration projects for DRI coupled with coke oven gas hydrogen production by learning from the development experience of Shuozhou City. Shuozhou and Changzhi will carry out the demonstration project of DRI coupled with integrated hydrogen-rich fuel gas produced by low-rank coal-derived modified coking gasification. Technological paths, such as DRI coupled with hydrogen production from unconventional natural gas, hydrogen production from renewable energy, and integrated hydrogen-rich fuel gas produced by low-rank coal-derived modified coking gasification, will enter the pilot test and initial demonstration test stage of the project before 2025, and each demonstration project will be completed before 2030.

In the stage of rapid development, by 2035, a reserve base in northern Shanxi with Shuozhou as the core and an industrial agglomeration area with Taiyuan, Changzhi, and Yuncheng as the core areas will be initially formed, and the development layout of coal–coke–iron triangle will begin to take shape. A batch of coal–coke–hydrogen–iron industry chain projects with characteristics and market in iron and steel enterprises in Shanxi Province will be built. Shanxi coal–coke–hydrogen–iron industry scale (DRI output) will exceed 1×10^7 t, making it the largest coal–coke–hydrogen–iron industry development zone in the Beijing–Tianjin–Hebei–Shanxi region. By 2050, the coal–coke–hydrogen–iron industrial cluster scale (DRI output) of Taiyuan–Changzhi–Yuncheng will reach 2.5×10^7 t, ranking first in China.

In the stable consolidation period, by 2060, gray hydrogen steelmaking will not be adopted and green hydrogen steelmaking will flourish. The scale of Taiyuan–Changzhi–Yuncheng coal–coke–hydrogen–iron triangle industrial cluster will remain stable, and the quality of industrial development will improve significantly, representing the higher development level of China’s industry.

5 Suggestions on the development of China’s coal-coke-hydrogen-iron industry chain

5.1 Establishing the concept of clean and low-carbon development to drive the energy revolution

It is important to implement the new development concept completely, accurately, and comprehensively and carry out energy revolution and ecological civilization construction against the goals of carbon peaking and carbon neutrality. Combined with the characteristics of energy resource transformation in different technological paths of the coal–coke–hydrogen–iron industry chain, the strategic development goals of energy production and consumption revolution, energy science and technology revolution, industrial structure adjustment, and strategic low-carbon clean industry are coordinated. Clean and efficient utilization of coal, dissolution of excess capacity in the coking industry, development planning of hydrogen energy industry, and the reduction/adjustment/upgrade of iron and steel industry are the key factors in the promotion of the energy revolution and efforts to achieve clean, efficient, green, and low-carbon development of coal–coke–hydrogen–iron industry chain, which is linked with the national energy transformation strategy and guarantees the construction of ecological civilization in all directions.

5.2 Promoting energy transformation to transform the advantages of energy resources into development advantages

There is need to accurately grasp the development trend of clean and low-carbon energy, formulate the energy transformation strategy of the coal–coke–hydrogen–iron industry chain, and better implement the development strategy of the industry chain. It is necessary to give full play to the role of the coal–coke–hydrogen–iron industry chain in integrating traditional and emerging industries and promoting the conversion of old and new kinetic energy. The upstream of the industrial chain, coal, and coke will gradually be replaced by other energy sources, and their role will gradually transition from hydrogen supply carrier to auxiliary and reserve. The coal–coke–hydrogen–iron industry chain should make timely adjustments and focus on the long-term development of the transition and exit mechanism of gray hydrogen application. The coal–coke–hydrogen–iron industrial chain should be reasonably extended to effectively unite and jointly promote many industries involved in the energy production and consumption revolution, actively integrate carbon-based/carbon synthetic materials, high-end casting, and other industrial directions and increase the benefit of the industry to establish development advantages. Hydrogen and iron should be considered as industrial cores and coal and coke as industrial boosters to promote the comprehensive utilization of coke oven gas and cope with the increase in coking capacity for developing coal the coal–coke–hydrogen–iron industry chain.

5.3 Pay attention to the top-level design and formulate the overall development plan of industrial clusters

It is important to strengthen the top-level design, coordinate the construction of coal coal–coke–hydrogen–iron industrial chain cluster in Shanxi, Hebei, Shandong, and other key provinces, and demonstrate and issue a master plan for the development of coal–coke–hydrogen–iron industrial clusters in China. Moreover, it is necessary to break through the barriers between administrative regions and related industries, scientifically divide labor and rationally arrange the upstream and downstream product layout of coal–coke–hydrogen–iron industry chain, eliminate redundant construction, blind investment, vicious competition and overcapacity, realize regional resource complementarity, and expand the economic and social development. Further, it is important to comprehensively consider geographical location, factors of production, industrial linkages and other factors, promote diversified coal–coke–hydrogen–iron industry chain technology according to local conditions, and improve the industrial cluster planning. With the iron and steel industry adjustment as the goal, industrial integration and coordination as the starting point, and technological innovation as the key, it is imperative to reasonably determine the industrial structure and allocate production capacity, instead of following the existing path of “construction first and adjustment later.”

5.4 Improving policies, science and technology, and talent elements to support the high-quality development of the industry

Strengthening the policy guidance and support and scientifically constructing the development policy system of coal–coke–hydrogen–iron industry chain in China are required. In terms of the approval, establishment, and operation of demonstration projects, it is essential to give necessary policy support, implement standardized examination and approval procedures, create an excellent new industrial policy environment, diversify the pattern of the coal–coke–hydrogen–iron industry with government guidance, have enterprises as the mainstay, and encourage social participation. According to the employment characteristics of universities, research institutes, and enterprises, it is important to optimize the talent cultivation mechanism and rationally set up research topics on the coal–coke–hydrogen–iron industry chain; actively deploy at the level of national science and technology plans (special projects); overcome basic theories and key common technologies, especially core technologies and equipment; make breakthroughs in cutting-edge technology; and train outstanding talents and innovative teams.

Taking enterprises as the main platform, we recommend the training of compound talents who are urgently needed by the coal–coke–hydrogen–iron industry and who have both engineering and management experience and simultaneously introduce high-end talents in the key technical fields of the coal-coke-hydrogen-iron industry chain.

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