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Article

Assessment of relocation of electric furnace steelmaking process by province-level regions in China under carbon neutrality target

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ABSTRACT

Achieving deep decarbonization in industry sector is a central socio-environmental challenge for achieving global climate targets, particularly in countries with large industrial bases. In China, the iron and steel sector is one of the most carbon-intensive industries and therefore plays a decisive role in the realization of the 2030 carbon peaking and 2060 carbon neutrality goals. Electric arc furnace (EAF) steelmaking is widely regarded as a key technological pathway toward near-zero emissions, yet its large-scale deployment faces critical constraints related to material availability, regional heterogeneity, and infrastructure conditions. In particular, the lack of systematic, province-level assessments of resource constraints and spatial allocation hampers effective planning of EAF-based decarbonization pathways. To address this knowledge gap, this study applies the AIM-China/Steel model to quantitatively assess the provincial production potential of EAF steel in China. The analysis integrates cost optimization with regional scrap availability, inter-provincial scrap transportation, and energy costs to simulate future EAF capacity deployment under decarbonization constraints. The results show that regional scrap supply and the feasibility of scrap transport jointly determine the spatial distribution of EAF capacity. In scrap-scarce regions, EAF expansion is significantly constrained, requiring either cross-regional scrap flows or complementary low-carbon options such as hydrogen-based direct reduced iron (H-DRI). Moreover, energy prices, infrastructure conditions, and policy interventions strongly influence the timing and scale of EAF deployment. These findings demonstrate that China’s steel decarbonization depends not only on green electricity expansion but also on coordinated planning of scrap recycling systems, transportation networks, and regional resource allocation. This study provides quantitative evidence to support province-level EAF capacity planning and informed policymaking for the steel industry’s transition toward near-zero carbon emissions.

KEYWORDS

Industry relocation, near-zero emissions, iron and steel industry, electric arc furnace steel, climate change.

1 Introduction

In September 2020, China announced its dual carbon goals: to peak carbon emissions before 2030 and to achieve carbon neutrality by 2060. These targets have since become central to the country’s overarching strategy for energy system transformation and economic restructuring. In response, various industrial sectors and provincial governments have formulated tailored action plans to align with the national carbon neutrality agenda.

As one of the most energy- and carbon-intensive sectors, the iron and steel industry faces significant challenges in reducing its CO_2 emissions[1]. China’s iron and steel industry (CISI) is not only the largest industrial CO_2 emitter but also a critical pillar of the national economy and industrial output.

Between 2010 and 2024, China’s crude steel production exhibited a generally increasing trend, though it began to decline after 2020, as illustrated in Figure 1. In 2024, global crude steel production reached approximately 1.88 billion tonnes, of which China contributed 1.014 billion tonnes, representing 53.9% of the global total. Of this, 914 million tonnes—equivalent to 90.3%—were produced using the conventional blast furnace–oxygen furnace (BF-OF) process. Electric arc furnace (EAF) steelmaking accounted for only 99 million tonnes, or 9.7% of China’s steel output. In contrast, the share of EAF-based steel production globally in 2023 was significantly higher, at 28%[2,3].

In 2022, the energy consumption per ton of steel among key statistical enterprises reached 551.36 kg of standard coal equivalent per ton (kgce/t), representing an increase of 1.27 kgce/t compared to 2021[4]. By the end of 2022, approximately 68% of China’s crude steel production capacity had completed the ultra-low emission retrofit[5]. As illustrated in Figure 2, both CO_2 emission by energy resource and CO_2 emissions from the CISI have shown a consistent downward trend, primarily due to the successful implementation of energy efficiency improvements and technological upgrades across the sector.

In recent years, the steel industry has often been regarded as one of the most challenging sectors for achieving deep decarbonization, primarily due to its heavy reliance on coal resources—either directly or in the form of coke—as both a fuel and a reducing agent[6]. However, renewed efforts are being made to identify and implement innovative solutions for industrial decarbonization. Numerous studies have shown that CISI possesses significant potential for CO_2 emission reductions. For instance, Ren et al.[7] developed an integrated bottom-up and top-down modeling framework to analyze low-carbon development

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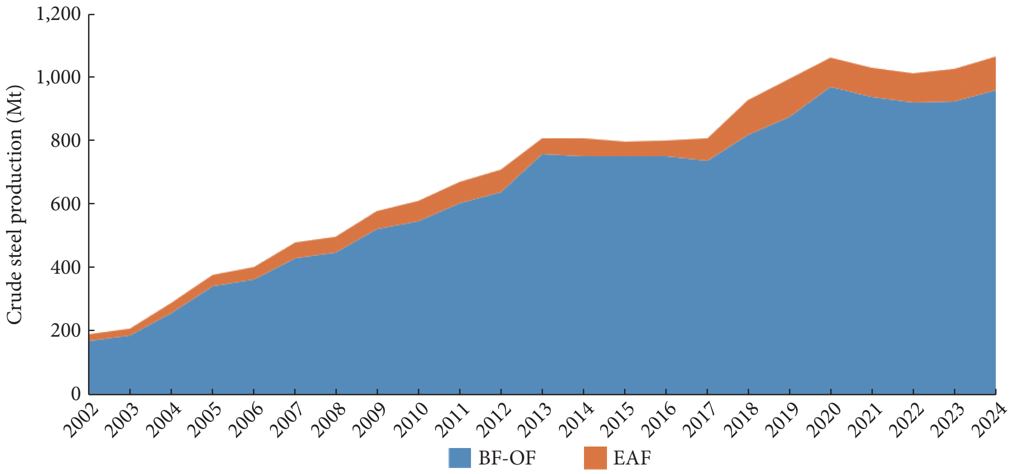

Fig. 1 Total production of crude steel in China and the proportion of electric arc furnace (EAF) steel and blast furnace–oxygen furnace (BF-OF) steel during 2010–2024.

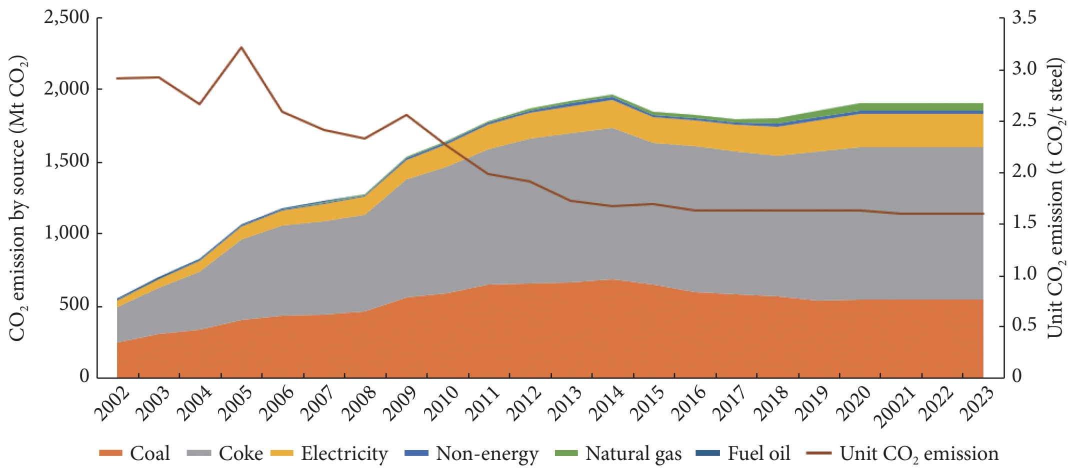

Fig. 2 CO_2 emission and energy consumption from China's iron and steel industry (CISI).

pathways for CISI under the carbon neutrality target. Wang et al.[8] constructed a dynamic modeling framework to simulate technological advancements and evaluate carbon neutrality trajectories for the industry. Jiang et al.[9] applied the AIM-China/Steel model and cost optimization analysis to assess the potential for CISI to achieve near-zero emissions, highlighting electric arc furnace (EAF) steelmaking as a key strategy for emission mitigation. These studies collectively agree that CISI has a high potential for emission reduction, which will largely depend on declining crude steel demand and the adoption of advanced technologies. In a similar context, Xin et al.[10] developed a comprehensive assessment framework to explore a carbon peaking roadmap for Henan province's iron and steel sector. A consensus emerging from these studies is that the CISI holds significant potential for emission reductions, and EAF technology identified as a key.

Currently, CISI's decarbonization efforts focus on enhancing energy efficiency in the blast furnace–oxygen furnace (BF-OF) steelmaking route, expanding EAF deployment, and developing emerging technologies such as hydrogen-based direct reduced iron (H-DRI) and blast furnace carbon capture (BFCC). Over the past decade, significant progress has been made in eliminating outdated capacity and resolving excess capacity, including the early completion of the target to reduce 150 million tons of capacity under the 13th Five-Year Plan[11]. According to Gu et al.[12], there is still a 15%–20% potential reduction in energy intensity across China's steel sector. Nonetheless, deep emission reductions are difficult to achieve through production cuts and BF-OF upgrades alone. Although technologies like H-DRI and BFCC have made technical advances, their application in CISI is still not been developed by scale.

As a result, the Chinese government is accelerating the promotion of EAF steelmaking, which is a relatively mature and energy-efficient process. Moreover, EAF aligns well with the principles of circular economy, a critical pillar of China's sustainable development[13]. Compared with BF-OF steelmaking, the EAF process consumes significantly less energy—approximately 350 kgce/t—and emits only 500–700 kg CO_2 per ton of crude steel[14].

To expedite emission reductions in the steel sector, China has introduced a series of policy measures to support EAF development. The *Action Plan for Continuous Improvement of Air Quality*, issued by the State Council[15], sets a target for EAF to contribute 15% of total crude steel production by 2025, thereby providing a favorable policy environment for the growth of electric furnace steel (EFS). Additionally, the *14th Five-Year Plan* *for Energy Conservation and Emission Reduction* encourages the conversion of traditional BF-OF processes to EAF steelmaking[16].

Given its low-carbon potential, EAF should receive significant attention in the transition of CISI. Most current research on steel sector decarbonization focuses on the national level, but regional heterogeneity in emissions reduction capacity and development potential must also be addressed. Particularly in China, regional disparities in resource distribution and economic development are pronounced. The eastern coastal province-level regions have developed rapidly and host the majority of China's major steel refineries. Scrap steel availability is also unevenly distributed, with the eastern and southern regions having more abundant scrap resources than the western and northern areas. Over 80% of China's scrap resources are concentrated in highly industrialized regions such as Beijing, Tianjin, and Shanghai.

Besides scrap supply, energy cost is another critical constraint for EAF expansion. Industrial electricity prices are generally higher than coal, and some regions experience electricity shortages, further limiting EAF adoption. In contrast, China's western regions have abundant renewable energy resources, particularly solar energy, making renewable electricity more accessible and affordable[17]. This supports the long-term goal of industrial electrification. Some studies have proposed that industry will increasingly relocate to areas with rich renewable energy in the future[18,19]. Research also suggests that China's energy transition, driven by low-cost zero-carbon electricity, will lead to substantial industrial reallocation from eastern to northwestern and northeastern regions[18,20].

Scrap steel is the only renewable raw material that can significantly replace iron ore, and it is infinitely recyclable. The emissions reduction potential of renewable electricity has also been widely confirmed. Hence, EAF development must be grounded in an in-depth assessment of regional scrap supply and clean electricity availability.

This potential industrial reallocation may take place over the next one to three decades, making strategic planning essential. Evaluating the production potential and competitiveness of EAF steel across province-level regions under the carbon neutrality target is thus critical. In this study, we analyze the future EAF steel production potential at the provincial level using the AIM-China/Steel model, a cost optimization framework, and an inter-regional transportation model. Moreover, we discuss key challenges in industry relocation and raw material matching, providing valuable insights for policymakers in designing region-specific emission reduction strategies for the steel industry in the era of carbon neutrality.

2 Current development of EAF in China

The proportion of EAF steel production in China remains significantly lower than the global average, primarily due to limitations in scrap supply. The production cost of EAF steel in China is approximately 400–500 yuan per ton higher than that of BF-OF steel[21]. The principal raw materials and energy sources for EAF steelmaking are scrap and electricity. Over the past few decades, the development of EAF production in China has been hindered by inadequate scrap supply and high electricity costs[22]. Despite progress in steel recycling, China still lags behind several developed countries, including the United States, Germany, and Japan, in terms of waste utilization[23]. While the demand for steel in China has increased steadily over the years, the low availability of scrap and the limited steel stock have resulted in a relatively small share of EAF steel production.

Since the 1980s, China has been the fastest-growing economy globally, leading to a gradual rise in steel production and consumption[24]. However, most of the steel produced in China is used in the engineering and construction sectors, where recovery cycles are lengthy, and the average scrap recovery rate remains significantly lower than that in industrialized nations[25].

In terms of production methodology, the EAF process in China is distinctively different from that in other countries, often referred to as the "Chinese style EFS". This method typically operates with a low scrap ratio, since China's industrial electricity prices is high, which results in expensive energy costs[26]. Some studies suggest that incorporating a certain proportion of pig iron in the EAF process can significantly reduce electricity and scrap consumption, as well as smelting time[27]. However, this reduction in production cost comes at the expense of increased CO_2 emissions, with the production of one ton of pig iron generating 1.5 to 1.7 tons of CO_2[28].

Consequently, the CO_2 emissions from China's EAF steel production are much higher than those of developed countries. Only through the exclusive use of 100% scrap and zero-carbon electricity can EAF production approach near-zero CO_2 emissions.

According to McKinsey's projections, China's scrap supply is expected to increase by 5% by 2030[29]. Further studies suggest that scrap resources will reach 280–430 million tons by 2030 and 490–600 million tons by 2050[30]. Therefore, it is essential for China to continue increasing investments in EAF technologies.

Additionally, the geographical distribution of EAF capacity in China remains uneven. Figure 3 indicated the EAF production based on seven geographical regions of China. In 2024, the East China and South China account for more than 50% of the national total production. The Southwest, North China, and Central China also have relatively large shares, totally combined represent over 90% of China's total EAF capacity.

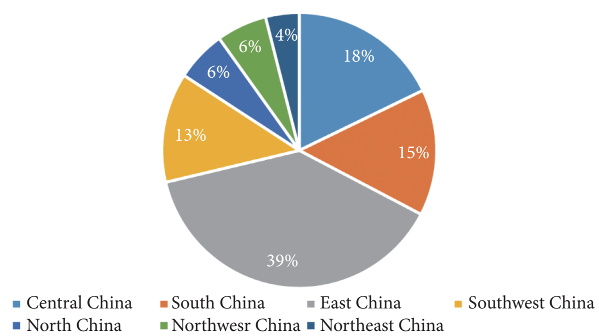

Fig. 3 EAF capacity distribution.

In order to achieve low-carbon development, promoting the EAF production processes remains a key focus for the CISI's future transformation.

In 2024, China is expected to phase out 4.42 million tons of EAF capacity, mainly in East China, Central China, and Northeast China. Meanwhile, 10.5 million tons of new EAF capacity will be added, primarily in East China, South China, and Northwest China[31].

The primary factors contributing to this widespread phase-out include the persistent shortages of scrap steel, high electricity costs, and the increasing challenges posed by air pollution. Additionally, the government's "dual control of energy consumption" policy has played a significant role in reducing the operational and capacity utilization rates of EAFs across the country[32].

3 Methodology

3.1 Methodology framework

This study aims to analyze the EAF production potential across 30 province-level regions in China by considering critical technological advancements (Beijing is not considered in this paper since it is not allowed to produce steel. The Hong Kong and Macao Special Administrative Regions, and Taiwan province are not included due to data available). A technology assessment model will be employed to assess key EAF technologies, followed by a cost optimization method to evaluate production costs in each province-level region. Technology and cost parameters will be derived from a comprehensive review of relevant literature. Additionally, the model will incorporate key data on energy consumption, raw material costs, including electricity prices, scrap availability, and steel demand.

The capital cost, operational parameters, and energy consumption data for electric furnace steelmaking in this study are primarily derived from surveys conducted on 15 representative steel enterprises across China, as well as publicly available industry reports. These enterprises are distributed across the eastern coastal, central inland, and western regions, and include both large state-owned enterprises and small- to medium-sized private steelmakers, ensuring representativeness in terms of geographic coverage and enterprise types. In selecting the sample, priority was given to companies with EAF production lines that have publicly disclosed energy efficiency and investment data. In addition, data were cross-validated and supplemented using official sources such as the China steel industry yearbook, and green development report of the steel industry[33,34].

Furthermore, the study will account for the provincial transportation costs associated with both scrap and EAF steel production. The time frame for this analysis extends through 2050, aligning with the time span used in previous studies to ensure consistency in projections[9].

3.2 Model description

In this study, the AIM-China/Steel model is developed to simulate regional EAF steel production potential, considering feedstock supply, total production costs, and regional demand. The AIM-China/Steel model is an adaptation of the AIM/Enduse model developed by the NIES, Japan[35]. The AIM/Enduse model is a bottom-up linear programming framework that facilitates technology selection and local CO_2 emissions control analysis.

The AIM-China/Steel model extends this approach to the EAF steelmaking process, covering different technologies and regional processes across China. It simulates the flows of energy and materials across 31 regions, aiming to meet the final steel demand. Additionally, optimization cost models and inter-regional grid transportation models are integrated into the framework. In this study, future regional steel demand and scrap supply are forecasted to facilitate a cost comparison between local EAF production and the import of steel from other regions.

The production optimization cost is calculated based on the levelized cost of steel (LCOS), which includes material costs (C_m), investment costs (C_apex), operational and maintenance costs (C_op), and transportation costs (C_t).

$$\mathrm{LCOS} = C_\mathrm{m} + C_\mathrm{apex} + C_\mathrm{op} + C_\mathrm{t} \tag{1}$$

$$C_\mathrm{m} = aC_\mathrm{cs} + C_\mathrm{re} \times E + b \times G_\mathrm{e} \tag{2}$$

The main material in EFS production is mainly include the scrap (C_cs), electricity (C_re), graphite electrode (G_e).

The optimization LCOS is a key factor to present the EFS potential in specific region.

3.3 Scenario setting

The prediction of the proportion of EAF steel production in each province-level region is based on projected future demand for crude steel and the supply of scrap steel. Previous research shows considerable variation in estimates for both the total demand for crude steel and the total supply of scrap steel[9]. To address this uncertainty, future steel demand is categorized into high and low demand scenarios, while scrap steel supply is divided into high and low supply scenarios. This results in the formulation of four distinct scenarios in this study: the high demand and low supply (HDLS) scenario, the high demand and high supply (HDHS) scenario, the low demand and high supply (LDHS) scenario, and the low demand and low supply (LDLS) scenario.

The steel demand projections for 2030 and 2050 are based on the works of Tan et al.[36] and Li and Hanaoka[37], while national scrap supply data are sourced from Vercammen et al.[29] and Wang et al.[25,30]. Detailed data for these scenarios are provided in Table 1.

Table 1 Scenario description.

Scenarios	Crude steel demand (Mt) in 2030	Scrap supply (Mt) in 2030	Crude steel demand (Mt) in 2050	Scrap supply (Mt) in 2050
HDLS	1,074	280	845	480
HDHS	1,074	340	845	570
LDHS	690	340	430	570
LDLS	690	280	430	480

4 Model parameters

4.1 EAF technologies

Given the current low production capacity of EAF in China, there is a significant need for new EAF capacity in the future. In alignment with national policy, new EAFs in China are expected to be predominantly large-scale, with capacities of 100 tons. EAFs with capacities below 30 tons have already been phased out.

For future EAF installations, this study considers four mainstream EAF technologies in China: the 75t EAF, standard 100t EAF, 100t Quantum EAF, and 100t Consteel EAF. The key parameters for these technologies are summarized in Table 2, with the data sourced from various steel refineries in China.

4.2 Regional scrap supply

Previous studies have extensively examined the steel cycle using various modeling approaches. Among them, substance flow

Table 2 Different technologies of EAF in China.

Technology	Capacity (t)	Smelting period (h)	Electricity consumption (kWh)	Graphite electrode consumption (kg)	Capital cost (million USD)
EAF	100	0.67	350	1.6	25
EAF Quantum	100	0.75	310	0.9	62
EAF Consteel	100	0.65	348	1.2	72
EAF 75	75	1.2	410	3	21.7

analysis (SFA) and material flow analysis (MFA) are widely applied to assess steel lifecycle flows at both national and global levels[38–40]. MFA, in particular, is frequently utilized to quantify material flows across defined system boundaries, encompassing stages such as extraction, production, utilization, transformation, recycling, and disposal[41]. For instance, Daigo et al.[42] applied MFA to evaluate the recovery potential of scrap metals.

Building on these studies, this research develops a modified MFA model to estimate the regional scrap steel supply for 2030 and 2050 across Chinese province-level regions. In the model, China's steel consumption is disaggregated into five major end-use sectors: construction, automotive, machinery, electrical appliances, and others. Notably, construction, automotive, and machinery accounted for approximately 80% of total apparent steel consumption in 2020. These accumulated in-use steel stocks are projected to generate substantial quantities of scrap during the 2030–2050 period.

And the equations are shown as Eqs. (3) and (4).

$$S_s(p) = F_{in} - F_{out} \tag{3}$$

$$F_{out} = \sum L_t F_{in} \times r_i \tag{4}$$

In this study, the estimation of regional scrap supply is based on a dynamic stock-driven model, where $S_s(p)$ represents the historical in-use steel stocks in each region. The variables F_{in} and F_{out} denote the annual inflow and outflow of steel-containing products into and out of the in-use stock, respectively. The outflow F_{out} also reflects the depreciation of products, which is determined by the product's maximum lifetime L_t and the depreciation rate r_i.

To enhance regional accuracy, three socioeconomic indicators are incorporated into the model: population, per capita steel consumption, and gross domestic product (GDP). These variables serve to adjust and project the final scrap supply for each province-level region.

Data on newly constructed urban and rural building areas for each province-level region were obtained from the National Bureau of Statistics[3]. Steel consumption per capita is based on estimates from Zhang et al.[41]. Provincial population projections for the period of 2019–2050 are sourced from the baseline scenario in the study of Li et al.[43]. The resulting regional scrap supply projections are summarized in Table 3.

4.3 Regional steel demand

China's national steel demand is projected to decline in the coming decades. Based on existing study, regional steel demand is estimated by downscaling national projections using key regional indicators in the study of Li and Hanaoka[37]. A modified MFA model, previously applied for scrap supply estimation, is also employed to forecast regional crude steel demand.

As outlined in the preceding section, future steel demand is concentrated in five major end-use sectors: construction, automotive, machinery, electrical appliances, and others. The model incorporates four primary factors for demand estimation at the provincial level: future population, per capita steel demand, GDP, and the sectoral distribution of steel consumption[22,44,45].

The projected regional crude steel demand under these assumptions is presented in Table 4.

Table 3 Regional scrap supply.

	High scrap supply (Mt)		Low scrap supply (Mt)	
	2030	2050	2030	2050
Beijing	10.6	12.2	8.7	10.2
Tianjin	13.1	7.9	10.8	6.8
Hebei	9.5	29.0	7.8	19.4
Shanxi	5.2	13.9	4.3	6.2
Inner Mongolia	6.6	10.0	5.4	5.1
Liaoning	12.4	19.4	10.2	16.4
Jilin	4.8	10.5	3.9	4.7
Heilongjiang	8.7	14.9	7.1	8.5
Shanghai	9.5	12.7	7.9	11.3
Jiangsu	38.4	39.9	31.6	35.8
Zhejiang	38.4	29.9	31.6	28.4
Anhui	6.4	23.5	5.3	13.8
Fujian	11.0	16.4	9.1	13.0
Jiangxi	7.1	17.0	5.8	8.0
Shandong	9.2	41.8	7.5	33.0
Henan	29.0	36.9	23.9	16.4
Hubei	10.2	24.3	8.4	18.9
Hunan	12.2	27.1	10.0	16.9
Guangdong	15.2	47.8	12.5	50.6
Guangxi	7.4	18.0	6.1	7.9
Hainan	1.4	3.4	1.1	1.3
Chongqing	0.8	15.6	0.7	17.9
Sichuan	8.4	34.9	6.9	32.0
Guizhou	5.5	12.7	4.5	5.4
Yunnan	3.8	18.5	3.1	12.1
Xizang	0.7	1.1	0.6	0.2
Shannxi	11.1	13.9	9.1	7.6
Gansu	4.6	9.5	3.8	6.9
Qinghai	5.2	2.1	4.3	1.3
Ningxia	2.2	2.5	1.8	1.9
Xinjiang	1.5	9.3	1.2	6.0

Table 4 Regional steel demand.

	High steel demand (Mt)		Low steel demand (Mt)	
	2030	2050	2030	2050
Beijing	82.0	65.4	52.7	33.1
Tianjin	50.0	38.4	32.1	19.4
Hebei	23.6	19.0	15.1	9.6
Shanxi	23.8	19.2	15.3	9.7
Inner Mongolia	34.6	27.4	22.2	13.8
Liaoning	28.4	23.1	18.3	11.7
Jilin	24.6	20.0	15.8	10.1
Heilongjiang	20.4	16.6	13.1	8.4
Shanghai	76.8	59.5	49.3	30.1
Jiangsu	58.6	45.9	37.6	23.2
Zhejiang	50.3	40.5	32.3	20.5
Anhui	29.6	21.6	19.0	10.9
Fujian	52.0	42.3	33.4	21.4
Jiangxi	28.1	22.6	18.1	11.4
Shandong	34.7	26.9	22.3	13.6
Henan	27.8	22.0	17.9	11.1
Hubei	37.5	29.6	24.1	15.0
Hunan	31.3	25.3	20.1	12.8
Guangdong	43.8	34.3	28.1	17.3
Guangxi	21.2	15.7	13.6	7.9
Hainan	27.0	20.7	17.4	10.5
Chongqing	39.3	31.6	25.2	16.0
Sichuan	29.0	22.9	18.6	11.6
Guizhou	23.0	17.0	14.8	8.6
Yunnan	25.1	18.5	16.1	9.4
Xizang	26.2	21.1	16.9	10.7
Shannxi	32.0	24.8	20.5	12.5
Gansu	17.1	13.1	11.0	6.6
Qinghai	24.5	18.8	15.8	9.5
Ningxia	26.4	21.5	17.0	10.9
Xinjiang	25.3	19.6	16.2	9.9

Table 5 Regional industrial electricity price (unit: yuan/(kWh)).

	2030	2050
Tianjin	0.74	0.67
Hebei	0.67	0.48
Shanxi	0.66	0.49
Inner Mongolia	0.52	0.35
Liaoning	0.67	0.49
Jilin	0.69	0.42
Heilongjiang	0.72	0.59
Shanghai	0.80	0.73
Jiangsu	0.74	0.53
Zhejiang	0.72	0.61
Anhui	0.82	0.67
Fujian	0.68	0.57
Jiangxi	0.72	0.55
Shandong	0.81	0.50
Henan	0.84	0.55
Hubei	0.75	0.62
Hunan	0.72	0.60
Guangdong	0.68	0.58
Guangxi	1.10	0.80
Hainan	0.61	0.50
Chongqing	0.74	0.63
Sichuan	1.07	0.61
Guizhou	0.68	0.60
Yunnan	0.72	0.64
Xizang	0.78	0.60
Shannxi	0.68	0.47
Gansu	0.60	0.41
Qinghai	0.53	0.33
Ningxia	0.62	0.47
Xinjiang	0.60	0.43

4.4 Regional electricity cost

Future electricity prices are closely linked to the generation costs of various power sources, including coal-fired power, natural gas, nuclear energy, solar photovoltaic (PV), wind power, and hydropower, as well as the implementation of carbon capture and storage (CCS) technologies. The projected electricity prices also depend on the energy mix and the relative share of each generation technology in the power supply of individual province-level regions.

The electricity data is derived from the IPAC-AIM/Technology model[18,20]. Based on provincial energy consumption and power supply scenarios aligned with China's carbon neutrality goals, the energy mix and corresponding electricity prices were estimated at the provincial level.

The results of the regional electricity price projections are presented in Table 5. Notably, electricity prices are expected to decline in the long term, particularly due to the increasing cost competitiveness and growing share of solar PV and wind power in the national energy mix by 2050.

4.5 Transportation cost

Considering the consistency, capacity, and availability of transportation infrastructure, this study assumes railway transportation as the primary mode for both scrap steel and EFS logistics. A regional grid transportation model was developed to estimate interprovincial transportation costs.

The transportation model is a regional-dimensional table that shows the cost of transporting goods among different regions or provinces.

Transportation pricing is based on official freight rate standards obtained from the 95306 Freight Platform, which is operated by China State Railway Group. The calculated interregional transportation costs are incorporated into the overall cost model. The detailed data and transportation rates are presented in Table 6.

Table 6 Transportation cost of the key regions (unit: yuan/t).

	Shanxi	Inner Mongolia	Liaoning	Jilin	Heilongjiang
Hebei	118.55	120.8	97	138.4	172
	Shanghai	Zhejiang	Anhui	Fujian	
Jiangsu	56	71	53	162	
	Zhejiang	Jiangxi	Henan		
Anhui	83	83	106		
	Shandong	Hubei			
Henan	96	90			
	Chongqing	Gansu	Qinghai	Xizang	Xinjiang
Sichuan	84.4	163.95	186.067	445.35	421.1
	Gansu	Shanxi	Heilongjiang		
Inner Mongolia	171.2	104	244.58		

5 Result and discussion

Figure 4 show LCOS produced by different technologies in different province-level regions in 2030 and 2050 (unit: yuan/t). The results show that in both years, the LCOS of EAF Quantum is the lowest. The investment cost of 100t EAF is the lowest, but the power consumption and electrode consumption are higher and result in that the LCOS is still higher. Therefore, the national new capacity of EAF should come from EAF Quantum.

Based on result, in 2030, the LCOS of the national average quantum EAF will be about 2,855 yuan/t. Henan's LCOS is the highest and Qinghai's LCOS is the lowest. In 2050, the national average LCOS of quantum EAF will decrease to 2,800 yuan/t. Shanghai is the region with highest LCOS and Qinghai also has the lowest LCOS.

Whether the local government can promote the development of EFS depends on the local scrap price, which will be determined by local policies and the market. Based on the model's calculation results, we also divide the production cost into three regions: high LCOS region, middle LCOS region and low LCOS region (Table 7)

The proportion between the cost of each part and the total cost are calculated. The result shows that in 2020, electricity cost accounted for 8% of the total cost, but with the upgrading of technology, it will decline to 6% in 2030 and continue to drop to 5% in 2050. This shows that electricity price will not be the main factor restricting EFS production in the future.

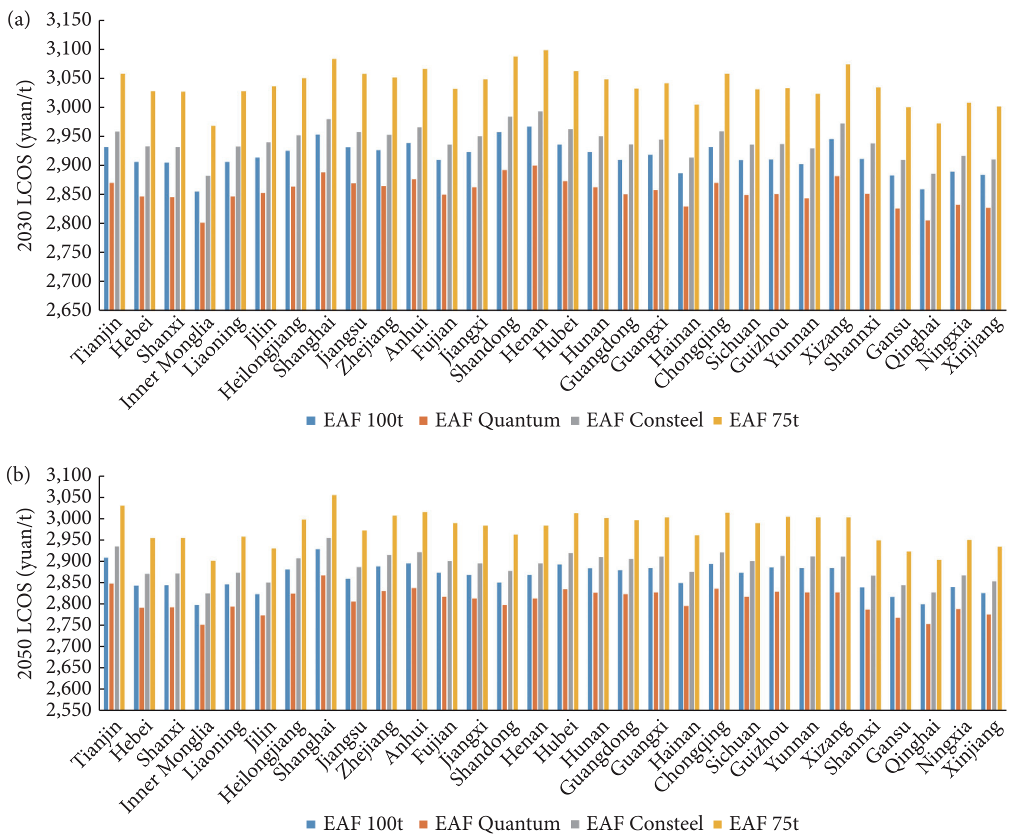

Fig. 4 LCOS of EFS in (a) 2030 and (b) 2050.

Table 7 LCOS level in different province-level regions.

Region	Province-level rgions	LCOS range (yuan/t)
High LCOS	Tianjin, Jiangsu, Anhui, Shandong, Henan, Hubei, Chongqing, Xizang, Shanghai	LCOS > 2,870
Middle LCOS	Hebei, Shanxi, Liaoning, Jilin, Heilongjiang, Fujian, Jiangxi, Zhejiang, Hunan, Guangdong, Guangxi, Sichuan, Guizhou, Yunnan, Shannxi	2,870 > LCOS > 2,840
Low LCOS	Hainan, Gansu, Qinghai, Ningxia, Xinjiang, Inner Mongolia	LCOS < 2,840

Due to the large land area of China, although the road transportation is relatively mature, LCOS does not have obvious competitiveness when the inter-provincial transportation costs are added. Therefore, the scrap should be produced locally as much as possible so as to meet part of the local steel demand in the future and reduce the extra cost and environmental impact during transportation. Meanwhile, EAF also has advantages in investment. Firstly, the total investment of EAF is 1/3 to 1/2 of that of BF-OF steelmaking. Secondly, the construction period of EAF is shorter. The construction period of new production line of EAF is about 1 year to 1.5 years, and the construction period of BF-OF new production line is about 4 years.

The following results are based on the prediction of regional steel demand and EAF production in 2030 and 2050.

In the HDLS scenario (Figure 5), the EFS production in China will reach 20% in 2030 and 40% in 2050. In 2050, in Guangdong, Jiangsu, Shandong, and Sichuan, the EFS can meet all their steel demand, and scrap will have a surplus. According to the transportation matrix and LCOS, the remaining scrap steel in Jiangsu can be transported to Shanghai after EFS is produced locally. Shandong province can transport scrap steel to Hebei and produce EFS in Hebei province. Because there is little difference in LCOS between Guangxi and Guangdong, Guangdong can choose to transport excess scrap steel or EFS to Guangxi. Due to policy reasons, Beijing cannot realize local EFS production. Our results show that Beijing can transport scrap to Tianjin or Hebei to produce EFS in the future (Table 8).

Figure 6 presents the EFS production in LDLS scenario in 2030 and 2050. In this scenario, the total scrap supply can meet 33% and 77% of the national steel demand in 2030 and 2050. And in 2030, only Henan can achieve 100% EFS production and only has a little scrap reminding. In 2050, Hebei, Liaoning, Jiangsu, Zhejiang, Anhui, Shandong, Henan, Hubei, Hunan, Guangdong, Sichuan and Yunnan can achieve 100% EFS production. And the transportation model demonstrates the following result (Table 9).

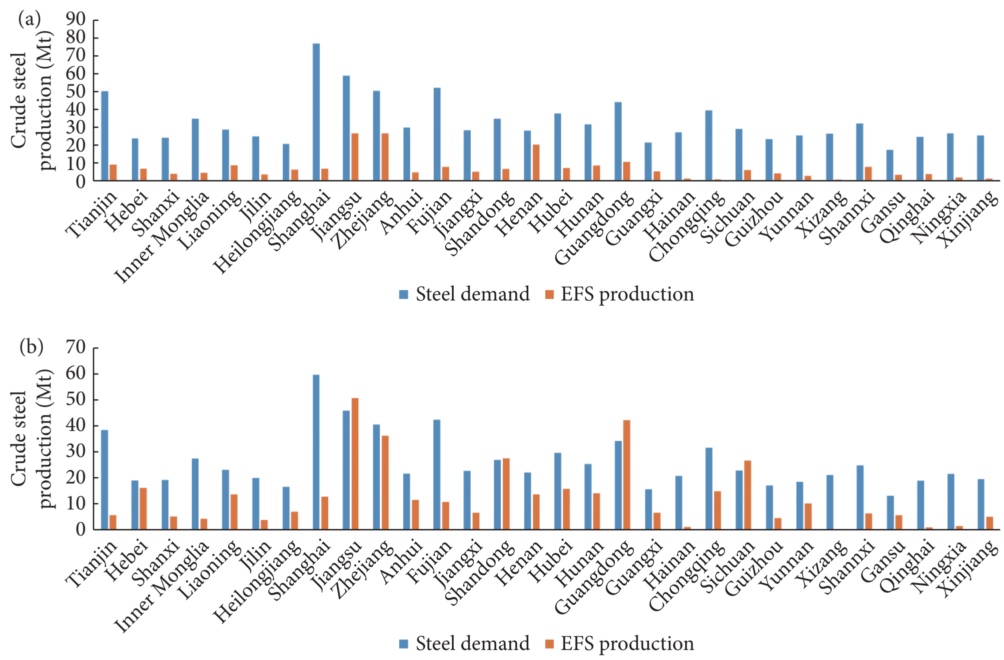

Fig. 5 Technology share in HDLS scenario in (a) 2030 and (b) 2050.

Table 8 Transportation method in HDLS scenario in 2050.

Region	Transport to	Material	100% EFS production?
Hebei	Tianjin/Beijing	EFS	N
Jiangsu	Shanghai	Scrap	Y
Zhejiang	Shanghai	Scrap	Y
Shandong	Hebei	EFS	Y
Guangdong	Guangxi/Hunan/Jiangxi	Both/scrap/scrap	Y
Sichuan	Chongqing/Guizhou	EFS/EFS	Y

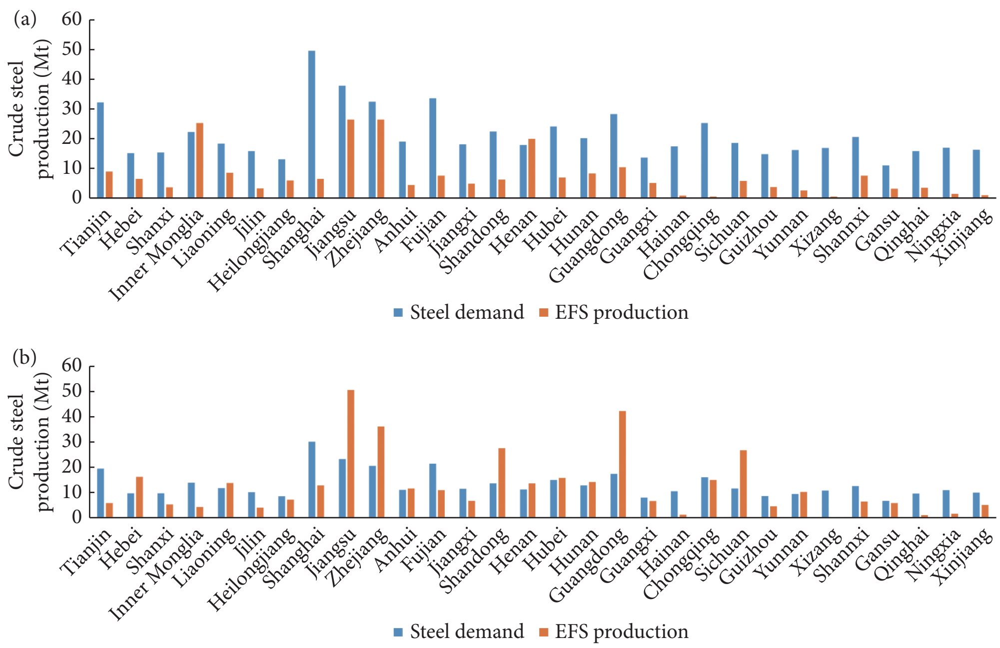

Fig. 6 Technology share in LDLS scenario in (a) 2030 and (b) 2050.

Table 9 Transportation method in LDLS scenario.

Region	Transport to	Material	100% EFS production?
Hebei	Tianjin/Beijing	EFS	N
Henan	Shanxi	EFS	Y
Shandong	Hebei	EFS	N
Guangdong	Guangxi/Hunan	Both/scrap	Y
Sichuan	Chongqing	EFS	N

In this scenario, 16 regions in China can achieve 100% EFS production. The province-level regions that have more scrap supply can directly transport the scrap or EFS to the regions next to them. The extra EFS produced in Shandong province can be transported to Hebei, and then the EFS produced in Hebei is transported to Beijing.

Figure 7 shows the EFS production in the HDHS scenario in 2030 and 2050. The EFS production in China will reach 26% in 2030 and 56% in 2050. In 2030, Anhui and Liaoning can achieve 100% EFS production. Therefore, the excess scrap can be transported to Jiangsu and Liaoning to produce EFS. In 2050, Hebei, Shandong, Guangdong, Henan, and Sichuan will achieve 100% EFS production. And the transportation model shows the following result (Table 9).

And in this scenario, seven regions in China can achieve 100% EFS production in China.

Figure 8 presents the EFS production in the LDHS scenario in 2030 and 2050. The EFS production in China will reach 49% in 2030 and 100% in 2050. In 2030, Inner Mongolia, Zhejiang, and Henan can achieve 100% EFS production. Therefore, the excess scrap can be transported to Liaoning from Inner Mongolia, and then Liaoning also can achieve 100% EFS production. And the excess scrap can be transported to Hubei to increase the EFS production.

In 2050, without transportation, 17 regions will be able to achieve 100% EFS production. And with transportation, all the regions can achieve 100% EFS production. The local scrap in most province-level reigons in the eastern region can meet the local demand for crude steel in 2050. Fujian, Shanxi, Jilin and other province-level regions can also achieve 100% EFS production through transportation from neighboring regions. However, due to the shortage of scrap steel supply in the western region, EFS accounts for a relatively small proportion. When we transport raw materials or EFS from the central or eastern regions to western region, it will significantly increase the transportation cost, thus reducing the competitiveness of EFS in the western region.

For the scrap supply, there is an uneven distribution in all scenarios, especially in the LDHS scenario. There is a shortage of scrap supply in the low LCOS area. Western regions such as Gansu and Xizang have low scrap reserves due to slow economic and industrial development. However, areas with enough supply of scrap are concentrated in middle LCOS and high LCOS. Therefore, when there is enough scrap, EFS can become the main production method for local zero carbon steel production for the eastern and central regions. Compared to H-DRI steelmaking process, the production of EFS will save the hydrogen costs. However, for the western region, additional transportation would be an uneconomical choice. However, the low-priced zero carbon electricity in these regions also provides possibilities for the future development of H-DRI in these province-level regions. Based on Xiang et al. and Jiang et al.'s study, in 2050, the hydrogen cost in the H-DRI steelmaking process in the western region will be lower than the transportation cost[9,20]. The scrap or EFS can only be transported between some neighboring cities in the central or eastern regions.

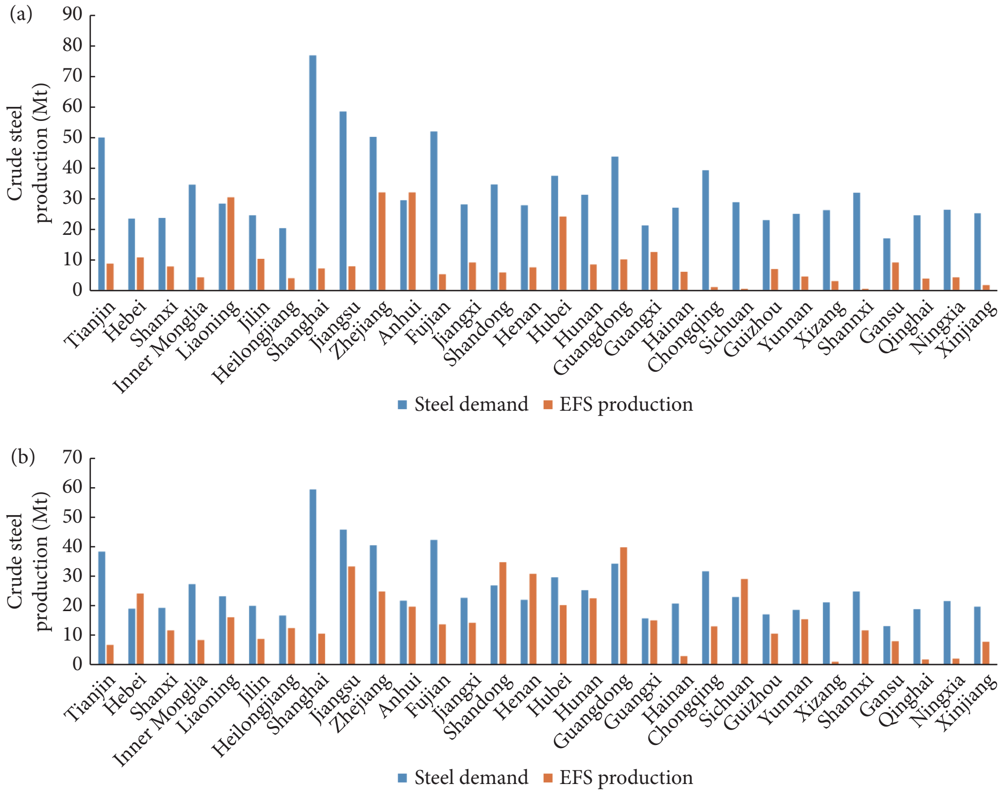

Fig. 7 Technology share in HDHS scenario in (a) 2030 and (b) 2050.

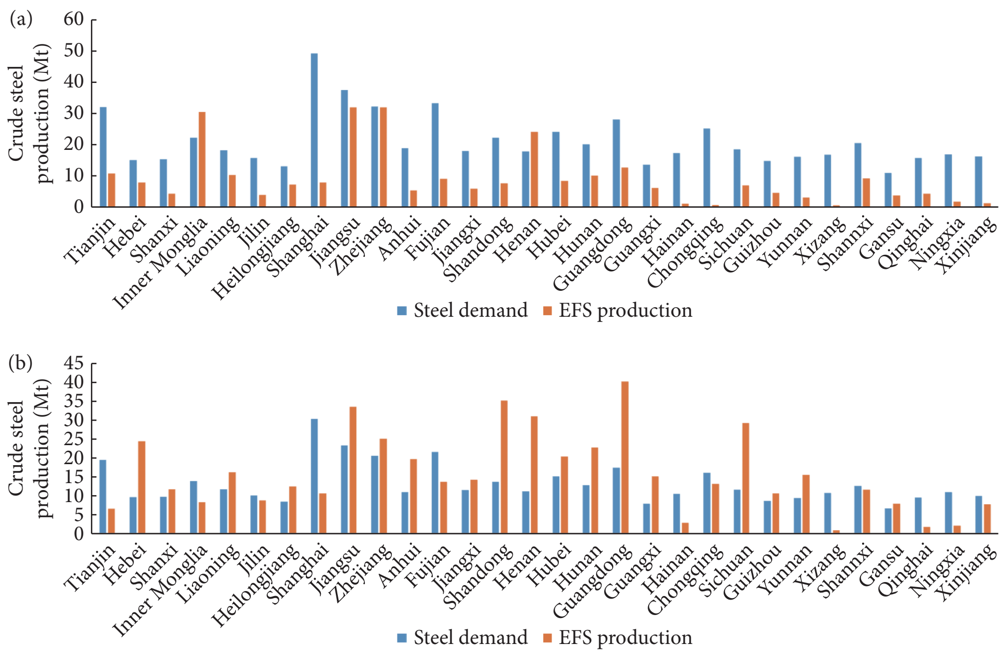

Fig. 8 Technology share in LDHS scenario in (a) 2030 and (b) 2050.

In addition, by 2023, the new production capacity of EAFs is over 100 million tons, and the average scale of newly built EAFs will be 120 tons. EAF capacity is characterized by large-scale development.

In this study, the annual production capacity of a 100t EAF could be 1.5 million tons. Ningxia, Qinghai, Xizang and Hainan due to the shortage of scrap, the regional EFS production will less than 1.5 Mt.

If only the large capacity EAF is installed, its working time will be greatly reduced, leading to an increase in average investment costs. Moreover, if the scrap steel from these province-level regions is transported to factories in specific locations, it will significantly increase transportation costs especially in Xizang and Qinghai with large areas. Transportation of scrap or EFS within the province-level region is generally carried out by road, and the cost of road transportation is also higher than railway transportation. However, these regions also have abundant and cheap solar resources. Due to the shortage of electricity supply and the high electricity price, China is keen to vigorously develop large-scale EAFs. Especially in some southern regions, affected by high temperatures in summer, the government has proposed a policy requirement of "making electricity accessible to the people", and all industrial power users have been shut down[46]. Serious impact on EFS production in these regions. But for these western regions, even with more electricity usage, the low zero carbon electricity prices make their LCOS competitive, and the electricity supply in western regions is much higher than that in other regions. For example, if Qinghai uses a 50-ton small EAF with a power consumption of about 500 kWh/t, the electricity price for producing 1 ton of EFS is 165 yuan/t. Jiangsu as the second crude steel producer in China and use energy-saving large EAFs, which produce 1 ton of EFS at electricity prices of 169 yuan/t. Although Qinghai uses high energy consuming EAF, its electricity cost is still lower than some regions, and the capital cost of small scale EAF is also lower. Therefore, installing small EAFs in some western regions would be a better choice to match scrap resources and optimize costs.

Although scrap steel availability remains a critical constraint for the deployment of EAF technology in western China, this limitation can be mitigated through targeted policy and infrastructure interventions. For instance, government subsidies and tax incentives could encourage interregional transportation of scrap from coastal to inland province-level regions. Additionally, investing in local recycling and dismantling facilities would enhance the regional scrap supply capacity. Developing digitalized reverse logistics systems and establishing interprovincial coordination mechanisms may also help balance supply-demand mismatches across regions.

Compared to the 2020 EAF production capacity distribution (Figure 3), there is clearly potential to increase production capacity in the western region. Due to high transportation costs and continuously decreasing electricity costs, all province-level regions will be equipped with electric furnace steel by 2050.

Figure 9 also shows that the LCOS of EFS will continue to decline in the future. As the supply of scrap steel increases, the price of scrap will correspondingly decrease based on the supply and demand relationship in the market. It may even form price competition with iron ore. When China can recycle more local scrap, it can also reduce its dependence on imported iron ore.

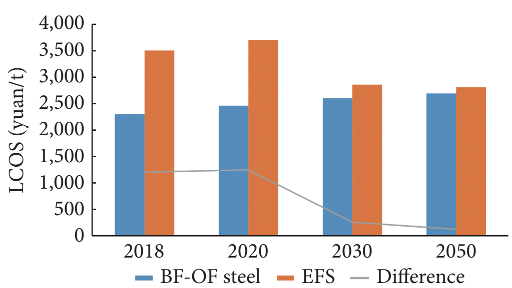

Fig. 9 LCOS difference between BF-OF steel and EFS.

6 Conclusion

This study explores an EAF production location under the carbon neutral goal by developing a technology assessment. While the EAF development in China has been widely studied, this paper focuses on assessing the regional development potential and cost competitiveness.

The following conclusions were drawn from this research:

(1) With the increase of scrap steel, the production of EFS increases in all scenarios, especially in LDHS scenarios, which can reach 100% EFS production in China. Some experts also declare that "the era of all scrap steel will surely come" in the next few decades, when the supply of scrap steel will exceed the demand for steel, which is consistent with our conclusion.

(2) In all scenarios, the supply of scrap steel in the western region is in short supply. At the same time, due to the large area, the transportation cost is extremely high. Therefore, transporting scrap steel or EFS to the western region is not cost competitive. In addition, due to its cheap and abundant solar energy, the western region will have greater potential to develop H-DRI steelmaking technology.

(3) With the decrease of electricity cost and the application of energy-saving technology, the electricity cost accounts for a relatively small proportion in the LOCS. Although some areas have lower electricity costs, even the transportation costs between neighboring province-level regions are greater than the difference between the two regions electricity price. Therefore, when scrap is available, EFS should be produced locally. When there is not enough scrap steel supply locally, considering transportation of scrap or EFS from neighboring regions can be a choice.

(4) The policy has a great influence on the location of steel refinery, because the government can attract factories to a certain area by reducing taxes or exemptions and reducing land rents. For example, if steel refineries are built in Qinghai and Xizang, the production capacity can be replaced equally. At the same time, Qinghai and Xizang are economically underdeveloped areas, and the steel industry is capital-intensive and labor-intensive, with obvious economic driving effect.

(5) With the decrease in electricity prices, the EAF production capacity in the western region has significantly increased. And it has the potential to install small EAFs. EAF has the potential to move westward.

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Author contribution statement

Weiyi Jiang is responsible for conceptualization, methodology, investigation, data curation, and writing—original draft preparation. Tae-Yong Jung is responsible for supervision, project administration, funding acquisition, and writing—review & editing. Hancheng Dai is responsible for supervision,validation, and formal analysis. Pianpian Xiang is responsible for resources, visualization, and methodology. Sha Chen is responsible for review & editing, and conceptualization.

Data availability

The data that support the findings of this study is available from the corresponding author upon reasonable request.

Use of AI statement

During the preparation of this work, Deepseek was only used to check for grammar and spelling errors in this manuscript. AI tool was solely employed to improve the linguistic accuracy of the text without participating in any intellectual content creation, including but not limited to conceptualization, methodology, data analysis, and discussion of research findings. The final content of the manuscript was independently reviewed and confirmed by all authors.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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