International Journal of
Science and Engineering Investigations
vol. 7, issue 73, February 2018
ISSN: 2251-8843

The Optimal Technological Development Path to Reduce Pollution and Restructure Iron and Steel Industry for Sustainable Transition

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Abstract- China is the world's largest iron and steel producer and Jing-Jin-Ji (Beijing-Tianjin-Hebei) region accounts for nearly 1/3 of the national iron and steel production, while it is facing serious air pollution. Among the top 10 worst polluted cities in China, seven were located in Hebei province in 2014. Recent years Jing-Jin-Ji region has been promoted iron & steel industry with green clean technology for accelerating sustainable economic transition. This paper tries to response the basic questions: How can we reduce pollution and restructure the iron and steel industry for sustainable economic transition in Jing-Jin-Ji? How can the iron-steel industry achieve its 13th five year plan targets? How does its outlook look like in the next 10 years? For the analysis, we develop a dynamic optimization model to explore the optimal technological development path of iron and steel industry under the environment (CO_2, SO_2, NO_x, and $PM_{2.5}$) in combing with overcapacity reduction targets over the next 10 years. The results show that increasing capacity of scrap-EAF and DRI-EAF technologies can significantly co-decrease CO_2, SO_2, NO_x and $PM_{2.5}$ by 50%, 60%, 57%, and 62% respectively. The optimal technological portfolio indicates that the production share of EAF technology will increase with the potential increase trends of scrap volumes. The paper indicates that in China, iron and steel production shift from BOF to EAF technology is an optimal way for lower energy/CO_2 and air pollutants emissions, and for iron and steel industry transition to green and sustainable development. The paper argues that reducing iron and steel production volume does not mean stopping iron and steel industry development, but low-carbon and green development in the iron & steel industry, it can achieve the goal for sustainable transition in the region.

Keywords-*Iron and Steel Industry, Pollution and Emission, Optimal Technological Portfolio, Dynamic Optimization Model*

I. INTRODUCTION

China, the world's largest steel production area, is facing serious air pollution problems, especially in Jing-Jin-Ji region. Of the top 10 worst polluted cities in China, seven were located in Hebei province in 2014[1]. Air pollution is affecting health and quality of life in this region. The iron and steel production of Jing-Jin-Ji accounts for nearly 1/3 of China's iron and steel production [2], which is a main energy consumer and one of major air pollution sources in the region. In 2014, the emissions of SO2, NOx, and dust from iron and steel industry accounted for 27.75%, 13.56% and 17.17% of total industrial emissions in Jing-Jin-Ji region [3]. Given the importance of this industrial sector, the Chinese government has issued a series of policies and regulations aims to eliminate backward and excess capacity[4], introduce advanced technologies with lower energy/CO_2 [5] and air pollutants [6] emission, and encourage iron and steel industry transition to green and sustainable development.

The Jing-Jin-Ji region is the seat of China's central government, one of the fastest-growing urban areas, and one of the most important industrial zones in China—has the potential to dramatically reduce emissions and lead the way for China's nationwide transformation toward a more sustainable economic model. Jing-Jin-Ji region is well-positioned to become a model for the rest of the country, and potentially for the globe. The main reasons are: the region's size, diverse economic mix, and strong policy and regulatory environment contribute to its potential to transition its economy; Hebei Province, currently the most industrial part of the region, has existing manufacturing infrastructure and strong wind and solar resources that could provide the basis for a significant increase in clean, renewable energy production and deployment.

How can we reduce pollution and restructure the iron and steel industry for sustainable economic transition in Jing-Jin-Ji Region? The paper argues that reducing iron and steel production volume does not mean stopping iron and steel industry development, but circular, low-carbon, and green development in the iron & steel industry, so that it can achieve the goal of transition to green and low-carbon iron-steel industry in the region.

As China's products and infrastructure enter the replacement phase, the growing availability of scrap is likely to fuel a shift from steelmaking based on oxygen furnace (BOF) technology to electric arc furnace (EAF) technology that relies more heavily on scrap. With the increase supply of scrap and natural gas, scrap based EAF technology and natural gas-based DRI technology can be introduced as clean production routes, which have potentially lower environmental footprint. Reliance on electricity and natural gas as cleaner and cheaper sources of energy can lead in the short- and in the long-run to significant improvement of environmental quality without sacrificing profits.

With aim to explore how to reduce pollution and restructure the iron and steel industry for sustainable economic transition in Jing-Jin-Ji Region over the next 10 years, this paper focus on the technology innovations and their diffusion paths under the environmental and resource efficiency performance targets under restructuring of Iron and Steel industry process. We develop a dynamic optimization model, which includes current and future advanced alternative iron and steel production technologies along with environment (CO_2, SO_2, NO_x, and $PM_{2.5}$) and overcapacity reduction targets.

The structure of the paper is as follows. Following the instruction, section 2 detailed analysis of technology innovation trends and strategic outlook in restructure the iron and steel industry; Section 3 describes the framework of the model and data; Section 4 presents the results and discussion. Section 5 summarizes the conclusions.

II. BACKGROUND

A. Technology innovation trends

It is difficult to further decrease the energy, consumption, CO_2 and air pollutants emissions, if the steel and iron industry does not introduce novel breakthrough technologies. The improvement of energy efficiency as well as the compliance with environmental standards is possible only through the introduction of alternative cleaner iron and steel production routes based on scrap or natural gas, which are expected to play an increasingly significant role in the iron and steel industry[7].

Currently, there are two main routes of technologies) for iron and steel production in China. In Jing-Jin-Ji region, the share of BF-BOF and EAF are 99% and 1% respectively [8]. The liquid steel obtained through both routes is cast into semis and further processed in mills. Apart from blast furnace (BF), alternative technologies for ironmaking is natural gas based direct iron ore reduction (DRI) technology, and then the iron ore reduction can be fed to EAF. The current existing BF-BOF and EAF technologies and the advanced future DRI technology is listed in table I and table II, which shows different composition of raw materials, energy consumption intensity, air emission intensity and cost.

1) Traditional Integrated Iron and Steel Production Route BF/BOF

The blast furnace-basic oxygen furnace (BF-BOF) route is traditional iron and steel production process, in blast furnace iron ores are reduced to metallic iron using coke as a reductant and energy source and subsequently converted to steel in the basic oxygen furnace (BOF). The integrated route is based on the reduction of iron ore and relies on the use of coke, sinter, blast furnaces and Basic Oxygen Furnace (BOF) converters [9]. This route of iron production typically involves the sintering of fines, which is the most polluting component of the ironmaking process [10].

2) Electric Arc Furnace (EAF) Using Recycled Steel Scrap

This route is called “recycling route” uses scrap as raw material. The main energy requirement is electricity, which is used for smelting the scrap material. In this process, the coke production, pig iron production, and steel production steps are omitted, resulting in much lower energy consumption and a primary energy intensity [11]. EAFs are a less energy and air emissions intensive way of making steel [12]. However, prospective reductions by shifting from BOF to Electric Arc Furnace (EAF) is confined by the scrap availability and its quality.

3) Direct Reduction Iron- Electric Arc Furnace (DRI-EAF)

One alternative method for ironmaking are based on direct iron ore reduction (DRI) technologies where the coke making requirement is avoided and iron ores are reduced directly to sponge iron in a shaft furnace with either coal gas or natural gas (via hydrogen and/or CO) as the reductant, the sponge iron and steel scrap is then melted in an electric arc furnace in order to obtain crude steel [13]. Globally, natural gas is widely preferred and used in the leading processes Midrex. For Jing-Jin-Ji region of China, DRI technology can be introduced as natural gas availability is increasing, and the Chinese government is encouraging iron and steel industry to increase the share of natural gas in energy structure.

Based on the increasing supply of scrap [14], the share of Electric Arc Furnace (EAF) steel production will increase significantly to 30% in 2025. With the increase supply of natural gas and serious air pollution in Jing-Jin-Ji region, Chinese government is encouraging iron and steel sector to adjust its energy structure and increase the share of natural gas to 15% in 2020 and 20% in 2025[13].

TABLE I. THE ENVIRONMENT INDEXES OF DIFFERENT IRON AND STEEL PRODUCTION ROUTES.

Emission intensity of different iron and steel production routes			
Routes	resource/emissions	Unit	emission intensity
BF/BOF	CO_2	t/ton steel	2.10
	SO_2	kg/ton steel	1.21
	NOx	kg/ton steel	0.83
	$PM_{2.5}$	kg/ton steel	1.59
Scrap-EAF	CO_2	t/ton steel	0.70
	SO_2	kg/ton steel	$7.40*10^{(-4)}$
	NOx	kg/ton steel	0.04
	$PM_{2.5}$	kg/ton steel	$3.00*10^{(-3)}$
DRI-EAF	CO_2	t/ton steel	1.10
	SO_2	kg/ton steel	0.19
	NOx	kg/ton steel	0.24
	$PM_{2.5}$	kg/ton steel	0.08

TABLE II. THE RAW MATERIALS AND ENERGY CONSUMPTION INTENSITY OF DIFFERENT IRON AND STEEL PRODUCTION ROUTES.

Raw materials/ energy intensity of different steel routes			
Routes	Raw materials/energy	Unit	Raw materials/energy intensity
BF/BOF	Coal	GJ/t	14.9
	electricity	GJ/t	0.90
	Natural gas	GJ/t	0.00
	scrap	t/t	0.00
	Iron ore	t/t	1.44
Scrap-EAF	Coal	GJ/t	2.20
	electricity	GJ/t	1.80
	Natural gas	GJ/t	0.00
	scrap	t/t	1.00
	Iron ore	t/t	0.00
DRI-EAF	Coal	GJ/t	0.00
	electricity	GJ/t	1.00
	Natural gas	GJ/t	17.50
	scrap	t/t	0.00
	Iron ore	t/t	1.44

B. *Strategic outlook towards to lower energy consumption and reducing emissions*

In recent years the government has adopted strict measures to reduce the overcapacity in iron and steel industry. Hebei [15] promised to cut crude steel capacity to less than 200 million ton by the end of 2020. Steel capacity in Beijing will be removed gradually. Tianjin plans to cut its steel capacity to less than 17 million ton by the end of 2020. Regarding to the near future strategic outlook towards to lower energy consumption and emissions, and then we combine two parts up to 2025: the 13th Five-Year Plan to 2020, and we assume that the 14th plan will following the path of the 13th plan up to 20205. Both of the plan and scenario have two dimensions: production and environmental targets. The steel output in 2020 and 2025 are predicted to be 179.78 and 132.14 million ton, respectively Jing-Jin-Ji region.

Adjustment and upgrading plan for iron and steel industry (2016-2020) states that during the "13th Five-Year Plan" total air emission will decrease 15%, and sulfur dioxide emissions per ton steel will decrease by 20%. During 2015-2025, we set total SO_2, NOx and $PM_{2.5}$ emission will decrease by 15%, 15%, and 20% every five years, respectively.

III. METHODOLOGY

A. *Parameters and structure of dynamic optimization module*

Based on the 13th five year plan and the assumed 14th five year plan for the iron and steel industry in Jing-jin-ji region, we analysis the optimal technological development path of iron and steel industry for the next 10 years, and develop a dynamic integrated modeling framework by using linear programing methodology. The model includes current and future advanced iron and steel production technologies along with comprehensive constraints on energy and environmental (CO_2, SO_2, NO_x, and $PM_{2.5}$), while combine production reducing plan and scrap and natural gas availability. The optimization model enables the adoption and operation of iron and steel production technology in Beijing, Tianjin, and Hebei under the constraints of scrap, natural gas availability, and CO_2, SO_2, NO_x, and $PM_{2.5}$ reduction targets to meet the steel demand with minimum costs. This model can offer the alternative options for decision making on investments and operation of technologies. The model structure is shown in Figure 1, which includes dynamic optimization module, and input & output.

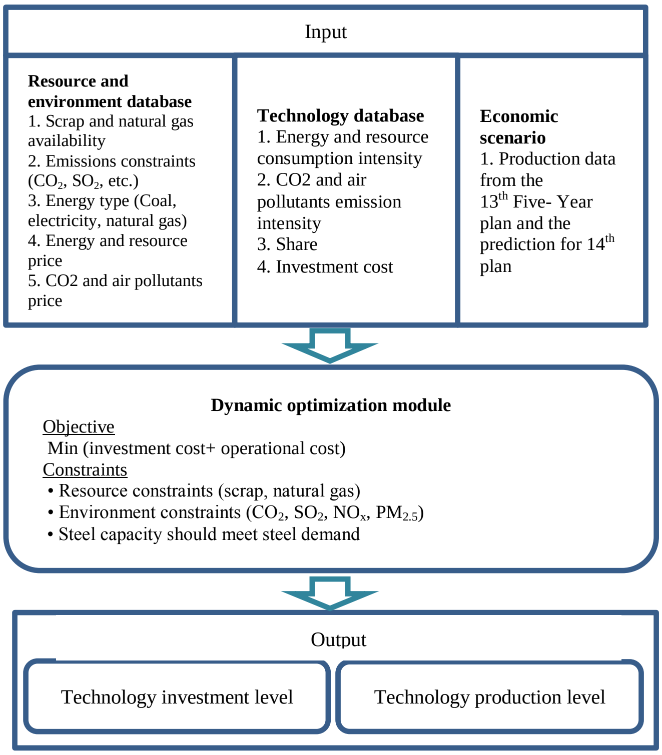

Figure 1. The dynamic optimization model structure

B. *Mathematical function*

The model is established based on the linear programing methodology, index *i* stands for the iron and steel production technologies, *i=1,…,n*. Indexes *j* and *k* identify iron and steel production locations, for example, Beijing, Tianjin, and Hebei, and *m* is the number of iron and steel production locations (in this study *m=3*); *t* denotes simulation time interval, *t=1,…,T*, the planning (modeling) time horizon is from 2015 to 2025 with a 5-years' time step; variables x_{ij}^t define newly introduced capacity of technology *i* in region *j* at time *t*; variables y_{ijk}^t define operational decision on how much of steel is produced by technology *i* in region *j* and transported to region *k* at time *t*.

The objective function is represented in (1), including the investment cost and the operational cost

$$\min_{x,y} \sum_{t=1}^{T} \sum_{i=1}^{n} \sum_{j=1}^{m} \left(c_{ij}^t x_{ij}^t + \sum_{k=1}^{m} q_{ijk}^t y_{ijk}^t \right) \qquad (1)$$

where:

c_{ij}^{t} is the unit investment cost of technology *i* in region *j* at time *t*;

q_{ijk}^{t} is the operational cost of technology *i* to produce unit of steel produce in region *j* and transport to region *k* at time *t*, the operational cost includes raw material (iron ore, scrap) cost, energy (coal, natural gas, and electricity) cost, emission (CO_2, SO_2, NO_x, and $PM_{2.5}$) cost, transportation cost, and the operational cost can be calculated based on consumption intensity, emission intensity, and transportation distance multiply by their prices.

The cumulative capacity of technology *i* in region *j* at time *t* is denoted by S_{ij}^{t}. Formula (2) presents the dynamic changes of cumulative capacity:

$$\begin{cases} S_{ij}^{t} = S_{ij}^{t-1} + x_{ij}^{t} - x_{ij}^{t-L_i} \\ i = 1, \cdots, n, t = 1, \cdots, T \end{cases} \tag{2}$$

where:

L_i is the life time of technology (steel facility) *i*;

S_i^0 is initial capacity of technology *i* existent before *t=1*

The model use exogenous steel demand. The steel demand in each region *k*, at time *t* is met by producing in *j* and importing to *k* of y_{ijk}^{t} units of steel. Formula (3) defines the constraints on steel production

$$\sum_{j=1}^{m} \sum_{i=1}^{n} y_{ijk}^{t} \geq d_k^t \tag{3}$$

where:

d_k^t is steel demand in region *k* at time *t*.

Constrains (4) and (5) mean that steel production cannot exceed steel production capacity of technology *i* in region *j* and time *t*,

$$\begin{cases} \sum_{k=1}^{m} y_{ijk}^{t} \leq \gamma_{ij}^{t} S_{ij}^{t} \\ j = 1, \cdots, m \end{cases} \tag{4}$$

$$y_{ijk}^{t} \geq 0 \tag{5}$$

where:

γ_{ij}^{t}, $1 \leq \gamma_{ij}^{t} \leq 1$ determines the availability factor of technology *i* in region *j* at time *t* characterizing the actual production of steel by technology. Obviously $\gamma_{ij}^{t} = 0$ for not yet existing technologies.

Each technology *i* is characterized by its set of input-output (conversion) coefficients $a_{i,r}^{t}$, which define the amount of input resources of type *r* (*r=1, 2* stand for scrap and natural gas respectively) to produce one unit of product (steel) by technology *i* (*i=1,…, m)*) in region *j* at time *t*; $R_{j,r}^{t}$ is resource availability of *r* in region *j* at time *t*. For resource supply, the supply of scrap and natural gas are limited. So the constraint on resource availability in region *j* at time *t* considered and expressed as Eqs. (6)

$$\sum_{k=1}^{m} \sum_{i=1}^{n} a_{i,r}^{t} y_{ijk}^{t} \leq R_{j,r}^{t} \tag{6}$$

In order to tackle climate change and reduce air pollution, Chinese government has set CO2 reduction target and total air pollutants (CO2, SO2, NOx, or PM2.5) reduction targets for iron and steel industry. The air emission targets constraint is shown as Eqs. (7)

$$\sum_{k=1}^{m} \sum_{i=1}^{n} ER_i^{t,g} y_{ijk}^{t}(\omega) \leq Em_j^{t,g*} \tag{7}$$

where:

$ER_i^{t,g}$ is emission rate of *g* by technology *i* at time *t*;

$Em_j^{t,g*}$ is emission target *g=1.2.3.4* stand for CO_2, SO_2, NO_x, and $PM_{2.5}$ respectively.

C. *Prices of feedstock, investment cost, and emissions accounting*

1) *Prices of feedstock*

The main feedstock of alternative iron and steel production routes are iron ore, scrap, coal, electricity, and natural gas. In 2015, the price of iron ore [16] was 74$/ton, coal price [17] – 3.629 $/ GJ, scrap [18] price - 247 $/ ton, electricity price [19] – 36.03 $/ GJ, natural gas [20] price – 12.99 $/ GJ.

2) *Investment costs*

In 2015, the investment cost of BF/BOF, scrap based EAF, and DRI-EAF were 423.10, 173.68, and 365.36 $ per ton steel every year respectively [21].

3) *Other cost and prices*

In 2015, the price of CO_2, SO_2, NO_x, and $PM_{2.5}$ were 0.00585, 1.6387, 1.3152 and 2.8916$ per kilogram respectively [22]. Transportation cost was 0.49 $ per kilometer per ton steel in 2015. Technology life is assumed to be 20 years [23].

The basic year price is based on 2015, and then we consider an increase of 15% per year for all the prices and investment costs.

IV. RESULTS AND DISCUSSION

A. *Optimal technology development trends*

The dynamic optimization model result for technology paths is shown in Figure 2. Because of high investment costs, CO2 and air emissions intensity, the traditional integrated BF/BOF route is gradually replaced by alternative technologies. The shares of scrap-EAF route and DRI-EAF route slowly increase. The penetration rates of scrap-EAF route are 20% and 28% in 2020 and 2025 respectively, which are limited by the scrap availability. The penetration rates of DRI-EAF route are 9% and 12% in 2020 and 2025 respectively. So, scrap-EAF route is more cost-effective with lower investment cost and better environment performance. With the stricter environment constraints natural gas based DRI-EAF route will be introduced, however for the high natural gas price this route develops rather slowly.

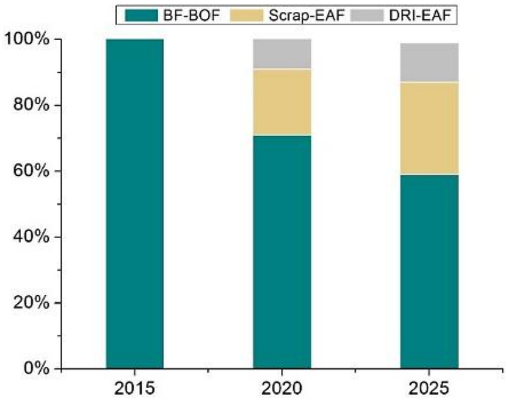

Figure 2. Technology development pathway of the iron and steel industry

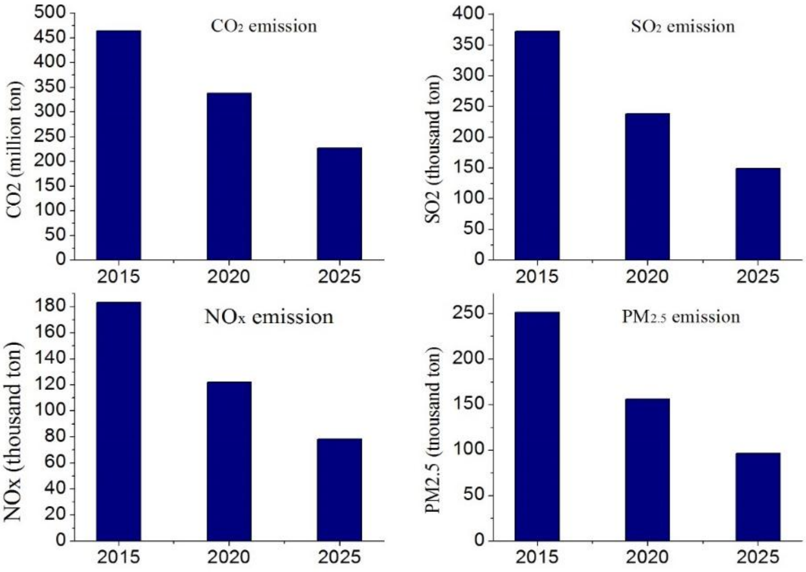

Figure 3. Air emissions 2015-2025 in Jing-Jin-Ji region

B. *Downward trend of emissions when promoting the green Technologies*

Figure 3 indicates air emissions in Jing Jin Ji region, which showing a clear downward trend over the next 10 years.

CO_2 emission in 2015, 2020 and 2025 are 0.46, 0.34 and 0.23 billion ton respectively. By 2025, 50% CO_2 emission will be saved compared with 2015.

SO_2 emission during 2015-2025 in Jing Jin Ji region shows a clear downward trend during 2015-2025. SO_2 emission in 2015, 2020 and 2025 are 0.37, 0.24 and 0.15 million ton respectively. By 2025, 60% SO_2 emission will be saved compared with 2015.

NOx emission in 2015, 2020 and 2025 are 183.23, 122.21 and 78.29 thousand ton respectively. By 2025, 57% NO_x emission will be saved compared with 2015.

$PM_{2.5}$ emission in 2015, 2020 and 2025 are 251.90, 156.16, and 96.47 thousand ton respectively. By 2025, 62% $PM_{2.5}$ emission will be reduced compared with 2015. One reason is that the output of steel in Jing-Jin-Ji region will decrease 37% in the planning horizon. Another reason is the introduction of alternative technologies like scrap based EAF technology and DRI-EAF technology, which have lower $PM_{2.5}$ and other air emissions intensity.

V. CONCLUSIONS

Iron and steel industry is one of the biggest energy consumers and air emission sources. It is difficult to further decrease the energy, consumption, air pollutants and emissions, if the steel and iron industry does not introduce novel breakthrough technologies in Jing-Jin-Ji region.

With an integrated manner, we build a dynamic optimization model to explore the optimization technology paths for sustainable iron and steel growth, which aims to meet the high standards for coal control, low carbon, and emission reduction for Jing-Jin-Ji region up to 2025. The optimal technology pathway is endogenously determined based on cost minimization criteria under three dimensions: 1) emissions reduction targets; 2) scrap and natural gas availability; and 3) production output. Our results show that decreasing CO_2, SO_2, NO_x, and $PM_{2.5}$ emissions can be collectively controlled in iron and steel industry, if the Jing-Jin-Ji region increases the Scrap-EAF and DRI-EAF rotes in the iron and steel production process.

Reducing iron and steel production volume does not mean for stopping iron and steel industry development, but is for development of circular, low-carbon and green development in the iron & steel industry. The key remarks are included:

In the next 10 to 15 years, the increase supply of scrap and natural gas are likely to fuel a shift from steelmaking based on basic oxygen furnace (BOF) technology to electric arc furnace (EAF) technology and DRI technology, which have lower environmental footprint and lower investment cost. However, their diffusion relies on scarp and natural gas availabilities and their prices. Under stricter air pollution and climate change constraints, the integrated BF-BOF route will be replaced gradually to a certain extent for its high CO_2 and air pollutants emissions.

By comparing cost to produce one ton steel of the three different route we can find that the cost of scrap based EAF route is the lowest. The Scrap based EAF route not only has the lowest environmental footprint but has the lowest cost. The cost of natural gas based DEI-EAF route is higher than the traditional BF-BOF route, in which it relies on the price of natural gas that higher than coal, however the natural gas based DEI-EAF route has lower environmental footprint, so under the strict constraints of air pollution emission this route will be introduced in the future. To what extent is the region ready to allow the steel industry to make the switch from BOF to EAF? Perhaps the biggest challenge for the scrap industry lies in tradeoff decision between the profit and environmental protection and willingness to make the shift to EAF technology.

In particular to Heibei province, it prioritizes iron and steel industry, especially in renewable energy and energy efficiency since these industries have strong growth and job creation potential. But given the region's high local demand, excellent wind and solar resources and good transmission connection to neighboring regions, that the province can benefit economically and environmentally from greater investment in wind and solar.

ACKNOWLEDGMENT

The authors are grateful to the fund from the Natural Science Foundation of China (NSFC: 71403270) and Ministry of Environmental Protection of the People's Republic of China (2015207010161), and thank you for the YSSP supervision in IIASA.

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