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A technology-based analysis of the water-energy-emission nexus of China's steel industry

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ABSTRACT

Steel production is a main water consumer, energy consumer, and a major source of air pollution in China. To mitigate the steel industry's environmental pressures, the government is promoting several water-saving, energy-saving, and emission-reduction technologies. This study developed a technology-based approach to investigate the water, energy and emission nexus (WEEN) of the steel industry. The results indicate that 4.1 m^3 of water use and 21.4 kWh of electricity use were related with the WEEN per ton of crude steel production in 2014, which accounted for around 66% of the total water use and 7% of electricity consumption of steel production, respectively. Of the WEEN water consumption, 66% and 34% was for cooling and emission control, respectively; 96% of the WEEN electricity consumption was for emission control. The water-energy-SO_2 nexus was more intensive in the coking and sintering processes, whereas the water-energy-dust nexus was more intensive in the steel-making process. Diffusion of advanced technology and improved raw material quality can reduce existing SO_2 and NO_x emissions by 57% and 25%, although at the expense of 5%, 56%, 0.2%, and 40% increases of dust emissions, water consumption, energy consumption, and costs, respectively. Technology sets identified by the Pareto optimization method can reduce the SO_2, NO_x and dust emissions by 97%, 50%, and 75%, respectively, and water and energy consumption can be reduced by 10% and 2%, respectively; however, costs could increase by 51–74%. This study highlights the need and opportunities for integrating emissions and resource use in nexus studies and production planning.

1. Introduction

The Chinese steel industry makes up nearly half of the world's crude steel production by volume (World Steel Association Steel, 2015). While contributing 4.1 trillion RMB Yuan to China's economy (11% of the total industry gross output) (, 2015), the steel industry accounted for 22% (or 7% of water withdrawal), 24% (in 2013), 14%, 8%, and 34% of the country's industrial water consumption, energy use, SO_2, NO_x, and dust emissions, respectively (National Bureau of Statistics China, 2015; Ministry of Environment Protection, 2015) in 2014. Approximately 23% of Chinese crude steel, which is 1.6 times the production volume of Japan, the world's second largest steel production country (World Steel Association Steel, 2015), was produced in Hebei Province (National Bureau of Statistics, 2015). Among all industries in Hebei, the steel industry contributes the largest water withdrawal (28%) and energy consumption (52%) (Hebei Government, 2015) and is a top emitter of NO_x, SO_2, and dust (Hebei Environment Protection Agency, 2015). As global overcapacity continues to weigh on the steel industry and the province's prevailing water shortage and air pollution worsen, the central and provincial governments recently introduced strict regulations to reduce existing steel production capacity and upgrade technologies (The State Council; Hebei Government, 2014). Both productive (mainly referring to water and energy savings) and auxiliary (mainly referring to pollution control) technologies, especially those affecting the coupled relationships of water use, energy consumption, and air pollution, i.e., the water-energy-emission nexus (WEEN), will play a critical role in achieving environmental goals.

Existing nexus studies have focused on the coupled relationships between the water and energy sectors and have revealed the water and energy implications associated with implementing various processes and technologies designed to provide water services (Stillwell et al., 2011; Lofman et al., 2002; Cutter et al., 2014; Mo et al., 2014; Wang et al., 2012; Scott et al., 2009; Wakeel et al., 2016; Mo et al., 2010) or energy services (Stillwell et al., 2011; Lofman et al., 2002; Yang and Chen, 2016; Huang et al., 2016; Zhang et al., 2016a; Macknick et al., 2012; Ma et al., 2015). The scope of the water-energy nexus studies has also been extended to relevant environmental impacts, greenhouse gas (GHG) emissions, and climate change implications (Mo et al., 2014; Liu

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et al., 2011; Nair et al., 2014; Hu et al., 2008). Despite the facts that the extraction and use of fossil fuel are pollution-intensive (Nansai et al., 2003; Edgar Hertwich and Larderel, 2016; Menyah and Rufael, 2010) and pollutant removal processes require substantial water and energy inputs (Yan et al., 2006), pollutants (e.g., SO_2, NO_x, dust, and COD) have been largely neglected in existing water-energy nexus literature. Studies have demonstrated that the application of pollution mitigation technologies may have synergistic effects or trade-offs regarding water and energy consumption (Yan et al., 2006; Feeley et al., 2008; Liu and Wen, 2012) and the emissions of other pollutants (Fang et al., 2011; Yu et al., 2007; Li et al., 2014).

Water-energy nexus studies have increasingly begun to investigate the technical solutions or policy interventions that can satisfy multiple goals, such as minimizing energy use and water pollution (Wen et al., 2015), energy use and water consumption (Siddiqi and Anadon, 2011; Hussey and Pittock, 2012), and environmental impacts and economic costs (Cristóbal et al., 2012; Luo et al., 2014). To better elucidate the effects of technologies within the complex industrial processes, technology was used as the basic unit in several nexus analyses (Macknick et al., 2012; Larsson and Dahl, 2003; Worrell et al., 2001; Gadipelly et al., 2014; Walker et al., 2014). The process-based, systems analysis approach and material flow analysis (MFA) have been successfully employed to simulate the complex industrial system (Colledani and Tolio, 2013; Thiede et al., 2016; Duflou et al., 2012). Despite the importance of the industrial sector in energy consumption (Cai et al., 2016; Javied et al., 2016; Xu et al., 2012; Rérat et al., 2012), water use (Ölmez and Kretzschmar, 2009; Porter et al., 1972), and pollutant emissions (Huo et al., 2014; Wen et al., 2016), there are few integrated studies in the literature of the three dimensions, i.e., the water-energy-emission nexus, as a whole. Kyle (Kyle et al., 2016) extended the concept to "*water and energy for other purposes*", that is, processes use water and energy as inputs to produce products or services that are neither water- nor energy-related.

For the steel industry in particular, recent research has emphasized overall environmental impacts (Yellishetty et al., 2011; Strezov et al., 2013; Hasanbeigi et al., 2016), the influences on local environments with respect to both quality and quantity (Dai, 2015; Qing et al., 2015), and the optimal resource use of the production processes as a result of technical advancements and economic driving forces (Johansson and Söderström, 2011; Wang et al., 2007a; Sheinbaum et al., 2010; Andersen and Hyman, 2001; Lin et al., 2011; Johansson, 2015; Wang and Lin, 2017; Yang et al., 2016; Tian et al., 2013; Mousa et al., 2016; Vadenbo et al., 2013; Xuan and Yue, 2017; Wang et al., 2011). The energy consumption (Costa et al., 2001; Chen et al., 2014; Li and Zhu, 2014; Li et al., 2016), water consumption (C-k et al., 2016), and pollutant generation or emissions mitigation (Wu, 2015; Wang et al., 2016; Olmez et al., 2016; Xu et al., 2016; Guo et al., 2017; Ma et al., 2012) have been calculated from the microscopic view of technology choices (Guan et al., 2015; Yilmaz et al., 2015; Liu and Yuan, 2016; Zhang et al., 2016b; Lin and Wang, 2015; Yu et al., 2015; Kuramochi, 2016; Colla et al., 2016; Hasanbeigi et al., 2014; McBrien et al., 2016; Huisingh et al., 2015; Wang et al., 2017) or technology combinations (Quader et al., 2015; Lu et al., 2016). For example, sintering is responsible for particulate matter emissions (e.g., its emission factor is 40 times higher than that of the steel-making process) (Guo et al., 2017) and SO_2 emission (e.g., 58% of total SO_2 emission) (Ma et al., 2012). Moreover, the relationship between different environmental aspects, e.g., the water footprint for energy consumption (Gu et al., 2015), has been quantified. Still, the relationships between pollutant control and resources consumption in specific processes as well as the entire industry are not yet well understood. What are the energy and water requirements of pollution control and how do different technology choices with regard to pollution control, water use and energy supply influence water and energy use as well as pollution levels?

In this study, the water-energy-emission nexus (WEEN) was defined as *water consumed for providing energy services and/or emission control* and *energy used to enable water services and/or pollution control*. Using individual technology as the basic analytical unit, the WEEN of the steel industry in Hebei Province, China, was systematically modeled and optimized towards various environmental and economic goals, accounting for 1.9 million sets of water-saving, energy-saving, and air pollution-mitigation technologies. First, the production processes and the associated water, energy, and pollution flows of a typical steel-making plant were modeled. The model was parameterized based on peer-reviewed literature and a field survey of 286 steel-making plants in Hebei in 2015. Second, for each technology, materials and energy flow analysis (MEFA) was employed to balance the water, energy and emission flows along the production processes of the typical steel-making plant. The WEEN nexus was then identified. Third, the WEEN effects were assessed under six technology diffusion scenarios. Finally, a Pareto optimization, based on the non-dominated sorting genetic algorithm-II (NSGA-II) (Deb et al., 2002), was applied to identify the most feasible technology sets given the following objectives: minimization of dust, SO_2 and NO_x emissions. The water consumption, energy consumption, and installation and operational costs were compared among optimized technology sets.

2. Methodology

2.1. Analytical framework of the WEEN

A technology-based bottom-up approach was applied to develop an analytical framework for the WEEN (cf. Fig. 1A). As illustrated in Fig. 1B, a typical steel-making plant is modeled with five main production processes (*i*), main production units (*j*) within each process, and relevant technologies (*k*) associated with each production process or unit. The five main production processes, coking, sintering or pelletizing, iron-making, steel-making, and rolling, are modeled after the blast oven/basic oxygen furnace (BF/BOF) route (Porzio et al., 2013), which accounted for 94% of the total crude steel production in China in 2015 (World Steel Association, 2016). The production units (*j*) refer to the combustion, cooling, slash washing, pollutant removal, and others (c.f. ①–⑬ and dashed unit boxes in Fig. 1B), which are necessary to produce steel from raw materials (e.g., coal, iron ore). In this study, the technologies were classified into two categories: the production technologies and the auxiliary technologies. The production technologies enhance the production efficiencies and reduce or recover energy use. They were implemented at the process level (*i*), affecting the water and energy consumption and emission of all units in that process. The auxiliary technologies are mainly emission mitigation technologies, such as air pollutant removal technologies and wastewater treatment technologies. In the model, all wastewater treatment processes were simplified as a single treatment plant for the entire steel production process because of the lack of detailed wastewater treatment data (e.g., wastewater treatment methods, energy consumption, and cost for each process). Based on the production model, the material and energy flows of the steel-making plant were subsequently quantified and balanced for each process (*i*) using material and energy flow analysis approaches, resulting in the plant-level WEEN model.

2.2. Material and energy flow analysis

Materials and energy flow analysis (MEFA) was used to separately quantify the water, energy and emission flows throughout the five main production processes. Both the production and auxiliary technologies may have direct and/or indirect effects on the WEEN. For example, the application of desulfurization, using water and energy, removes SO_2 in exhaust smoke while at the same time reducing dust concentration.

2.2.1. Energy flow

The energy flow of each process (*i*) that employs technology (*k*) was modeled, including various energy uses, electricity recovery, and gas

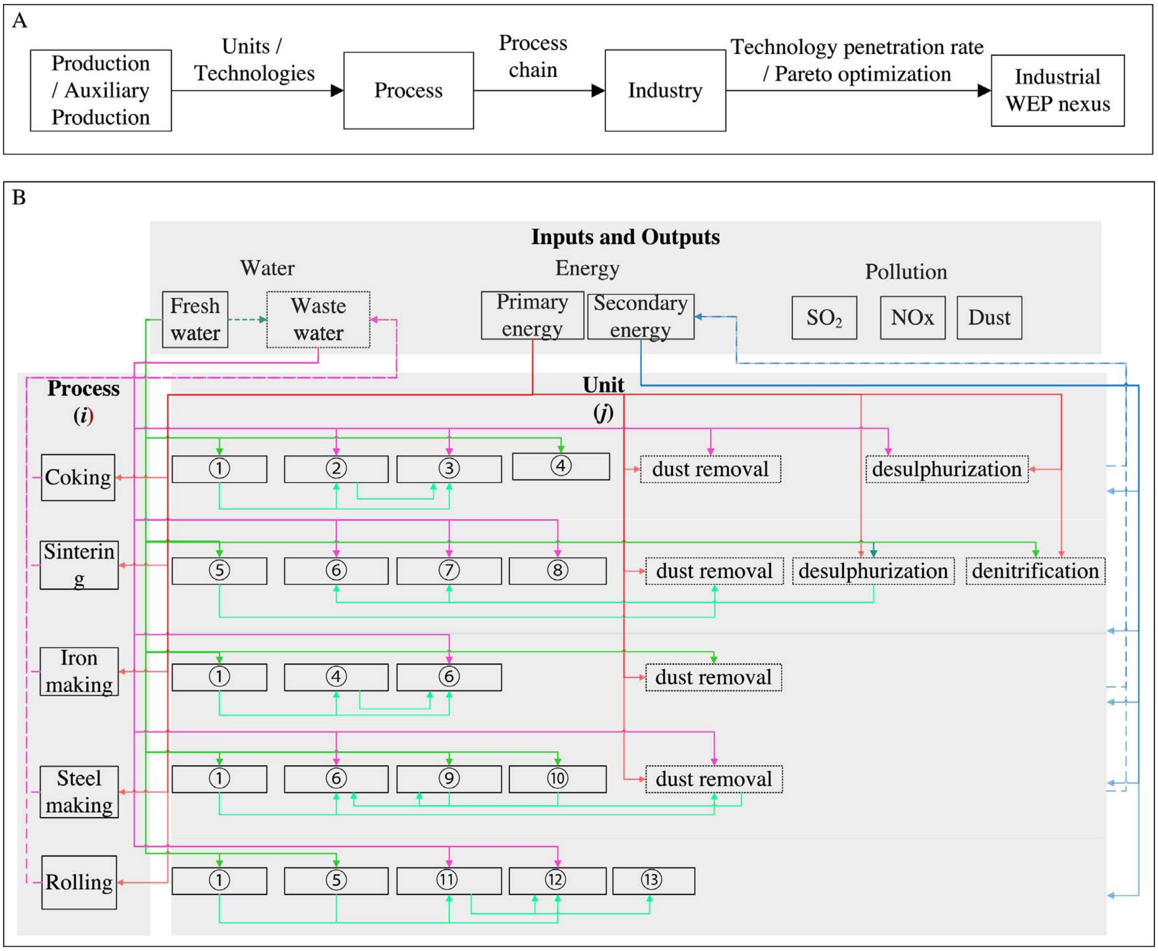


Fig. 1. An analytical framework for the WEEN of the steel industry.Note:(a): Unit (j) refers to ① equipment cooling, ② coke oven body, ③ coke quenching, ④ gas purification, ⑤ indirect cooling, ⑥ slag washing, ⑦ mixing, ⑧ heat return ore cooling, ⑨ external refining, ⑩ oxygen, ⑪ laminar cooling, ⑫ direct cooling, and ⑬direct water use;(b): Solid unit boxes refer to production units, and the dashed unit boxes refer to auxiliary units where auxiliary technologies can be applied;(c): ⟶ refers to freshwater consumption, ⟶ refers to recycled water, ⇢ refers to water discharge, ⟶ refers to water cycling within units without treatment, ⟶ refers to primary energy use, ⟶ refers to secondary energy use, and ⇢ refers to secondary energy recovery.

recovery. The energy categories are summarized based on statistics of all 286 steel-making plants in Hebei province in 2015 (detailed in the supporting information (SI)).

(1) Energy use

The energy use, depending on the technology k applied, was calculated using Eqs. (1) and (2):

$$FC_i = FC_{initial,i} \times (1 - FSR_{i,1}) \times (1 - FSR_{i,2}) \times \cdots (1 - FSR_{ik}) \tag{1}$$

$$EC_i = EC_{initial,i} \times (1 - ESR_{i,1}) \times (1 - ESR_{i,2}) \times \cdots (1 - ESR_{i,k}) \times \cdots + EC_{i,k} \tag{2}$$

where

■FC_i = fuel consumption of process i (kg/ton product or m^3/ton product);

■$FC_{initial,i}$ = initial fuel consumption of process i (kg/ton product or m^3/ton product);

■$FSR_{i,k}$ = fuel-saving rate of production technology k if employed at process i (%);

■EC_i = electricity consumption of process i (kWh/ton product);

■$EC_{inital,i}$ = initial electricity consumption of process i (kWh/ton product);

■$ESR_{i,k}$ = electricity-saving rate of production technology k if employed at process i (%);

■$EC_{i,k}$ = electricity consumption if emission control k is employed at process i (kWh/ton product);

(2) Electricity recovery

It is common that plants apply electricity recovery technologies to reduce energy use costs (Liu and Gao, 2016; Wu et al., 2016; Cao et al., 2016). The electricity recovery was quantified by Eq. (3):

$$ER_i = ER_{i,1} + ER_{i,2} + \cdots ER_{i,k} \tag{3}$$

where

■ER_i = electricity recovery of process i (kWh/ton product);

■$ER_{i,k}$ = electricity recovered from process i through technology k (kWh/ton product).

(3) Gas recovery

In addition to electricity recovery, gas recovery technologies are widely adopted in the steel production processes (Liu and Gao, 2016; Wu et al., 2016; Cao et al., 2016). The volume and heat value of the recovered gas depend on the technical configurations of the production processes, such as the quantity of imbibed fresh air in iron-making and the intensity of oxygen blowing (Wang et al., 2007b). The initial volume of recovered gas refers to the amount of recovered gas when there is no energy saving production technology applied. The gas recovery was calculated by Eq. (4):

$$GR_i = GR_{initial,i} \times (1 + GRR_{i,1}) \times \cdots (1 + GRR_{i,k}) \tag{4}$$

where

GR_i = gas recovered from process i (m^3/ton product);

$GR_{initial,i}$ = initial gas recovered from process i (m^3/ton product);

$GRR_{i,k}$ = the additional gas recovery rate of production technology k at process i (%).

2.2.2. Water flow

As illustrated by Eqs. (5)–(7), production technologies and auxiliary technologies can both be implemented to affect the quality and quantity of water flows at production units (*j*) of process (*i*). The variation of freshwater quality was not considered in this study because of data inaccessibility. The water flow, including direction and quantity, was balanced at each technology unit and upscaled to the entire production process of the plant (as illustrated in Fig. 1B), based on the field survey in 2015 and a literature review (Yu, 2009; Wan et al., 2002) (c.f. SI). The application of wastewater treatment technologies determines the quality and thus the potential uses and quantity of the wastewater effluents. Given that effluents could be recycled and used at production units where low water quality is sufficient, freshwater was assumed to be used only at the units where high water quality is required or the volume of wastewater effluents is not sufficient. Eq. (8) calculates the electricity consumption for treating the drainage water of process *i*.

$$WD_i = (WD_{initial,i} + WD_{k,i}) \times (1 - WSR_{i,1}) \times \cdots (1 - WSR_{i,k}) \tag{5}$$

$$fWC_i = \sum_{1}^{n} fWD_{i,j} + (\sum_{1}^{n} RWD_{i,j} - RWS_i) \tag{6}$$

$$RWS_i = \sum_{1}^{n} (WD_{i,j} \times DWR_{i,j} - DWD_{i,j'}) \tag{7}$$

$$EW_i = RWS_i \times EWR \tag{8}$$

where:

WD_i = water demand, including freshwater and recycled water, of process i (m^3/ton product);

$WD_{initial,i}$ = initial water demand, including freshwater and recycled water, of process i (m^3/ton product);

$WD_{k,i}$ = additional water demand of process i when emission control technology k is implemented (m^3/ton product);

$WSR_{i,k}$ = water saving rate of production technology k employed at process i (%);

n = the total number of units of process i;

fWC_i = fresh water consumption of process i (m^3/ton product);

$fWD_{i,j}$ = fresh water demand for unit j in process i (m^3/ton product);

$RWD_{i,j}$ = recycled water demand for unit j in process i (m^3/ton product);

RWS_i = recycled water supplied by treated wastewater effluents of process i (m^3/ton product);

$WD_{i,j}$ = water demand for unit j of process i (m^3/ton product);

$DWR_{i,j}$ = drainage rate for unit j in process i (%);

$DWD_{j'}$ = drainage water of unit j used directly by other unit j' in process i without treatment (m^3/ton product).

EW_i = electricity consumption for wastewater treatment of process i (kWh/ton product);

EWR = electricity intensity for wastewater treatment in steelmaking (kWh/m^3).

2.2.3. Emission flow

Because water pollution is comparatively less intensive in the steel industry (4.6% of industrial wastewater discharge, 2.7% of industrial COD discharge, and 2.7% of industrial NH_4-N discharge (Ministry of Environment Protection, 2015)), this study focused on three main air pollutants: SO_2, NO_x, and dust. As specified by Eqs. (9)–(12), the emissions are generated directly during the production process (i.e., sintering) or indirectly when energy is consumed (i.e., during the coking, iron-making, steel-making, and rolling). The emissions of the pollutants are estimated based on the pollutants generation and the pollutants removal rate of production and/or auxiliary technologies. The heat values of various energies were derived from (National Bureau of Statistics, 2014) (c.f. SI). The coal quality (concentration of sulfur or H_2S) was summarized based on statistics of all 286 steel-making plants in Hebei province in 2015 (c.f. SI). The equations and their coefficients were obtained from (Ministry of Environment Protection, 2014) (more information about the equations is in SI).

(1) SO_2 generation

For sintering, SO_2 generation was calculated by:

$$G_{SO_2-s} = (M_1 \times S_1 + M_2 \times S_2 + M_3 \times S_3) \times 82.5\% \times 2 \tag{9}$$

where

G_{SO2-s} = SO_2 generation of sintering process (kg/ton product);

M_1, M_2, M_3 = the consumption of concentrated ore powder, coke, etc. (kg/ton product);

S_1, S_2, S_3 = comprehensive sulfur content of concentrated ore powder, coke, etc. (%).

For coking, iron-making, steel-making, and rolling, SO_2 generation was calculated by:

$$G_{SO_2} = 1.882 \times 10^{-6} \times (Q_1 \times R_1 + Q_2 \times R_2 + \cdots Q_n \times R_n) \tag{10}$$

where

G_{SO2} = SO_2 generation (kg/ton product);

Q_1, Q_2, …, Q_n = the consumption of gases, such as coke oven gas, blast furnace gas, etc. (m^3/ton product);

R_1, R_2, …, R_n = the concentration of H_2S in gas, such as coke oven gas, blast furnace gas, etc. (mg/m^3).

(2) NO_x generation

Because of the lack of detailed monitoring data (which is needed in the calculation of NO_x generation) in sintering, the generation rate of NO_x (0.5 kg/ton sinter ore) was adopted from (Ministry of Environment Protection, 2010).

For coking, iron-making, and rolling, NO_x generation was calculated by:

$$G_{NO_x} = 8.36 \times 10^{-8} \times (Q_1 \times H_1 + Q_2 \times H_2 + \cdots Q_n \times H_n) \tag{11}$$

where

G_{NOx} = NO_x generation (kg/ton product);

H_1, H_2, H_n = the heat value of gas, such as coke oven gas, blast furnace gas, etc. (kJ/m^3).

For steel-making, NO_x generation was calculated by:

$$\begin{aligned} G_{NO_x-sm} = {} & 8.36 \times 10^{-8} \times (Q_1 \times H_1 + Q_2 \times H_2 + \cdots Q_n \times H_n) \\ & + 4.18 \times 10^{-12} \times (150 \times 10^4 - G_r) \times H_r \end{aligned} \tag{12}$$

where

G_{NOx-sm} = NO_x generation of steel-making process (kg/ton product);

Gr = the gas recovered (m^3/ton product);

Hr = the heat value of recovered gas (kJ/m^3).

(3) Dust generation

Because of the lack of detailed information about the machinery and equipment applied in each production process, the generation rates of industrial dust were derived from (, 2010). For each process, i.e., coking, sintering, iron-making, steel-making and rolling, 8.0 kg, 32.8 kg, 43.5 kg, 34.2 kg, and 0.03 kg dust were generated per ton of product, respectively.

(4) Effects of production and auxiliary technologies on the emission flow

Both the production technologies and emission control technologies can affect the flows of the three pollutants (Ministry of Environment Protection, 2014). The production technologies may reduce or increase the emissions according to:

$$G = G_{initial} \times (1 - GPR_{i,1}) \times (1 - GPR_{i,2}) \times \cdots (1 - GPR_{i,k}) \tag{13}$$

where

G = emission of SO_2, NO_x or dust (kg/ton product);

$G_{initial}$ = generation of SO_2, NO_x or dust (G_{SO2}, G_{NOx}, G_{dust})(kg/ton product);

$GPR_{i,k}$ = SO_2, NO_x or dust reduction rate of production technology k at process i (%).

The emission can be mitigated when emission control technologies are adopted according to:

$$P = G \times (1 - RP_{i,1}) \times (1 - RP_{i,2}) \times \cdots (1 - RP_{i,k}) \tag{14}$$

where

P = the emission of SO_2, NO_x or dust (kg/ton product);

$RP_{i,k}$ = the SO_2, NO_x or dust removal rate of auxiliary technology k at process i (%).

2.3. *The industry-level WEEN model*

2.3.1. *Production process chain*

The conceptualized process chain is used to represent the production system in which a production process is connected by its inputs and outputs with other up- and down-stream processes (Herrmann and Thiede, 2009). In this study, the conversion coefficients were defined as the amounts of (by-) products from process *i* needed for the associated process *i + 1*; they were applied to link the five processes of the steel industry. The conversion coefficient of the rolling process, however, often refers to the amount of steel product that one ton of crude steel can produce. The initial conversion coefficients (referring to the conversion coefficients when no production technology is applied) were obtained based on the field survey in 2015 and were adjusted according to (Sun et al., 2013) (c.f. SI).

The implementation of different technologies may affect the conversion coefficients according to:

$$CE_i = CE_{initial,i} \times (1 + CER_{i,1}) \times (1 + CER_{i,2}) \times \cdots (1 + CER_{i,k}) \tag{15}$$

where

CE_i = conversion coefficient of process i;

$CE_{initial,i}$ = initial conversion coefficient of process i;

$CER_{i,k}$ = the effect on conversion coefficient by implementing production technology k at process i (%).

2.3.2. *Scaling the plant-level WEEN model to the steel production industry*

The plant-level WEEN model was scaled-up to the industry level based on the technology penetration rate, regional resource supply and the installation and operation costs.

(1) Penetration rate

In this study, it was assumed that 1) the adoption of each different production technology is independent from the others, and 2) only one auxiliary technology can be adopted for desulfurization, denitrification, and dust removal. The penetration rate for technology *k* is the percentage of its application to all 286 steel-making plants in Hebei. The compiled parameter was applied to represent an aggregated average level (water use, energy consumption, emission and costs) of various production/auxiliary technologies that are applied to the same process *i* or the same unit *j*. The penetration rate of production technologies was obtained from (Ministry of Industry and Information Technology, 2012). The penetration rate of the auxiliary technologies was obtained from the field survey in 2015 (c.f. SI). The relevant equations are:

a) Production technology:

$$Para_{com} = (1 \pm P_{1,i} \times Para_{ptech1}) \times (1 \pm P_{2,i} \times Para_{ptech2}) \times \cdots (1 \pm P_{k,i} \times Para_{ptechk}) \tag{16}$$

where

$Para_{com}$ = the compiled parameter of production technology k;

$Para_{ptechk}$ = the parameter of production technology k (e.g., $FRS_{i,k}$, $EC_{i,k}$, $GPR_{i,k}$, etc.);

$P_{k,i}$ = the penetration rate of production technology k of process i.

- Auxiliary technology:

$$Para_{com} = 1 \pm P_{1,i} \times Para_{atech1} \pm P_{2,i} \times Para_{atech2} \pm \cdots P_{k,i} \times Para_{atechk} \tag{17}$$

where

$Para_{atechk}$ = the parameter of auxiliary technology k (e.g., $RP_{i,k}$, etc.);

$P_{k,i}$ = the penetration rate of auxiliary technology k of process i.

(2) Resource supply

Usually, the resource supply consists of the quantity and quality of water supply, energy supply and raw material supply. The quantity of resource supply has already been discussed or calculated by the equations mentioned in the previous sections. The quality of water supply has close relationship with the water source (i.e. seawater and groundwater), and the energy use for treating seawater and groundwater differ greatly. However, it is out of the boundary of this study because 1) the freshwater quality is inaccessible and 2) it has a rather weak direct relationship with the WEEN (only the water-energy nexus, not the water-energy-emission nexus). Therefore, only the quality of energy and raw material supply, e.g., the sulfur concentration of the primary energy and ore, was considered, obtained from the field survey.

(3) Cost

The installation and operation costs of each technology was calculated by Eq. (18):

$$Cost_{total} = \sum_i ((\sum_k (cost_{instal,i,k} + cost_{opera,i,k})) \times CE_i) \tag{18}$$

where

$Cost_{total}$ = total costs of implementing the production and auxiliary technologies (Yuan/ton product);

$Cost_{instal,i,k}$ = installation of applied technology k at process i (Yuan/ton product);

$Cost_{opera,i,k}$ = operation cost of implementing technology k at process i (Yuan/ton product).

2.4. *Pareto optimization*

In this study, Pareto optimization was used to identify feasible, multi-objective optimal technology sets given different environmental and economic goals, i.e., minimizing freshwater consumption, energy use, air emissions, and economic cost. A technology set is defined as a combination of production and auxiliary technologies that could be applied to steel production processes. The seven production technologies were assumed to be independent, which means that selection of one production technology will not be affected by the installation of other technologies. The choice of SO_2 removal technologies was considered for the coking and sintering processes, and different dust removal technologies were generated for the coking, sintering, iron-making, and steel-making processes. More than 1.9 million technology sets were generated using Eq. (19).

$$TS = A_m^m \times \prod_i C_n^1 \tag{19}$$

where

TS = total number of technology sets;

m = the number of production technologies k of all processes;

n = the number of auxiliary technologies k of process i for desulfurization, denitrification or dust removal.

A and C are the algorithms of Permutations.

The technologies have different effects on the multiple environmental and economic goals. A Pareto optimization method (Marler and Arora, 2004) aims to adopt NSGA-II to screen Pareto optimal solutions and identify quantifiable trade-offs that satisfy conflicting objectives (Deb et al., 2002; Huang et al., 2015):

$$f_i(x^*) \le f_i(x) \tag{20}$$

where

f_i = the optimization goal, i.e. SO_2 emission, NO_x emission, and dust emission;

x^* = the optimized technology set;

x = the non-optimized technology set.

For the optimized technology set x^*, its environmental performances (i.e. pollutants emissions) should be better than any non-optimized technology set. The median value of each technical parameter was selected to implement the optimization runs. The WEEN simulation and Pareto optimization were conducted in MATLAB.

3. Results

3.1. The coupling WEEN

Based on the industrial-level WEEN model, the steel industry in Hebei province used 6.2 m^3 of water (including 3.11 m^3 of freshwater and 3.12 m^3 of upstream drainage water or recycled water) and consumed 299.6 kWh of electricity to make one ton of crude steel in 2015 (c.f. Fig. 2, more detailed information is listed in SI). Approximately 85%, 11% and 99% of the SO_2, NO_x, and dust generated were removed, respectively. The total installation and operation costs for technology implementations were 76.8–83.0 RMB Yuan/ton of crude steel. Approximately 7% of the total electricity consumption was related to the WEEN, 95% of which was used for emission control. The water use associated with the nexus was 66% of the total, of which 71% was used for direct and indirect cooling.

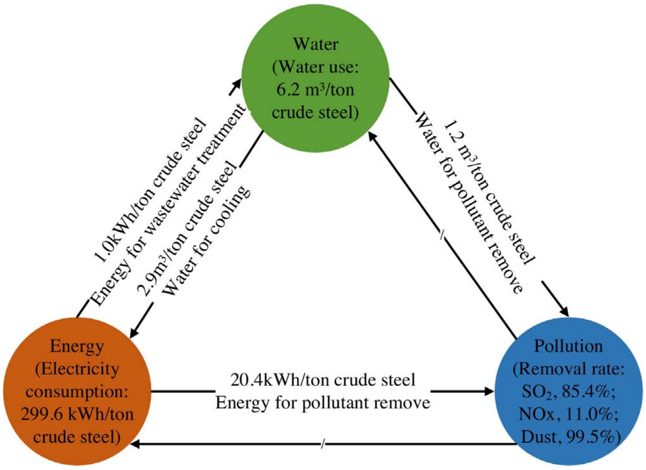


Fig. 2. The WEEN of Hebei steel industry.Note:(a): "/" means that there is no direct connection between two terms of the WEEN;(b): The energy in this WEEN is referred to electricity because the massive use of coal is considered as raw material input in steel production;

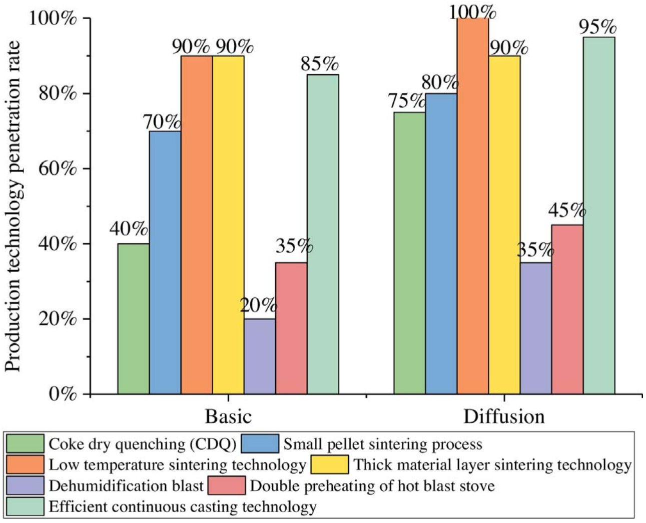


Fig. 3. Production technology penetration rate$^{(a)}$ (Ministry of Industry and Information Technology, 2012; Ministry of Industry and Information Technology, 2012).Note:(a): Given the lack of policy on thick material layer sintering technology and the fact that the current penetration rate has already reached 90%, the technology adoption level is assumed to remain the same in the future.(b): Diffusion represents the diffusion of particular technologies, hereinafter.

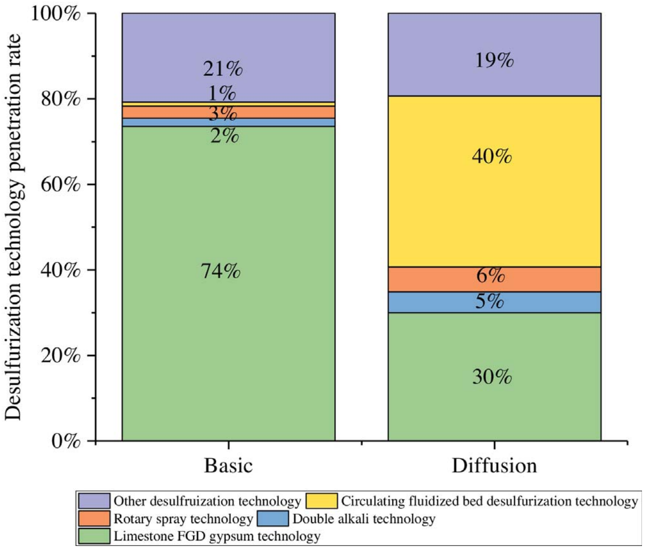


Fig. 4. Desulfurization technology penetration rate (Ministry of Industry and Information Technology, 2012; Ministry of Industry and Information Technology, 2012).

The quantified water, energy and emissions flows associated with the nexus are shown in Table 1. Generally, sintering is the process that takes the major portion (57%) of electricity for the WEEN and rolling is the process with the smallest portion. However, rolling is the largest consumer (31%) of water for the WEEN, and coking and sintering are the least and second least. The sintering process accounts for most SO_2 emissions and NO_x emissions, 56% and 40%, respectively. Iron-making contributes most to the dust emissions (64%).

The water-energy-SO_2 nexus was dominated by coking and sintering processes, especially the latter. SO_2 removal in sintering accounted for 10% of the WEEN water use and 37% of the electricity consumption. However, sintering was the largest emitter of SO_2. Note that the water-energy-NO_x nexus was not significant in 2015, mainly because few

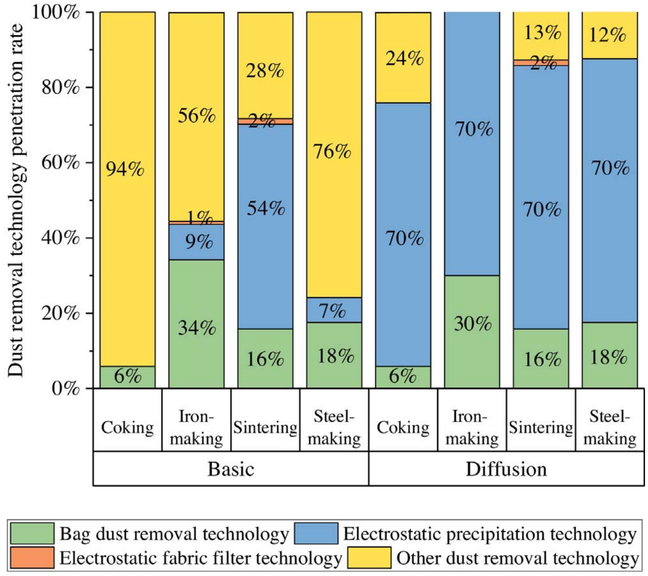


Fig. 5. Dust removal technology penetration rate(a) (Ministry of Industry and Information Technology, 2012; Ministry of Industry and Information Technology, 2012).*Note*:(a): Predictions for the process-specific penetration rates of dust removal technologies are not available and the predicted penetration rates of each process are thus treated as the same as that of the steel industry.

plants in Hebei were using NO_x removal technologies.

The water-energy-dust nexus was dominated by the sintering, iron-making and steel-making processes because of their high dust generation rates. The water use for dust accounted for 19% of total water use for the WEEN. Dust removal was the biggest consumer of electricity and was responsible for 56% of the WEEN electricity use. The iron-making process, as the largest dust emitter (i.e., 64% of the total), accounted for only 7% of the electricity use of the nexus and 4% of water use for the WEEN. Steel-making was the largest consumer of water and electricity for dust removal, using 15% of the water and 24% of the electricity for dust removal. Coking and sintering rarely used water for dust removal, and their electricity consumption for dust was 5% and 19%, respectively.

Based on the WEEN model, freshwater and energy consumption was calculated as 3.1 m^3 and 536.6 kgce (kg of coal equivalent) per ton of crude steel in 2015, respectively, a difference of 11.1% and −2.4% from the statistics for 2014 (Hebei Government, 2015). The estimated SO_2, NO_x, and dust emissions were 3.8, 0.8, and 0.6 kg/ton of crude steel, respectively. The calculated results for pollution emission were also compared with existing studies (cf. Table 2). Most estimates from the model were consistent with those reported by existing studies, except for SO_2 emissions in rolling, NO_x emissions in iron-making and rolling, and dust emissions in sintering and steel-making. This is probably because the assumption that the technologies were applied for all the emission outlets in each production process was adopted in this study. This again requires further improvement with more local data.

Table 2
Air pollutant emission of each process in the steel industry.

		Estimation	Wu (2015)	Wang et al. (2016)
SO_2 (kg/ton product)	Coking	1.8	–	–
	Sintering	2.4 (1.1–5.3)	2.4–2.8	3.2
	Iron-making	0.1	0.11–0.13	0.2
	Steel-making	0	–	0.1
	Rolling	0.02	0.14–0.27	–
NO_x (kg/ton product)	Coking	0.40	–	–
	Sintering	0.41 (0.4–0.5)	0.52-0.61	0.6
	Iron-making	0.02	0.15–0.17	0.2
	Steel-making	0.05	0.003	0.2
	Rolling	0.02	0.08–0.28	–
Dust (kg/ton product)	Coking	0.03 (0.01-0.07)	–	–
	Sintering	0.1 (0.02–0.2)	0.40–1.59	1.0
	Iron-making	0.4 (0.2–0.8)	0.35–1.03	2.0
	Steel-making	0.1	0.16–0.27	2.1
	Rolling	0.03	0.01–0.03	–

Note: (a): The data of the estimation column are calculated based on the average environmental performance level of each technology, and the data in the brackets are estimated range.

The simulation in this study was based on the field survey data in 2015. The data used for validation, i.e., the energy consumption and water consumption for crude steel, were obtained from the 2014 yearbook. This mismatch may have led to slight differences between estimations and statistics. However, the technologies did not change much from 2014 to 2015. The mismatch between estimation and literature (Wu, 2015; Wang et al., 2016) occurred where the process was not the major contributor to the emissions. Therefore, the data for these two years were comparable in this study and the WEEN model was considered reliable.

3.2. *The WEEN effects of technology diffusion*

3.2.1. *Scenarios*

Seven technology diffusion scenarios are explained in Table 3 and Fig. 5-5. The basic scenario refers to the status-quo technology penetration rates in 2015. Under Scenario 1 (S1), the diffusion rates

Table 1
Electricity consumption, water use, and emissions related to the WEEN nexus by production process (columns).

	Coking	Sintering	Iron-making	Steel-making	Rolling	Total
Total electricity for WEEN	5.1%	57.3%	8.8%	26.9%	1.9%	100.0%
Electricity for SO_2	0.0%	37.2%	0.0%	0.0%	0.0%	37.2%
Electricity for dust	5.0%	19.4%	6.6%	24.8%	0.0%	55.8%
Electricity for wastewater treatment	0.0%	0.7%	2.2%	2.1%	1.9%	6.9%
Total water use for WEEN	7.2%	14.0%	26.2%	21.9%	30.6%	100.0%
Water use for SO_2	0.3%	9.8%	0.0%	0.0%	0.0%	10.0%
Water use for dust	0.0%	0.0%	3.9%	15.1%	0.0%	19.0%
Water use for cooling	7.0%	4.3%	22.3%	6.8%	30.6%	71.0%
SO_2 emission	42.3%	55.8%	1.5%	0.0%	0.4%	100.0%
NO_x emission	44.9%	46.1%	2.0%	5.2%	1.9%	100.0%
Dust emission	5.1%	10.9%	63.5%	15.6%	4.9%	100.0%

Table 3
The 7 scenarios settings.

	Basic	S1	S2	S3	S4	S5	S6
Diffusion of production technologies(b)		√			√		√
Diffusion of desulfurization technologies and dust removal technologies(c)			√	√	√		√
Diffusion of denitrification technologies(d)				√	√		√
High quality materials						√	√

Note: (a): √ represents that the scenario applies the diffusion rate of particular technologies or high quality materials (rows).
(b): The penetration rate of the production technologies is shown in Fig. 3.
(c): The penetration rate of the desulfurization technologies is shown in Fig. 4 and the penetration rate of dust removal technologies is shown in Fig. 5.
(d): The penetration rate of the denitrification technologies (referring to the activated carbon technology, which is newly introduced advanced NO_x removal technology) increases to 40%.

of production technologies are the same as they were during the twelfth Five-Year plan (2011–2015) (Ministry of Industry and Information Technology, 2012a,b Ministry of Industry and Information Technology, 2012; Ministry of Industry and Information Technology, 2012). S2 represents the diffusion of desulfurization technologies and dust removal technologies (Ministry of Industry and Information Technology, 2012; Ministry of Industry and Information Technology, 2012). S3 represents the diffusion of denitrification technologies. S4 is a combination of S1 and S3, which contains the diffusion of both production and auxiliary technologies. Under S5, raw material of the highest quality (the average sulfur content of the raw material) and gases of the minimum H_2S concentration (c.f. SI) are used, obtained from the field survey in 2015 and (Ministry of Environment Protection, 2014). S6 combines the technological changes and material quality improvement (i.e., S4 + S5).

3.2.2. *Water savings, energy savings, and emission reduction potential*

Based on the scenarios settings, the pollutants emissions, total energy consumption, total freshwater consumption, cost, electricity consumption for WEEN, and water use for WEEN were simulated and compared with the status-quo (c.f. Fig. 6).

The scenario results suggest that SO_2 emissions would be reduced under each scenario (Fig. 6(1)). When the production and auxiliary technologies and the high-quality raw materials were jointly used (i.e., S6), SO_2 emissions would be reduced by up to 57%. The diffusion of auxiliary technologies (S3) would have the highest potential for NO_x removal, i.e., 25% of NO_x emissions compared with the status-quo (Fig. 6(2)). However, NO_x emissions would be higher than current emissions because of the weak synergistic effects of the production technologies on NO_x removal in S1. Industrial dust emissions would increase slightly, by 0.6%-8%, as shown in Fig. 6(3), because of two reasons: the weak synergistic effect on dust removal of the production and auxiliary technologies and the changes of predicted penetration rate of dust removal technologies.

The diffusion of production and auxiliary technologies (S4) would cause a 35% increase of energy for pollutant removal (Fig. 6(7)) and a 163% increase of energy for wastewater treatment (Fig. 6(8)), the highest increases among the scenarios. Only the change of production technology penetration rate (S1) could cause the decline of water consumption, as shown in Fig. 6(5). However, the decline could lead to a 0.2% increase of water for pollutants (Fig. 6(9)). The changes of auxiliary production (S2 and S3) could bring a nearly 57% increase in water consumption, mainly because of the promotion of water-intensive desulfurization technology in coking, i.e., vacuum potassium carbonate desulfurization technology. These could also bring a nearly 170% increase in water for pollutants (cf. Fig. 6(9)).

The changes of production and auxiliary technologies (S4) would bring as high as a 40% increase in installation and operational costs (Fig. 6(6)), of which the change of production technologies would contribute 25% and the change of auxiliary technologies would contribute 15%.

3.2.3. *Trade-offs and synergies within the WEEN*

From the perspective of the SO_2-water-energy nexus, changes of production and auxiliary technologies and improvement in raw material quality (S6) could lead to less SO_2 emission (57% reduction) (c.f. Fig. 6(1)); however, this would result in cost increases of 56% and 0.2% in water and energy consumption, respectively (c.f. Fig. 6(4) and (5)). Moreover, the synergistic effect of NO_x removal is significant, i.e., a 25% decline of NO_x emission (c.f. Fig. 6(2)). Note that these changes would result in more intensive relationships within the WEEN than currently exist in Hebei, a 35% increase of energy for pollutants, 163% increase of energy for wastewater treatment, and 170% increase of water for pollutants (c.f. Fig. 6(7)–(9)).

From the perspective of the NO_x-water-energy nexus, the changes of existing auxiliary technologies and the introduction of new nitrification technology (S3) would lead to the highest decline of NO_x emission (25%) (c.f. Fig. 6(2)) at the cost of the highest increase of water and energy consumption (57% and 0.2%) (c.f. Fig. 6(4) and (5)). These changes could also lead to relatively more intense relationships within the WEEN, a 34% increase of energy for pollutants, 162% of energy for wastewater treatment, and a 170% increase of water for pollutants (c.f. Fig. 6(7)–(9)).

From the perspective of the dust-water-energy nexus, the change of desulfurization technologies and dust removal technologies (S2) would lead to the highest increase (8%) of dust emission at the cost of 0.13% increase of energy consumption and 57% increase of freshwater consumption. Meanwhile, it could lead to relatively more intensive relationships within WEEN, a 20% increase of energy for pollutants, 162% increase of energy for pollutants, and 170% increase of water for pollutants.

3.3. *Pareto alternatives*

The Pareto optimization resulted in 32 technology sets that could achieve minimal SO_2-NO_x-dust emissions, as shown in Fig. 7 layer 1(the best Pareto alternatives). Layer 2 and layer 3 were the second and third best Pareto alternatives. Detailed technology sets of layer 1 are listed in SI. From Fig. 7(2), it is clear that the dots of layer 1(black dots) emit less SO_2, NO_x, and (or) dust (closer to the origin) than other dots of layer 2 (red dots) and layer 3(green dots). The fact that the emissions of technology sets from layer 1 were lower than layer 2 and layer 3 (c.f. Fig. 7(1)) illustrates that the results of Pareto optimization were reliable in this study. Other than the technology sets of layers 1–3, the remainder of the 1.9 million technology sets are not shown in Fig. 7 because they have worse performance with respect to SO_2, NO_x, and (or) dust emissions.

Based on Pareto optimization, 50% of the 32 technology sets (i.e., 16 technology sets) from layer 1 could consume less water with the same energy consumption than the rest of the 50% technology set. The emissions, water consumption and energy consumption of these 16 technology sets are shown in Fig. 8. Comparing these with the current WEEN, there is great potential for pollution reduction without increasing water or energy consumption or cost. The optimized technology sets could lead to the reduction of nearly 97% of SO_2 emissions, more than 50% of NO_x emissions, and almost 75% of dust emissions; additionally, they could save approximately 10% of water consumption and 2% of energy consumption. However, the installation and operational costs could be 52%-74% higher than costs of the status-quo.

From the perspective of the SO_2-water-energy nexus, technology set 7 (TS7) could emit the smallest amount of SO_2 at the second lowest cost of energy consumption as a tradeoff for the third highest water consumption among the 16 technology sets. TS2, as the second smallest SO_2 emitter, could have a significant advantage in water consumption

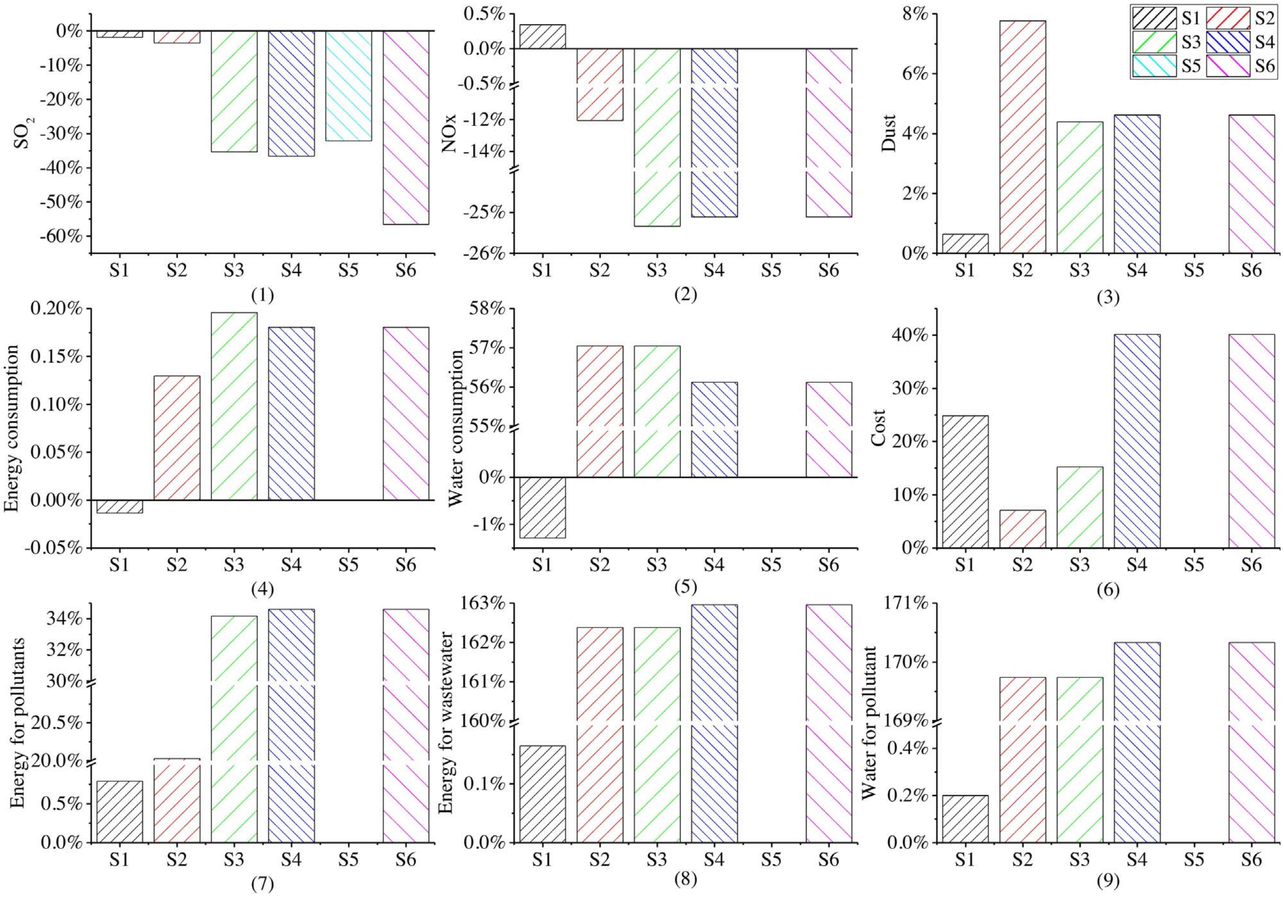
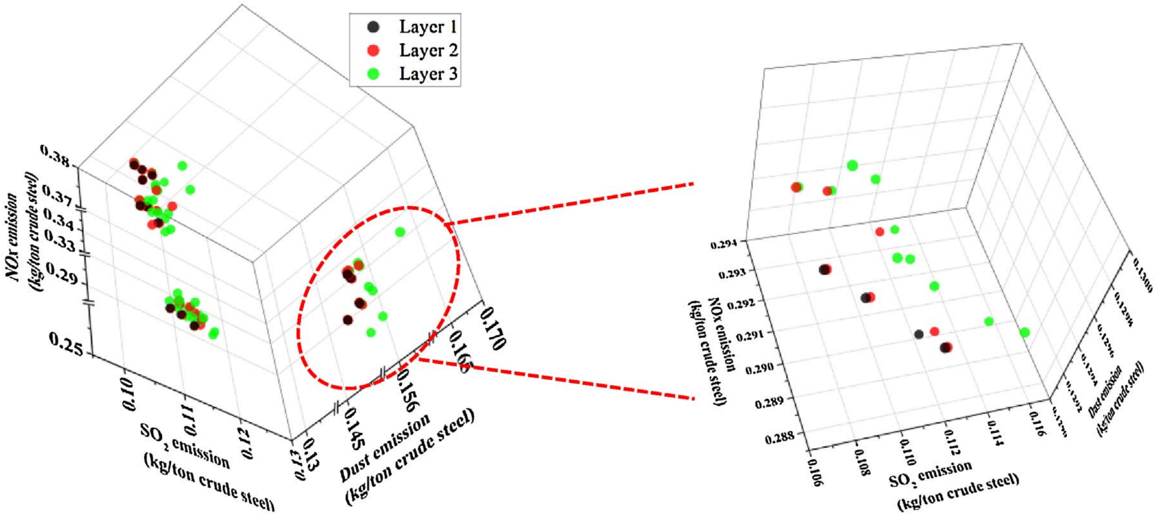
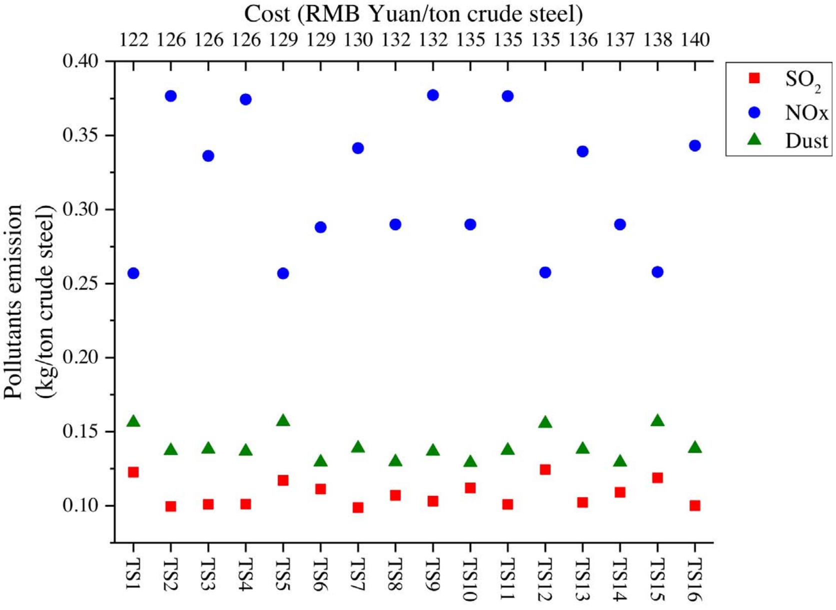


Fig. 6. The changes of the water-energy-emission relations of the steel industry in Hebei.*Note*:(a): The Y-axis represents the change rate compared with the status-quo;(b): Fig. 6(4) refers total energy consumption (raw materials, for example coal, are included) for steel production;(c): Fig. 6(5) refers total freshwater consumption for steel production;(d): Fig. 6(7) refers to the electricity (energy hereinafter) consumption for air pollutant removal;(e): Fig. 6(8) is the electricity (energy hereinafter) consumption for wastewater treatment;(f): Fig. 6(9) is the water use for air pollutants removal;(g): The cost of raw material supply was not included in the calculations because of data inaccessibility.

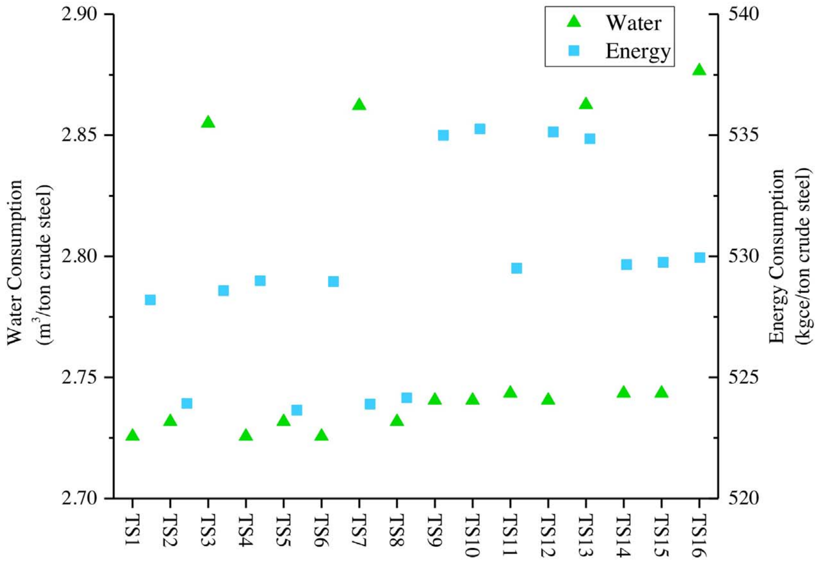


(1) (2)

Fig. 7. the Pareto layers of optimizing SO_2-NO_x-dust.*Note*:(a): Layers 1–3 (black, red, and green dots) represent the top three Pareto alternative outputs among all the technology sets. Technology set in layer 1 could achieve the least pollutant emissions;(b): Each dot of the three layers represents one technology set;(c): The Fig. 7(1) displays all technology sets of the three layers, and Fig. 7(2) zooms in the dots on the right side of Fig. 7(1);(d): The remaining layers are not shown in this figure because they have worse environmental performance than layers 1–3.



(1) Pollutants emission



(2) Water and energy consumption

Fig. 8. The WEEN nexus of optimized technology sets.*Note*:(a): TS stands for technology sets;(b): The rank of the technology sets represents the cost (from low to high);(c): The water consumption refers to freshwater consumption;(d): The energy consumption refers to the total energy consumption (including raw materials such as coal) for steel production.

over TS7, with only 0.01% more energy consumption. Note that the NO_x emission for TS2 is the second largest, 5% higher than TS7.

From the perspective of the NO_x-water-energy nexus, TS5 could emit the smallest amount of NO_x as a tradeoff for (almost) the least consumption of water and energy among all 16 technology sets. However, TS1 could emit only 0.01% more NO_x at 9% less cost and 0.2% less water consumption than TS5, although the energy consumption would be 0.8% more than that of TS5.

From the perspective of the dust-water-energy nexus, TS10 could emit the smallest amount of dust and it would consume a medium amount of water and the highest amount of energy among the 16 technology sets. However, TS14 could significantly reduce the consumption of energy with a slight increase of dust emission and water consumption. The cost could be 12% higher than TS5 without notable improvement of NO_x emissions.

Overall, the results of the Pareto optimization demonstrate the tradeoffs among pollution, water consumption, energy consumption, and cost. There is no technology set that could result in the least SO_2, NO_x and dust emission at the same time. Lower SO_2 emissions tend to lead to more dust emission as a tradeoff. This is because highly efficient desulfurization technologies have a low synergistic effect of dust removal. Moreover, the highly efficient dust removal technologies demand less water and more energy.

4. Discussion and conclusions

The development and implementation of an integrated assessment approach can help in understanding the coupled relationships between water, energy and emissions and can identify potential win-win strategies given the facts of universal synergistic effects and that only tradeoff solutions exist. The technology-based approach can facilitate selecting the most feasible technology sets within various constraints.

In this study, we quantified linkages of the WEEN (water for energy and/or pollutants, energy for water and/or pollutants, and pollutant removal rate) of the steel industry in Hebei, the largest steel production province in China. The results highlight the water and energy required for pollutant removal. The electricity consumption related to the WEEN was 7% of the total electricity consumption; nearly 95% of that was used for air pollutants removal, with the remaining 5% used for wastewater treatment. The water use associated with the nexus was 66% of the total, of which 71% was used for direct and indirect cooling and 37% was used for air pollutant removal. The promotion of highly efficient pollutant removal technologies, the introduction of advanced denitrification technologies, the improvement of production technologies, and high-quality raw material supply could lead to an SO_2 emission reduction as high as 57%, although with a 0.3% lower synergistic NO_x-reduction effect and nearly a 4% lower synergic dust-reduction effect than current situation. These pollutant reductions have tradeoffs of 0.2% higher energy consumption, 56% higher water consumption, and 40% higher costs than is currently the case in Hebei. Based on the Pareto optimization, it is clear that more feasible technology sets could be implemented if the water, energy, emission, and costs are fully considered at the same time. The most feasible technology sets could lead to reductions of SO_2 emissions of nearly 97%, more than 50% of NO_x emissions, and almost 75% of dust emissions; they could also save approximately 10% of water consumption and 2% of energy consumption. However, the installation and operational costs could be 52%-74% higher than current costs.

Some further efforts are required to address the universal uncertainty associated with the WEEN nexus. First, there is a need to elaborate the conceptualization of material and energy flow at a plant level. The complexity and uncertainty of these flows lead to the diversity of flow designs. Consequently, the inputs and outputs of the flows and the quantification of the WEEN could be influenced. Second, an uncertainty analysis is desired to take parameter variations into account. The median values used in this study may lead to deviations from reality. Multiple factors, e.g., equipment conditions and maintenance, could result in the performance of technologies being quite different than reported in this study (Wang et al., 2015). Third, the service life of technologies, which was used to calculate the installation and operation costs in this study, was obtained from technology instructions or engineering guidance. In fact, technical updates are often faster than the recommended service life because of the stricter regulatory requirements, which could lead to an increase in actual installment costs of technical equipment.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2017.04.014.

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