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Quantify the energy and environmental benefits of implementing energy-efficiency measures in China's iron and steel production

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Abstract

As one of the most energy-, emission- and pollution-intensive industries, iron and steel production is responsible for significant emissions of greenhouse gas (GHG) and air pollutants. Although many energy-efficiency measures have been proposed by the Chinese government to mitigate GHG emissions and to improve air quality, lacking full understanding of the costs and benefits has created barriers against implementing these measures widely. This paper sets out to advance the understanding by addressing the knowledge gap in costs, benefits, and cost-effectiveness of energy-efficiency measures in iron and steel production. Specifically, we build a new evaluation framework to quantify energy benefits and environmental benefits (i.e., CO_2 emission reduction, air-pollutants emission reduction and water savings) associated with 36 energy-efficiency measures. Results show that inclusion of benefits from CO_2 and air-pollutants emission reduction affects the cost-effectiveness of energy-efficiency measures significantly, while impacts from water-savings benefits are moderate but notable when compared to the effects by considering energy benefits alone. The new information resulted from this study should be used to augment future programs and efforts in reducing energy use and environmental impacts associated with steel production.

Keywords: Iron and steel; Energy-efficiency measure; Energy benefits; Environmental benefits; Cost effectiveness

Introduction

China is currently facing significant challenges in energy use, and emissions of associated air pollutants and carbon emissions. Controlling emissions of air pollutants and CO_2 not only is important for protecting the environment, but also is essential for achieving sustainability in the country's economic and societal development. According to International Energy Agency (IEA), more than one-third of global energy consumption and 36 % of CO_2 emissions are attributable to manufacturing industries (IEA, 2007). According to the 5th Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), greenhouse gas (GHG) emissions from industry (30 % of total global GHG emissions) arise mainly from material processing. For example, production of iron and steel and nonmetallic minerals results in 44 % of all industrial CO_2 emissions (IPCC, 2014). The crude steel production in China was 731 Million tonnes (Mt) in 2012, accounting for half of the world's total annual production (WSA, 2013). With such a high level of production and related energy consumption and CO_2 emissions, China's iron and steel industry must play an important role in the country's energy savings and emission reduction programs (Wang 2014b).

To improve energy efficiency and mitigate CO_2 emissions, Chinese governments have implemented many efficiency measures since the last decade. During the 11th and the 12th Five Year Plan (FYP), the National Development and Reform Commission (NDRC) released a series of *National Extension Directories of Important Energy Conservation Technology* (NDRC, 2008, 2009, 2011a, 2011b, 2012, 2013); the Ministry of Industry and Information Technology (MIIT) established the *Energy Savings and Emission Reduction Information Platform* and released the *Guidebook of Advanced and Applicable Energy Savings and Emission Reduction Technologies in Iron and Steel Industry* in 2012 (MIIT, 2012a, 2012b).

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In addition, NDRC, MIIT and the Ministry of Environmental Protection (MEP) jointly issued the *Cleaner Production Evaluation System for the Iron and Steel Industry* in 2012 (MEP, 2013). These government agencies proposed about 60 energy-saving and emission-reduction measures for the iron and steel industry collectively. Although many of the measures have been proposed, lacking full understanding of costs and benefits has created barriers against implementing these measures widely. It is important to evaluate cost effectiveness of energy-efficiency measures and select the most suitable and cost effective measures for implementation.

Literature review

Developing bottom-up energy system models and energy conservation supply curves (CSC) are two common methods for quantitative analyses of specific energy-efficiency measures. With the bottom-up modeling method, Wen et al. (2014) applied the AIM model to estimate the potentials of energy conservation and CO_2 mitigation in China's iron and steel industry during 2010–2020. Xu et al. (2014) and Karali et al. (2014) used the ISEEM model to analyze the roles of energy-efficiency measures in achieving specific carbon reduction targets in the same industry of U.S. Chen et al. (2014) also applied the China-TIMES model to study the carbon mitigation strategies and corresponding impacts. Using the CSC method, Morrow et al. (2014) analyzed 25 energy-efficiency measures applicable to India's iron and steel industry. Earlier, Hasanbeigi et al. (2013) assessed the costs of energy savings and emission reductions from applying energy-efficiency measures in the China's iron and steel sector. Recently, Li and Zhu (2014) also estimated the costs of energy savings and CO_2 emission reduction in China's iron and steel production. These papers report important works for specific energy-efficiency measures of iron and steel industry; however, knowledge gaps still exist. On one hand, detailed analyses of energy-efficiency measures promoted by the Chinese government during the 11th and the 12th FYP are limited in those studies; on the other hand, the majority of these studies only quantify energy-savings benefits, whereas non-energy benefits are neglected, such as carbon-emission mitigation, air-pollutants reduction, and water savings that are very important for China's sustainable development.

From a macro-perspective, inclusion of non-energy benefits would result in reducing costs and improving cost-effectiveness of energy-efficiency measures, thus influence the assessment of cost-effective potentials (Worrell et al., 2003). There are many types of non-energy benefits, such as: (1) saved water and minimized wastes, (2) reduced GHG emissions, (3) reduced air pollutant emissions, (4) saved labor and time, (5) improved working environment (Worrell et al., 2003; Lung et al., 2005; IEA, 2012). Given the limitations, uncertainties, and challenges of quantifying non-energy benefits, this study focused on three types of environmental benefits, namely the carbon emission reduction, the air pollutants reduction, and the water-savings benefits. This paper aims to advance the understanding of costs, benefits, and cost-effectiveness of energy-efficiency measures in China's iron and steel industry, by including both energy- and environmental benefits.

Overview of China's iron and steel production

China's iron and steel industry has grown rapidly in recent decades. The rapid growth has been attributed largely to increasing domestic demand; this growth is expected to continue in the coming years. During 1996–2012, China's crude steel production increased from 107 to 731 Mt; its corresponding share of world steel production increased from 13.5 to 50.0 %. Additionally, China's iron and steel industry made great progress in improving energy efficiency during the past decade. Average intensity of total energy use in key steel enterprises decreased from 761 kgce (kilogram of coal equivalent)/tonne steel in 2004 to 592 kgce/tonne in 2013. From 2004 to 2013, energy intensity of iron-making process decreased from 466 to 398 kgce/tonne iron; BOF (Basic oxygen furnace) process decreased from 26.6 to negative 7.7 kgce/tonne; and EAF (Electric arc furnace) process decreased from 209.9 to 60.8 kgce/tonne. Large "efficiency gap" still exists between the lowest and the highest energy intensity enterprises, as shown in Table 1 (Wang 2005, 2009, 2011, 2014a, 2014b).

Methodology

In order to quantify energy and environmental benefits of implementing energy-efficiency measures in China's iron and steel production, and to evaluate their impacts on cost effectiveness of the measures, we use the compiled data and information from literature reviews and developed a new evaluation framework in this paper, as shown in Fig. 1.

Data collection and basic assumption

The analysis for China's iron and steel industry is based on both international and Chinese technologies. Many energy-efficiency measures promoted by NDRC and MIIT are used in this analysis because other studies do not provide consistent and comprehensive data on energy-savings, emission-reduction, or associated costs of different energy-efficiency measures (NDRC, 2008, 2009, 2011a, 2011b, 2012, 2013; MIIT, 2012a, 2012b).

We use 2012 as the base year because that was the latest year for which energy and environmental data have been published by China's national statistical agencies at the time of this study. Data on total production of different products are obtained from China Iron and Steel Association (CISA, 2013) and the World Steel Association (WSA, 2013). For estimating the adoption rates and technology availability of

Table 1 Process primary energy intensity for Chinese key steel enterprises (kgce/tonne)

	Sintering	Pelleting	Coking	Iron-making	BOF	EAF	Rolling	Integrated energy consumption
The average primary energy intensity of key steel enterprises by process (kgce per tonne of product)								
2004	66.4	42.0	142.2	466.2	26.6	209.9	92.9	761.0
2007	55.2	30.1	121.7	426.8	6.0	81.3	63.1	628.0
2010	52.7	29.4	105.9	407.8	−0.2	74.0	61.7	604.6
2013	49.1	28.3	100.5	398.1	−7.7	60.8	59.5	592.0
Lowest primary energy intensity of key steel enterprises by process (kgce per tonne of product)								
2004	52.1	19.2	88.1	395.4	−3.8	146.3	53.7	-
2007	38.0	18.2	82.8	377.9	−16.1	46.7	28.2	-
2010	43.1	17.6	63.6	343.2	−13.3	27.5	25.9	-
2013	35.4	14.5	59.2	320.0	−23.6	21.9	32.3	-
Highest primary energy intensity of key steel enterprises by process (kgce per tonne of product)								
2004	108.6	83.3	229.2	591.8	75.2	325.5	286.9	-
2007	85.3	51.3	434.6	569.3	38.0	171.6	220.7	-
2010	66.8	45.5	188.3	502.8	29.1	221.33	255.7	-
2013	56.8	44.9	154.6	474.0	14.9	176.6	209.5	-

Note: Negative value means this process can produce additional energy, such as converter gas

different measures, we developed a questionnaire and sent it to several experts in the Chinese iron and steel industry. Additionally, we obtained data from two recent reports: Key Industrial Energy-efficient and Emission Reduction Technologies and Measures (MIIT, 2012b) and Roadmap Study on Achieving Technical Energy Conservation Potential in China's Industrial Sector by 2020 (ERI, 2013).

The carbon emission factors for fuels used for calculating CO_2 emissions from energy consumption are taken from the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2007). The emissions factor for electricity in 2012 is assumed to be 0.77 kg CO_2/kWh (NBS, 2013a). Given most of the fossil fuels used in the China's iron and steel industry are coal and coke, we use the weighted average CO_2 emission factor for coal and coke consumed in the iron and steel industry in 2012 as the CO_2 emission factor for fuel in this research, which is approximately 83.8 kg CO_2/GJ (NBS, 2013a). In the

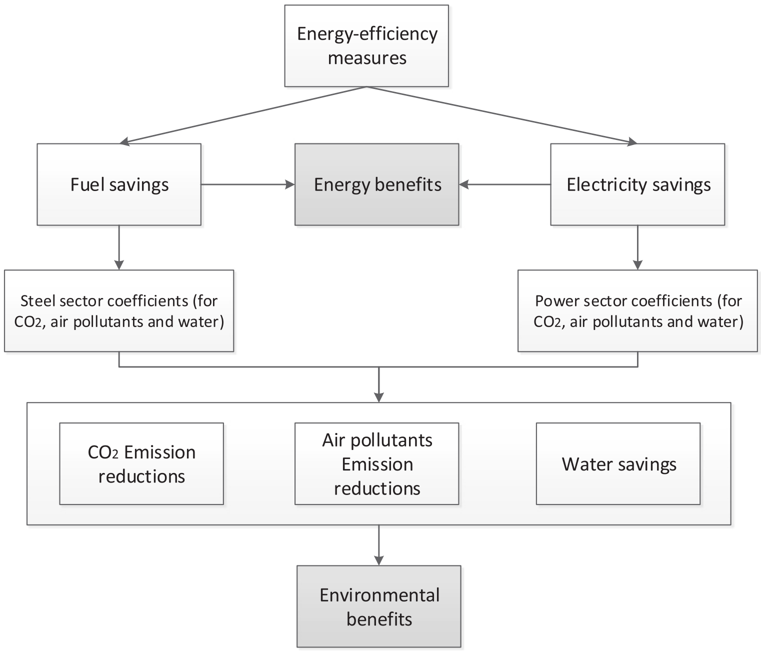

Fig. 1 Evaluation framework for quantifying energy and environmental benefits

processes of steel production and power generation, there are usually air pollution removal facilities, such as desulfurization equipment and de-nitrification equipment. For simplicity, we estimate the air pollutant emission factors based on the emissions and energy consumption in steel and power sectors, which are approximately 5 kg/tce and 1,654 kg/GWh for SO_2, 2 kg/tce and 2,114 kg/GWh for NO_x, and 4 kg/tce and 462 kg/GWh for PM_{10} (NBS, 2013a, 2013b). Additionally, we assume that impacts from interactions among energy efficiency measures are minimal, i.e., measures are analyzed as if they were implemented separately. For this reason and to avoid overestimation of total cumulative energy-saving potential, we have used the lower end of energy-saving range that was available for each energy-efficiency measure. We also estimate the average water coefficients (i.e., water volumes per energy production unit) based on published water factors in fuel production, and power generation processes, as shown in Table 2.

The average unit price of electricity is assumed to be 120 $/MWh (SERC, 2011), while the average unit price of thermal coal for industrial use is approximately 111 $/tonne in 2012, which is used as the fuel price in this report (CCTD, 2013). To convert costs reported in RMB to US dollars, we use an average exchange rate of 6.31 RMB/US$ (CFETS, 2013).

Estimate energy savings, emission reductions, and water savings

The technical potential of fuel savings and electricity savings from energy-efficiency measure j can be calculated using Eq. (1) and Eq. (2), respectively

$$SF_j = P_i \cdot (100\% - k_j) \cdot TA_j \cdot RF_j, \text{ in GJ} \tag{1}$$

$$SE_j = P_i \cdot (100\% - k_j) \cdot TA_j \cdot RE_j, \text{ in kWh} \tag{2}$$

Where

SF_j = technical potential of fuel savings from measure j (GJ);

SE_j = technical potential of electricity savings from measure j (kWh);

P_i = production in step i (Mt);

k_j = current adoption rate of measure j (%);

TA_j = technology availability of measure j, the extent to which the remaining adoption potential of the technology in Chinese iron and steel industry;

RF_j = specific fuel savings for measure j (GJ/Mt-production i);

RE_j = specific electricity savings for measure j (kWh/Mt-production i).

The air pollutants considered in this study are SO_2, NO_x, and PM_{10}, without considering $PM_{2.5}$ because of a lack of reliable emission and cost data for $PM_{2.5}$. Reduction of pollutant emissions (CO_2, SO_2, NO_x, and PM_{10}) corresponding to measure j can be calculated using Eq. (3).

$$RC_j = SF_j \cdot EF_1 + SE_j \cdot EF_2, \text{ in tonne} \tag{3}$$

Where

RC_j = emissions reduction corresponding to measure j, tonne;

EF_1 = direct emission coefficient of fuels (tonne/GJ);

EF_2 = indirect emission coefficient of electricity (tonne/kWh).

Water withdrawal is an important indicator for the iron and steel industry and power industry (NDRC 2013). In this study, we only consider energy related water savings, based on the energy savings and water coefficients, as shown in Eq. (4).

$$WS_j = SF_j \cdot WF_1 + SE_j \cdot WF_2 \tag{4}$$

Where

WS_j = total water savings due to measure j (m^3);

WF_1 = average water withdrawal coefficient for fuel production (m^3/GJ);

Table 2 Summary of water coefficients in fuel production and power generation processes

Type	Unit	Water coefficient	Data source
Coal production	m^3/TJ	4.0	Hejazi et al. (2014)
Coke production	m^3/TJ	0.02	Pan et al. (2012)
Nature gas production	m^3/TJ	0.01	Hejazi et al. (2014)
Crude oil production	m^3/TJ	44.0	Hejazi et al. (2014)
Unconventional Oil production	m^3/TJ	6.0	Hejazi et al. (2014)
Uranium	m^3/TJ	2.0	Hejazi et al. (2014)
Thermal power	m^3/MWh	2.85	Pan et al. (2012)
Nuclear power	m^3/MWh	2.6	McMahon and Price (2011); Li et al. (2012)
Wind Power	m^3/MWh	0.004	Li et al. (2012); Davis et al. (2013)
PV power	m^3/MWh	0.1	Davis et al. (2013)

WF_2 = average water withdrawal coefficient for power generation (m^3/kWh).

Quantify the benefits and evaluate the cost-effectiveness

To quantify the emission reduction benefits, we use the concept of an air pollutant (AP) price index, as shown in Eq. (5) (Mao et al., 2012; 2014).

$$AP = A \cdot RC_{CO2} + B \cdot RC_{SO2} + C \cdot RC_{NOx} + D \cdot RC_{PM10}, \text{ in} \tag{5}$$

Where

RC_{C02}, RC_{SO2}, RC_{NOx}, and RC_{PM10} represents the emission reduction of CO_2, SO_2, NO_x, and PM_{10}, respectively, in tonne.

A, B, C, and D is the price weighting factor of CO_2, SO_2, NO_x, and PM_{10}, respectively, in \$/tonne.

A is the average carbon price, based on historical trading volumes and trading turnovers in China's seven regional carbon markets, i.e., Beijing, Shanghai, Tianjin, Shenzhen, Guangdong, Hubei, and Chongqing (WHECA, 2014). As there are no trading markets for air pollutants in China, we use external environmental damage cost as the weighting factors of SO_2, NO_x, and PM_{10} (Zhang et al., 2007; Mao et al., 2012). The price weighting factors are listed in Table 3.

In this study, we define the carbon abatement cost for a specific measure as the change of total costs divided by the CO_2 reduction potentials, as shown in Eq. (6).

$$c_j = \frac{P_i \cdot (1-k_j) \cdot TA_j \cdot \left[\frac{I_j \cdot r}{(1-(1+r)^{-n})} + \Delta OM_j\right] - B_j}{RC_{CO2,j}} \tag{6}$$

Where

c_j = carbon abatement cost for an energy-efficiency measure j (\$/tonne);

P_i = production in step i (Mt);

k_j = current adoption rate of measure j (%);

TA_j = technology availability of measure j, the extent to which the remaining adoption potential of the technology in Chinese iron and steel industry;

I_j = change in total capital investment for an energy-efficiency measure j (\$/tonne);

ΔOM_j = change in non-energy annual operation and maintenance cost for measure j (\$/tonne);

r = discount rate (15 %), it should be noted that the choice of the discount rate depends on the purpose and approach of the analysis (prescriptive versus descriptive) used (Hasanbeigi et al., 2013).

n = lifetime (years);

B_j = benefits of measure j (\$), include energy benefits (i.e., reduced energy costs) and environmental benefits (i.e., emission reduction benefits and reduced water costs);

$RC_{CO2,\ j}$ = annual reduction of CO_2 emissions for measure j.

The cost-effectiveness for specific measure is determined by the carbon abatement cost: A negative cost c_j means the measure j is cost-effective.

If we consider the change in measure cost and energy-savings benefits only, Eq. (6) becomes the following

$$c_1 = \frac{P \cdot (1-k) \cdot TA \cdot \left[\frac{I \cdot r}{(1-(1+r)^{-n})} + \Delta OM\right] - p_1 \cdot SF - p_2 \cdot SE}{RC_{CO2}} \tag{7}$$

If we consider the change in measure cost, energy-savings benefits, and carbon-reduction benefits, Eq. (6) becomes the following:

$$c_2 = \frac{P \cdot (1-k) \cdot TA \cdot \left[\frac{I \cdot r}{(1-(1+r)^{-n})} + \Delta OM\right] - p_1 \cdot SF - p_2 \cdot SE - AP}{RC_{CO2}} \tag{8}$$

If we consider the change in measure cost, energy-savings benefits, and environmental benefits (CO_2 and air pollutant emission reduction benefits and water savings), Eq. (6) becomes the following:

$$c_3 = \frac{P \cdot (1-k) \cdot TA \cdot \left[\frac{I \cdot r}{(1-(1+r)^{-n})} + \Delta OM\right] - p_1 \cdot SF - p_2 \cdot SE - AP - p_3 \cdot WS}{RC_{CO2}} \tag{9}$$

Where

P_1 = average fuel price (\$/GJ);

P_2 = average electricity price (\$/kWh);

AP denotes the total emission reduction benefits; see Eq. (5);

P_3 = average water price (\$/m^3);

WS = total water savings (m^3).

Table 3 Price weighting factors for CO_2 and air pollutant emissions in the iron and steel industry

Price weighting factors	Zhang et al. (2007)	Yang et al. (2013)	Wei and Zhou (2003)	Liu et al. (2014)	Low	Average	High
CO_2 (\$/tonne) (WHECA, 2014)	-	-	-	-	3.5	6.0	11.0
SO_2 (\$/tonne)	1006.1	3680.0	983.0	1056.6	983.0	1682.0	3680.0
NO_x (\$/tonne)	902.0	2438.0	1311.5	750.0	750.0	1350.0	2438.0
PM_{10} (\$/tonne)	7720.0	2623.9	360.0	1169.5	360.0	2968.0	7720.0

Table 4 Compiled data of 36 energy-conservation and emission-reduction measures

	Technology	Product (Mt)	Fuel savings (kgce/t)	Electricity savings (kWh/t)	Capital cost ($/t)	O&M cost ($/t)	Lifetime (Year)	Current adoption rate k (%)	Data source
	Coke making								
1	Coal moisture control (CMC)	145.1	15.0	0	13.53	5.01	20	50 %	(Zhu and Chen 2004; MIIT, 2012b; ERI, 2013)
2	Coke dry quenching (CDQ)	145.1	0	75.0	36.69	11.00	18	50 %	(Xue, 2009; ERI, 2013; NDRC, 2013)
	Sinter								
3	Generation of sinter waste heat	808.9	0	65.0	3.96	0.12	10	21 %	(Lu, 2008; MIIT, 2012b)
4	Cooler fluid sealing ring	808.9	0	3.0	2.01	n/a	20	3 %	(Chen et al. 2012; MIIT, 2012b; ERI, 2013)
5	Improved process control in sintering	808.9	0.34	0	0.95	n/a	20	90 %	(MIIT, 2012b; Hasanbeigi et al. 2013)
6	Small pellet sintering process	808.9	9.0	0	0.21	0.19	20	50 %	(NDRC, 2011a; Hong et al. 2012)
7	Reduction of leakage rate in sintering process	808.9	0	2.0	0.12	0.40	20	80 %	(Lai et al. 1995; MIIT, 2012b)
8	Low temperature sintering technology	808.9	9.0	0	0.19	0.40	20	75 %	(Song, 2001; MIIT, 2012b; Morrow et al. 2014)
9	Low carbon and thick sinter-bed sintering	808.9	2.0	0	0.38	0.08	20	80 %	(Liu et al. 2006; MIIT, 2012b; Morrow et al. 2014)
	Pellet								
10	Grate-Kiln	232.7	9.9	0	39.62	n/a	15	48 %	(Feng et al. 2007; MIIT, 2012b; ERI, 2013)
11	Recovery of waste heat in pelletizing process	232.7	3.0	0	1.43	0.18	10	60 %	(Hasanbeigi et al. 2013; MIIT, 2012b; Wang 2014a, 2014b)
	Iron making								
12	Top-pressure recovery turbines (TRT)	657.9	0	50.0	2.38	0.63	15	62 %	(Zhang et al. 2011; NDRC, 2013; Morrow et al. 2014)
13	Recovery of BFG gas	657.9	1.37	0	0.44	n/a	10	94 %	(ERI, 2013; Hasanbeigi et al. 2013; Zhang, 2013)
14	Dehumidification blast	657.9	8.0	0	2.69	0.71	10	10 %	(NDRC, 2009,2011b; MIIT, 2012b)
15	Cyclone type top combustion hot stoves	657.9	7.96	0	34.80	n/a	20	50 %	(Gong and Chen 2012; ERI, 2013)
16	Injection of pulverized coal	657.9	4.3	0	9.33	−0.01	20	60 %	(ERI, 2013; Hasanbeigi et al. 2013; Morrow et al. 2014)
17	CCPP	657.9	16.0	0	15.06	n/a	15	20 %	(Zhang et al. 2006; MIIT, 2012b; ERI, 2013)
18	Process control of blast furnace	657.9	12.3	0	9.98	n/a	20	30 %	(ERI, 2013; Hasanbeigi et al. 2013; Zhou, 2013)
19	Waste plastic injected into blast furnace	657.9	3.76	0	9.51	n/a	20	3 %	(Xu, 2003; ERI, 2013; Morrow et al. 2014)
	Steel making-BOF								
20	Recovery of BOF gas	643.5	0	9.0	3.96	0.92	20	48 %	(Zhou, 2008; ERI, 2013)
21	Converter steelmaking with negative energy consumption	643.5	25.0	0	23.77	0.55	20	48 %	(MIIT, 2012b; ERI, 2013; Morrow et al. 2014)
	Steel making-EAF								
22	Scrap preheating	72.5	0	61.0	7.13	−3.49	20	10 %	(Zhou, 2008; ERI, 2013)
23	Generation of EAF waste heat	72.5	12.0	0	5.94	n/a	20	3 %	(Cheng and Shi 2009; ERI, 2013)
24	Improved process control	72.5	0	13.9	60.22	n/a	20	50 %	(Zheng, 2003; ERI, 2013)

Table 4 Compiled data of 36 energy-conservation and emission-reduction measures *(Continued)*

25	UHP transformer	72.5	0	58.3	29.16	n/a	20	40 %	(Zheng, 2003; ERI, 2013)
	Casting								
26	Integrated casting and rolling	704.7	8.53	42.0	2.38	0.24	20	50 %	(ERI, 2013; Hasanbeigi et al. 2013; NDRC, 2013)
27	Thin slab casting (TSC)	704.7	0	25.0	6.34	7.13	20	15 %	(Song et al. 2009; ERI, 2013)
	Hot Rolling								
28	Regenerative burners	716.7	0	85.0	1.58	0.36	10	22 %	(Pan, 2002; ERI, 2013; Hasanbeigi et al. 2013)
29	Process control in hot rolling	716.7	10.24	0	1.39	n/a	10	0 %	(ERI, 2013; Hasanbeigi et al. 2013; Morrow et al. 2014)
30	Enhanced radiation technology	716.7	6.5	0	0.48	n/a	10	10 %	
31	Recovery of hot-rolling waste heat	716.7	1.02	0	3.71	0.32	20	80 %	(Pan; 2002; ERI, 2013; Hasanbeigi et al. 2013)
	Cold Rolling								
32	Recovery of cold-rolling waste heat	123.9	10.24	3.0	4.29	0.19	15	45 %	(ERI, 2013; Ma and Sun 2013)
33	Multi rolling technique on the bar rolling	123.9	5.12	0	1.98	n/a	20	10 %	(Yang, 2011; MIIT, 2012b; ERI, 2013)
34	Continuous annealing technology	123.9	12.97	0	17.61	n/a	20	5 %	(MIIT, 2012b; Hasanbeigi et al. 2013; Morrow et al. 2014)
	General measures								
35	Energy management and system optimization	657.9	10.9	2.78	4.75	n/a	20	90 %	(MIIT, 2012a, 2012b; Hasanbeigi, 2013; Morrow, 2014)
36	Preventative maintenance	657.9	14.7	5.56	3.96	1.30	20	90 %	(MIIT, 2012a, 2012b; Hasanbeigi et al. 2013; Morrow et al. 2014)

Typical energy-savings and emission-reduction measures

Considering data uncertainties and information availability for some measures (e.g., emerging measures), we selected 36 energy-efficiency measures for the analyses and presentations in this study. Table 4 presents the compiled results from these measures, including energy savings, capital and change in O&M costs, adoption rates in 2012, and product amount for each process in China.

Results and discussion

Technical energy savings and environmental impacts

Table 5 summarizes the technical potential of energy savings, emission reduction, and water savings for each energy-efficiency measure in China's iron and steel production.

For individual measure, the regenerative burner measure (measure #28) exhibits the largest technical potential in energy savings (24,734 GWh electricity), emission reductions (19.1 Mt CO_2, 40.9 kiloton (kt) SO_2, 52.3 kt NO_x, and 11.4 kt PM_{10}), and water savings (559.7 million m^3); the recovery of BFG gas (measure #13) has the lowest technical potential in energy savings (37.7 ktce fuel), emission reductions (0.1 Mt CO_2, 0.2 kt SO_2, 0.1 kt NO_x, and 0.1 kt PM_{10}), and water savings (0.1 million m^3).

27 energy-saving measures are process technologies and the other nine measures are technologies for waste energy recovery. The 27 measures account for 82.8 % of fuel savings and 64.4 % of electricity savings, while the other nine measures are responsible for 17.2 % of fuel savings and 35.6 % of electricity savings. The largest potentials for energy savings and emission reduction come from the iron-making processes (27.0 %) and hot-rolling processes (25.0 %); the pellet process has the lowest potential for emission reduction (about 1.0 %).

For the 36 energy-efficiency measures, technical potential of total energy savings are about 36.5 Mtce fuels and 78,659 GWh electricity, corresponding to 7.8 % fuel savings and 15.1 % electricity savings, respectively. Annual emission reduction is 150.4 Mt CO_2, 321.8 kt SO_2, 243.7 kt NO_x, and 180.0 kt PM_{10}, corresponding to 10.0 %, 13.4 %, 25.0 %, and 10.0 % of the total emissions (by type), respectively; Water savings are 1,842.2 million m^3 (51.5 % of annual consumption in the sector).

CO_2 abatement cost analyses

Based on the main technical cost data (change in capital and O&M costs), and associated benefits (energy savings, emission reduction, and water savings), CO_2 abatement costs are

Table 5 Technical potentials of energy savings, emission reduction, and water savings in China's iron and steel industry (2012)

No.	Energy savings		Emission reduction (1,000 tonne)				Water savings (million m^3)
	Fuel savings (1,000 tce)	Electricity savings (GWh)	CO_2	SO_2	NO_x	PM_{10}	
1	761.5	-	1,868	4.0	1.6	3.0	1.3
2	-	3,249	2,512	5.4	6.9	1.5	73.5
3	-	21,716	16,787	35.9	45.9	10.0	491.4
4	-	665	514	1.1	1.4	0.3	15.1
5	115.5	-	283	0.6	0.2	0.5	0.2
6	2,548.2	-	6,251	13.4	5.4	10.0	4.3
7	-	227	175	0.4	0.5	0.1	5.1
8	1,274.1	-	3,125	6.7	2.7	5.0	2.2
9	226.5	-	556	1.2	0.5	0.9	0.4
10	838.5	-	2,057	4.4	1.8	3.3	1.4
11	182.5	-	448	1.0	0.4	0.7	0.3
12	-	8,750	6,764	14.5	18.5	4.0	198.0
13	37.7	-	93	0.2	0.1	0.1	0.1
14	1,473.7	-	3,615	7.7	3.1	5.8	2.5
15	1,832.9	-	4,496	9.6	3.9	7.2	3.1
16	792.1	-	1,943	4.2	1.7	3.1	1.3
17	2,210.5	-	5,422	11.6	4.7	8.7	3.8
18	3,965.2	-	9,727	20.8	8.4	15.7	6.7
19	1,679.6	-	4,120	8.8	3.6	6.6	2.9
20	-	486	376	0.8	1.0	0.2	11.0
21	5,855.9	-	14,364	30.7	12.4	23.1	9.9
22	-	2,786	2,153	4.6	5.9	1.3	63.0
23	529.8	-	1,230	2.8	1.1	2.1	0.9
24	-	775	599	1.3	1.6	0.4	17.5
25	-	1,766	1,365	2.9	3.7	0.8	40.0
26	1,262.6	6,215	7,901	16.9	15.8	7.9	142.8
27	-	6,783	5,243	11.2	14.3	3.1	153.5
28	-	24,734	19,119	40.9	52.3	11.4	559.7
29	5,137.0	-	12,601	26.9	10.9	20.3	8.7
30	2,935.0	-	7,199	15.4	6.2	11.6	4.9
31	102.8	-	252	0.5	0.2	0.4	0.2
32	310.8	91	832	1.8	0.9	1.3	2.6
33	222.0	-	545	1.2	0.5	0.9	0.4
34	1,068.7	-	2,621	5.6	2.3	4.2	1.8
35	502.0	138	1,338	2.9	1.4	2.0	4.0
36	677.0	276	1,874	4.0	2.0	2.8	7.4
Total of 36 measures	36,542.1	78,659	150,440	321.8	243.7	180.0	1,842.2
Total in steel sector in 2012	468,020	522,052	1,510,000	2,410	970	1,810	3,580
Savings (or emission reduction) percentage of the total (%)	7.8 %	15.1 %	10.0 %	13.4 %	25.0 %	10.0 %	51.5 %

calculated for each energy-efficiency measure listed in Table 6.

Table 6 indicates that both energy-savings benefits and environmental benefits have important impacts on the CO_2 abatement cost. When only energy-savings benefits are considered, the abatement costs range from negative \$212/tonne CO_2 (measure #22) to \$312/tonne CO_2 (measure #31); when the emission reduction benefits are considered, the abatement cost is reduced further, ranging from negative \$227/tonne CO_2 (measure #22) to 295 \$/tonne

Table 6 Costs, benefits, and carbon abatement costs for individual energy-efficiency measures

No.	Technical cost data (million \$)		Benefits (million \$)				CO_2 mitigation (kt)	CO_2 abatement cost (\$/tonne CO_2)		
	Change in capital cost	Change in non-energy O&M cost	Energy savings benefits	CO_2 mitigation benefits	Air pollutant reduction benefits	Water savings benefits		c_1	c_2	c_3
1	147	349	119	11.0	19.4	1.1	1,868	202	185	185
2	239	240	399	14.8	21.3	53.0	2,512	32	17	−7
3	273	41	2,670	99.1	142.5	354.5	16,787	−140	−155	−179
4	101	-	82	3.0	4.4	10.9	514	37	22	−2
5	53	-	18	1.7	2.9	0.1	283	125	109	108
6	10	56	397	36.9	64.9	3.1	6,251	−53	−69	−70
7	2	46	28	1.0	1.5	3.7	175	119	105	81
8	4	58	198	18.4	32.4	1.6	3,125	−44	−60	−60
9	7	9	35	3.3	5.8	0.3	556	−34	−50	−51
10	594	-	131	12.1	21.3	1.0	2,057	225	209	208
11	19	12	28	2.6	4.6	0.2	448	6	−10	−11
12	74	115	1,076	39.9	57.4	142.8	6,764	−131	−146	−170
13	3	-	6	0.6	1.0	0.0	93	−36	−53	−53
14	102	136	230	21.3	37.5	1.8	3,615	2	−14	−14
15	1,324	-	285	26.5	46.7	2.2	4,496	231	215	214
16	284	−2	123	11.5	20.2	1.0	1,943	82	65	65
17	368	-	344	32.0	56.3	2.7	5,422	4	−12	−12
18	532	-	618	57.4	100.9	4.9	9,727	−9	−25	−26
19	702	-	262	24.3	42.8	2.1	4,120	107	91	90
20	35	52	60	2.2	3.2	7.9	376	73	58	34
21	951	134	912	84.8	149.1	7.2	14,364	12	−4	−5
22	54	−168	343	12.7	18.3	45.5	2,153	−212	−227	−251
23	43	-	83	7.7	13.5	0.6	1,230	−30	−46	−47
24	176	−139	95	3.5	5.1	12.7	599	−97	−112	−136
25	147	-	217	8.1	11.6	28.8	1,365	−52	−66	−90
26	58	36	961	46.6	72.9	103.0	7,901	−110	−125	−140
27	213	1,334	834	30.9	44.5	110.7	5,243	136	122	98
28	95	110	3,041	112.8	162.3	403.7	19,119	−148	−163	−187
29	144	-	800	74.4	130.8	6.3	12,601	−52	−68	−69
30	45	-	457	42.5	74.7	3.6	7,199	−57	−74	−74
31	61	33	16	1.5	2.6	0.1	252	312	295	294
32	23	6	60	4.9	8.5	1.9	832	−37	−53	−55
33	14	-	35	3.2	5.7	0.3	545	−37	−54	−55
34	240	-	166	15.5	27.2	1.3	2,621	28	12	11
35	36	-	95	7.9	13.7	2.9	1,338	−44	−60	−63
36	30	62	139	11.1	19.0	5.3	1,874	−25	−41	−45

CO_2 (measure #31); when energy and all environmental benefits (including emission reduction and water-savings) are included, the abatement costs are reduced more, ranging from negative \$251/tonne CO_2 (measure #22) to 294/tonne CO_2 (measure #31) \$/tonne CO_2.

The three individual technologies having the lowest reduction cost are scrap preheating (measure #22), regenerative burners (measure #28), and generation of sinter waste heat (measure #3), all with negative abatement cost. The three technologies with the highest abatement costs are heat recovery from hot-rolling (measure #31), cyclone type top combustion hot stoves (measure #15), and Grate-Kiln (measure #10), all with positive costs.

Cost-effectiveness analyses

Based on the individual measure costs, energy benefits, and environmental benefits, we can evaluate and calculate the cost-effective potentials of energy savings, emission reduction, and water savings, as shown in Table 7.

When we consider the energy benefits only, 19 measures are cost effective, the total costs and benefits are 1,953 and 14,132 million \$, and the cost-effectiveness energy savings are 19.6 Mtce for fuel and 67,249 GWh for electricity, while the emission reduction are about 100 Mt CO_2, 214 kt SO_2, 184 kt NO_x and 109 kt PM_{10}, respectively. Additionally, the total water savings are about 1,555 million m^3.

When we consider the energy benefits and emission reduction benefits, 23 measures were identified cost effective, the total costs and benefits are 3,675 and 16,047 million \$, and the cost-effectiveness energy savings are 29.3 Mtce for fuel and 67,249 GWh for electricity, while the emission reduction potential are about 124 Mt CO_2, 265 kt SO_2, 204 kt NO_x and 147 kt PM_{10}, respectively. Additionally, the total water savings are about 1,572 million m^3.

When we consider the energy benefits and emission reduction and water-savings benefits, 26 measures were identified cost effective, the total costs and benefits are 4,494 and 16,855 million \$, and the cost-effectiveness energy savings are 29.3 Mtce for fuel and 71,164 GWh for electricity, while the emission reduction potential are about 127 Mt CO_2, 272 kt SO_2, 213 kt NO_x and 149 kt PM_{10}, respectively. Additionally, the total water savings are about 1,660 million m^3.

More than two-thirds of the 36 alternative measures are cost effective when energy and environmental benefits are accounted for, while many of them are not yet to be adopted widely. The main barriers to wider implementation include the following: (1) potential hidden costs associated with collecting and analyzing information, production disruptions, and inconvenience; (2) limited access to capital needed for investing in energy-efficiency measures; (3) risk aversion due to uncertain payback of energy-efficiency measure investments; (4) imperfect information about market conditions, technology characteristics and impacts of business' own behavior; and (5) inertia, e.g., opponents to change within an organization may result in neglecting of energy-efficiency measures (Rohdin et al. 2007).

Table 7 Total costs, benefits, energy savings, emission reduction, and water savings under three different assumptions

Items	All measures	Cost effective measures		
		Include energy benefits only	Include energy benefits and emission reduction benefits	Include energy benefits and all environmental benefits (emission reduction and water-savings)
Number of measures	36	19	23	26
Total extra capital costs	7,204	1,767	3,207	3,787
Total extra O&M costs	2,520	186	468	707
Total costs (million \$)	9,724	1,953	3,675	4,494
Energy savings benefits (million \$)	15,362	11,325	12,839	13,487
CO2 mitigation benefits (million \$)	888	591	732	765
Air pollutant reduction benefits (million \$)	1,446	941	1,188	1,241
Water savings benefits (million \$)	1,510	1,275	1,288	1,362
Total benefits (million \$)	19,206	14,132	16,047	16,855
Fuel savings (Mtce)	36.5	19.6	29.3	29.3
Electricity savings (GWh)	78,659	67,249	67,249	71,164
CO2 reductions (Mt)	150	100	124	127
SO2 reductions (kt)	322	214	265	272
NO*x* reductions (kt)	244	184	204	213
PM10 reductions (kt)	180	109	147	149
Water savings (million m3)	1,842	1,555	1,572	1,660

Table 8 The scenarios definitions of discount rates and environmental price factors

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Price factor	average	average	average	low	high
Discount rate (%)	15 %	10 %	20 %	15 %	15 %
CO_2 (\$/tonne)	6.0	6.0	6.0	3.5	11.0
SO_2 (\$/tonne)	1,682	1,682	1,682	983	3,680
NO*x* (\$/tonne)	1,350	1,350	1,350	750	2,438
PM_{10} (\$/tonne)	2,968	2,968	2,968	360	7,720
Fuel price (\$/tce)	160	160	160	148	180
Electricity price (\$/MWh)	125	125	125	106	140
Water price (\$/m^3)	0.7	0.7	0.7	0.5	1.0

Sensitivity analysis

The emission reduction costs and the potentials of cost effective measures are influenced by the discount rates and the price factors. We perform sensitivity analyses with three levels of discount rates (10 %, 15 %, and 20 %) and three types of environmental price factors (average, low, and high), as defined in Table 8.

Table 9 shows that an increase in discount rate decreases cost-effectiveness of energy-efficiency measures and results in lower levels of cost effective emission reduction and water savings. A higher environmental price factor corresponds to higher energy benefits and environmental benefits, leading to larger potentials of cost effective emission reduction and water savings.

When the discount rate is 10 % (Scenario 2), the environmental benefits have limited effect on the cost effectiveness of energy-efficiency measures; whereas the discount rate is higher (e.g., 15 % in Scenario 2 or 20 % in Scenario 3), the environmental benefits have more significant effect on the cost effectiveness of energy-efficiency measures. When the discount rate is 15 % and the environmental price level is relatively high, the cost-effectiveness of energy-efficiency measures is more sensitive to the price factors, whether or not to include environmental benefits. When the price factor is low, such as in Scenario 4, the effects of including environmental benefits or not on CO_2 abatement cost are more evident; however, the effects on the scales of cost-effective energy savings and emission reduction are minimal.

With only energy savings benefits, cost effective emission reduction exhibits the following ranges: 90 to124 Mt CO_2, 193 to 266 kt SO_2, 175 to 206 kt NO_x, and 93 to 147 kt PM_{10}, while water savings range from 1,548 to 1,587 million m^3.

With inclusion of energy savings and emission reduction benefits, cost effective emission reduction exhibits the following ranges: 100 to 129 Mt CO_2, 214 to 277 kt SO_2, 184 to 215 kt NO_x, and 109 to 153 kt PM_{10}, while

Table 9 Sensitivity analysis of the cost effective emission reduction and water savings

		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Energy benefits	CO_2 reductions (Mt)	100	124	90	100	110
	SO_2 reductions (kt)	214	266	193	214	235
	NO_x reductions (kt)	184	206	175	184	192
	PM_{10} reductions (kt)	109	147	93	109	124
	Water savings (million m^3)	1555	1587	1548	1555	1562
Energy benefits + emission reduction benefits	CO_2 reductions (Mt)	124	129	104	100	129
	SO_2 reductions (kt)	265	277	223	214	277
	NO_x reductions (kt)	204	215	187	184	215
	PM_{10} reductions (kt)	147	153	115	109	153
	Water savings (million m^3)	1,572	1662	1558	1555	1662
Energy benefits + environmental benefits	CO_2 reductions (Mt)	127	129	104	100	130
	SO_2 reductions (kt)	272	277	223	214	278
	NO_x reductions (kt)	213	215	187	184	216
	PM_{10} reductions (kt)	149	153	115	109	153
	Water savings (million m^3)	1,660	1662	1558	1555	1673

cost effective water savings range from 1,555 to 1,662 million m^3.

With inclusion of all environmental benefits (i.e., CO_2 emission reduction, air pollutants emission reduction benefits, and water savings benefits), cost effective emission reduction exhibits the following ranges: 100 to 130 Mt CO_2, 214 to 278 kt SO_2, 184 to 216 kt NO_x, and 109 to 153 kt PM_{10}, while cost effective water savings range from 1,555 to 1,673 million m^3.

Conclusions and recommendations

In this paper, we quantify the energy and environmental benefits, and evaluate the cost-effectiveness of 36 energy-efficiency measures under different scenarios for Chinese iron and steel industry. The results show that while energy-savings benefits are the main driver in reducing the carbon abatement costs, environmental benefits also affect the cost-effectiveness of the efficiency measures significantly. Among the environmental benefits, including emission reduction benefits in calculations reduces the carbon abatement cost substantially. While the effects from including water-savings benefits are moderate under the assumptions in this study, such effects may become more influential as water price goes up. It is both important and necessary to quantify and monetize environmental benefits when evaluating the costs of energy savings and carbon abatement associated with energy-efficiency measures. Future studies may benefit from including additional non-energy benefits.

To improve energy efficiency and narrow the "efficiency gap" in iron and steel production addressed in this paper, we recommend enhancing adoption of process energy-efficiency measures and waste energy recovery technologies, especially the cost effective measures (e.g., scrap preheating, regenerative burners, and generation of sinter waste heat). We have found that more than two-thirds of the 36 efficiency measures are cost effective when energy and environmental benefits are accounted for, while many of them are yet to be adopted more widely. The main barriers to wider implementation of cost effective measures are discussed, including potential hidden, limited access to capital, risk aversion, imperfect information, etc.

Advancing the understanding of cost effectiveness provides opportunities to diffuse cost barriers against adopting efficiency measures, and may help to promote effective programs and policies to overcome the barriers, such as development of energy-efficiency information resources, technical assistance in identifying energy-efficiency measures, and financing programs for efficiency measures. The new information resulted from this study should be used to augment future programs and efforts in reducing energy use and environmental impacts associated with steel production.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

1) DM carried out literature reviews and analysis, drafted the manuscript, and participated in its revisions; 2) WC served as DM's academic advisor providing guidance; 3) TX oversaw the development of the manuscript including scope and methodologies, performing editing, revising, and finalizing the manuscript; and corresponding with Journal office throughout the publication process. All authors read and approved the final manuscript.

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