Integrated assessment of co-benefits between energy efficiency improvement and emission mitigation in Chinese iron and steel industry

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Abstract

The iron and steel industry is one of the largest energy users and sources of greenhouse gas and air pollutant emissions worldwide. In 2010, China accounted for 45 % of the global steel production, and consumed 15.8 EJ in final energy and emitted an estimated 1,344 Mt CO_2eq of greenhouse gases, 8.4 Mt of PM, and 5.3 Mt of SO_2. China is facing severe challenges with respect to energy security, greenhouse gas and air pollutant emission mitigation. In this paper we analyse the co-benefits of best available energy efficiency measures that jointly tackle above problems, in contrast to end of pipe technology. We analyse the co-benefits in Chinese iron and steel industry using energy conservation supply curve (ECSC) and the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model. First, the ECSC was made to examine the costs and benefits of the energy efficiency measures, and to estimate the cost-effective potentials. The results of the ECSC were introduced exogenously to the GAINS model. The findings show that the annual technical energy saving potential for Chinese iron and steel industry for 2030 is around 5.7 EJ in terms of emission reduction of GHGs and air pollutants estimate to 463 Mt CO_2eq, 253 kt of PM, and 1,392 kt of SO_2. Investments and savings were calculated for different scenarios, showing that energy efficiency investments will result in a reduction in air pollution control costs.

Introduction

The iron and steel production is globally the largest industrial energy consumer and most important emission sources of greenhouse and air pollutants. In 2006, the Chinese iron and steel industry is third largest emitter for sulphur dioxide (SO_2), nitrogen oxides (NO_x), and Particulate matter (PM) emissions in China, which amounted to 10 %, 15 %, 10 %, respectively. The major reasons why of high emissions stand in lower control options (e.g., desulfurization technology) and higher pollution standards, compared with the US. With rapid growth of Chinese industrialization, crude steel production of China has increased from 95 Mt in 1995 to 639 Mt in 2010, which is about 6.7 times that in 1995 and the average annual growth rates amounted to 13.8 % from 1995 to 2010. It means that the share of crude steel production in China jumped from 12.71 % in 1995 to 45.07 % in 2010 of the world total, as shown in Figure 1. As a pillar industry in China, the iron and steel industry consumed 15.8 EJ of final energy and emitted 1,344 Mt CO_2eq of greenhouse gas, 8,433 kt of PM, and 5,279 kt of SO_2 respectively in 2010[1]. The energy consumption, GHGs and air pollutants emissions of China's iron and steel industry are expected to grow further in the future because of continuing production growth.

The Chinese Iron and steel industry has made much progress to improve energy efficiency and reduce air pollutants emission in recent years. The Chinese government provides abundant financial rewards for companies to help implement best available energy efficiency measures, end of pipe technologies, and phasing out inefficiency facilities in the 11th Five Year Plan

1. The emission of greenhouse gas and air pollutant sourced from our calculation through GAINS.

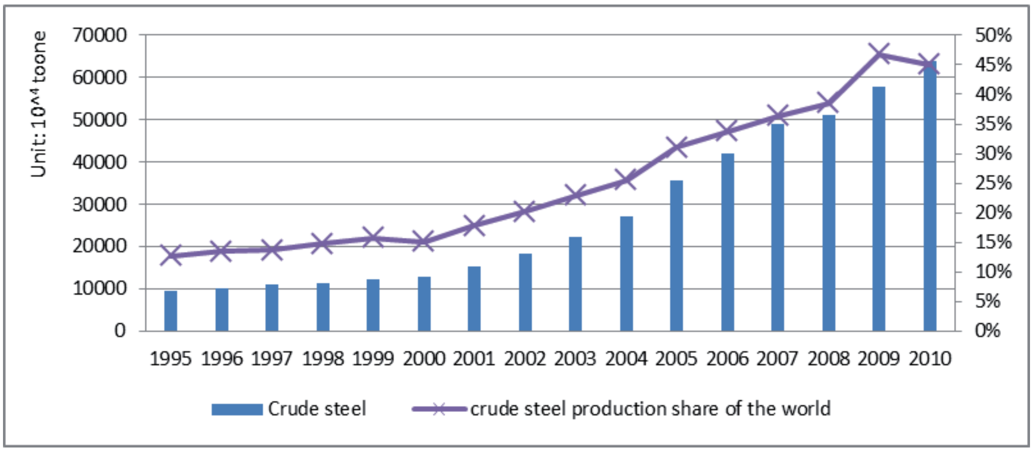

Figure 1. Chinese crude steel production and share of the global from 1995 to 2010.

period (2006–2010). During that period, the total amount of energy efficiency investment of iron and steel industry reached \$14.67 billion, which accounts for 18.7 % of the total industry energy efficiency investment. Around 1.2 EJ of energy was saved and 140 million ton of CO_2 emission was avoided during that period. In the 12th Five Year Plan period (2011–2015), the Chinese government set tougher targets to improve energy efficiency and carbon efficiency as well as reduce air pollutant emissions in manufacturing sectors. Under the new targets, the energy intensity and carbon intensity of the whole Chinese installed iron and steel industry will be reduced by 18 % in 2015, compared to 2010 levels. The SO_2 per unit of industrial added value will be reduced by 39 %. To achieve above targets, the National Development and Reform Commission (NDRC) and other departments announced a mandatory Top-10,000 Program, which aims to improve energy efficiency and reduce related emission through implementation of best available energy efficiency measures. Around \$15.79 billion[2] energy efficiency investment will be expected to accelerate the implementation of advanced energy efficiency measures and phase out inefficiency facilities. More details on the Top-10000 program and related information is available from http://iepd.iipnetwork.org/country/china.

Various authors have studied the iron and steel industry; they differ in theme (e.g., energy efficiency, GHGs and air pollutants emission), scope level (e.g., global, national and sector) and approach. Early research mainly focused on the impacts among institutional changes, productivity performance and technical efficiency before and after economic reform. Also, the characteristics of production, energy consumption and energy efficiency were evaluated on a process level in the Chinese iron and steel industry. All of them found that the impact of production growth has caused the rapid increase of energy consumption and related emissions. Other studies focused on the air pollutants emissions reduction potential at the industry level and demonstrated that the combination of end-of-pipe technologies (e.g. desulfurization technology) and other measures (e.g. structural adjustments and energy efficiency measures) is the best approach to control SO_2 emissions.

With the rapid growth of production and environmental issues, analyses of energy efficiency, GHGs and air pollutant emissions have been widely conducted on a global and national level, especially in China. However, the above issues were usually analysed separately. Other studies use the combination of energy efficiency measures and end-of-pipe options to find the best way to jointly tackle environmental issues. They found that end of pipe measures/policies might produce conflicting effects in the reduction of energy use and related CO_2 emission (i.e. the Sintering Flue Gas Desulfurization can reduce 1 kg SO_2, but 18.8 MJ additional thermal energy is consumed). However, only few typical technologies were considered to analyse the co-benefits of energy efficiency and emissions mitigation in these studies.

The objective of this paper is to assess the future potential and cost-effectiveness of energy efficiency improvement and emissions of greenhouse gases and air pollutants for the iron and steel industry of China. The aim of this paper is to analyse the co-benefits of best available energy efficiency measures, compared with end of pipe technology. Due to the lack of reliable data, this paper focuses mainly on the co-benefits of the reduction of air pollutants and GHG emissions but does not include other impacts (e.g., the human health, jobs, and welfare). In the section "Modelling methodology", the methodologies for the energy conservation supply curve (ECSC), the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model, and data sources are described. Next, the energy conservation supply curve (ECSC) allows examining the costs and benefits of the energy efficiency measures. The results of the ECSC are then introduced exogenously to the GAINS model to estimate the co-benefits of energy savings, and emissions reductions of GHGs and air pollutants. Results of energy saving potential and emissions mitigation of greenhouse gases and air pollutants for different scenarios are presented in the section "Result and discussion". We end with conclusions and recommendations.

Modelling methodology

As a first step, the energy conservation supply curve (ECSC) developed to analyse the cost-effectiveness of each best available energy efficiency measure. Next, the GAINS model is introduced to estimate the emissions of greenhouse gases and

2. The data was calculated based on future demand of energy efficiency investment in total industry and the trend at last five years.

air pollutants with and without end-of-pipe technologies under different scenarios. Then, the sources of data and best available energy efficiency measures are described. Finally, key assumptions of each scenario are constructed based on the ECSC. The results of the ECSC are then used as inputs into the GAINS model as exogenous parameters with the aim to evaluate the co-benefits between energy efficiency and emissions mitigation of GHGs and air pollutants.

INTRODUCTION OF COST CURVES OF ENERGY CONSERVATION AND EMISSION MITIGATION

Cost curves of energy conservation and emission mitigation, also called conservation supply curves and marginal abatement cost curves, play a key role in estimating the cost-effectiveness and technical potential of efficiency improvement and emission reductions. Because of its flexibility, the cost curves approach is either used independently or incorporated in energy models. McKinsey & company (2009) developed GHG abatement cost curves for different sectors in China using the cost curves approach. They found that energy efficiency improvement potentials remain important in the steel industry. The potential of GHG emission mitigation for Chinese steel industry is estimated to be 330 million tons in 2030. This cost curve shows the economic potential for energy efficiency improvement, but it ignores the future rate of implementation. The cost effective electricity and fuel saving potential for the Chinese iron and steel industry on economic and technical perspectives was analysed by Hasanbeigi (2013). The key assumption of this study is that the linear deployment rate was used to project the future potential application of each energy efficiency measure and it was assumed that the implementation rate of all measures will reach 70 % by 2030. The disadvantage of this approach is that the future energy price as an important uncertainty factor was neglected to evaluate the effects of changes for future energy saving and its associated benefits. None of these studies address impacts on air pollutant emissions.

In this study, the cost of energy conservation and associated with CO_2 reduction in the Chinese iron and steel industry are defined, which mainly include changes in fixed and variable cost. The cost of each energy efficiency measure is measured in 2005 dollars ($), the currency conversion factors derived from World Economic Outlook Database (2013). The cost of energy conservation and the associated CO_2 reductions costs are presented in Equations 1, 2, and 3 .

$$CCE = \frac{I \times AF + O\&M^{Fix} + O\&M^{Var} - ESP \times PE}{ESP} \quad (1)$$

$$CCR = \frac{I \times AF + O\&M^{Fix} + O\&M^{Var} - ESP \times PE \times EF}{ESP \times EF} \quad (2)$$

$$ESP = \Delta EI \times P \quad (3)$$

Where:

CCE	Cost of saved energy for an energy efficiency measure, in $/GJ
CCR	Cost of CO_2 emission reduction for an energy efficiency measure, in $/tonnes
I	Investment
AF	Annuity factor
$O\&M^{Fix}$	Annual change in operation and maintenance fixed cost
$O\&M^{Var}$	Annual change in operation and maintenance variable cost
ESP	Annual energy saving potential
ΔEI	Energy intensity reduction potential for energy efficiency measure
P	Production activity for each process
PE	Future energy price
EF	Emission factors

In this study, a discount of 10 % is assumed in the analysis, and the energy price is from GAINS database. The annuity factor can be calculated from Equation 4.

$$AF = \frac{d}{(1-(1+d)^{-n})} \quad (4)$$

Where:

d	Discount rate;
n	Lifetime of the energy efficiency measures

GREENHOUSE GAS AND AIR POLLUTION INTERACTIONS AND SYNERGIES MODEL

The integrated assessment model Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) provides a consistent framework for comparing the potentials of emission reduction and associated costs. It was developed by the International Institute for Applied Systems Analysis (IIASA). One advantage of the GAINS model is that it not only provides detailed data on technology options, but also quantifies the co-benefits of greenhouse gas and air pollutants emission reductions. It is has been widely used to investigate future emission potential and its costs on regional and national levels, including China, which might provide directions to tackle various environmental issues. Original studies using the GAINS model focused on assessing the potentials of emission mitigation of air pollutants and greenhouse gases and their synergy effects in China at the national and city level. GAINS city was developed to estimate the potentials of emission reduction of air pollutants and greenhouse gases, and co-benefits associated with policies in Beijing. They found that air pollutants control options might generate co-benefits by decreasing CO_2 emissions. However, the above studies hardly considered costs. In this study, the GAINS model will be used to analyse the emissions of greenhouse gases and air pollutants and related costs within and without end-of-pipe technologies for different scenarios, and to evaluate the co-benefits.

The emissions of air pollutants and greenhouse gases are calculated using the Equation 5, which is based on activity data, uncontrolled emission factors in absence of any emission control measure, the removal efficiency caused by which emission control measure are applied. More details have been described by Amann et al.

$$E_p = \sum_k \sum_m A_k ef_{k,m,p} x_{k,m,p} \quad (5)$$

Where:

k, m, p	activity type, abatement measure, pollutant, respectively
E_p	Emissions of pollutant p (for e.g. SO_2, $PM_{2.5}$, CO_2, PM_{10}, PM_{TSP}, etc.)
A_k	Energy consumption of each fuel (e.g., coal consumption) in iron and steel industry
$ef_{k,m,p}$	Emission factor of pollutant p for activity k after application of control measure m
$x_{k,m,p}$	Share of total activity of type k to which a control measure m for pollutant p is applied.

The unit cost of end-of-pipe measures (cn) is calculated using the Equation 6, which relate to investment (I), annual change in operation and maintenance (includes fixed cost and variable cost), and one unit of activity (A).

$$cn = \left(\frac{I \times AF + OM^{Fix}}{A} + OM^{Var}\right) / (ef - ef_m) \qquad (6)$$

Where:

A	Activity
ef	Uncontrolled emission factor
ef_m	Controlled emission factor under end-of-pipe measures

SOURCE OF DATA COLLECTION AND BEST AVAILABLE ENERGY EFFICIENCY MEASURES

The main data source for energy use assumptions is the World Energy Outlook 2009 Baseline scenario of IEA. We note that the energy intensity of each process is lower than in the Chinese official statistics in 2005 (refer to discussion section). The energy intensity of each process of the iron and steel industry on a provincial level are also considered. The difference between IEA data and official statistics of energy intensity in 2005 are around 1.27 for coke, 0.6 for sinter and pellets, 11.1 for pig iron, and 1.15 for Basic oxygen steel. Assumptions of future product activity and value-added of each process in the IEA data are lower than in the Chinese industrialization processes and government expectations. Hence, the productivity activity level of each process and value added has been calibrated in our study (see below for a more detailed discussion).

Existing international studies of the iron and steel industry can provide guidance on the potential to decrease energy consumption through energy efficiency and how much this would cost in relation to the Baseline scenario. 56 commercially available energy efficiency technologies/measures (including international measures and Chinese advance technologies) are used in our study. These technologies are classified by main production process (e.g., coke making, iron making, steel making, sintering, casting, rolling and finishing, and general measures) in the Chinese iron and steel industry. We noticed that some energy efficiency technologies/measures are already implemented to a certain degree in the Chinese industry. Hence, the current implementation rate of energy efficiency measures in the Chinese iron and steel industry in 2010 was defined based on literature. The future potential implementation rates were estimated based on implementation rate and expert communication in the alternative scenarios.

The Chinese iron and steel industry is a major contributor to air pollutant (e.g. PM and SO_2) emissions. As we could not obtain sufficient information on Chinese end-of-pipe technology, the International end-of-pipe technology from GAINS was adopted in our analysis. The detailed information of international end-of-pipe measures and how to analyse emission reductions of air pollutants are given by Klimont et al (2002), in this report, five types of control options were classified for each process in the iron and steel industry, i.e. cyclones, wet scrubbers, and three stages of electrostatic precipitators, separately. These end-of-pipe technologies were used to estimate the future air pollutants emission reduction potential and related costs. We also try to find the best way to solve environmental issue based on energy efficiency measures and end-of-pipe options.

KEY ASSUMPTION FOR SCENARIOS

In our study, the time period covered is 2010–2030 with 2010 as the base year. Cost will be treated as 2005 USD. Four scenarios are constructed, i.e. the Baseline scenario (BL), the BL within air pollutant policy scenario (BLAP), the energy efficiency policy scenario (BAEEM), and energy efficiency policy within air pollutant policy scenario (BAEEM_AP) . Three cost-based implementation stages are assumed in the BAEEM scenario, they are named Best Available Energy Efficiency Measures stage 1 (BAEEM_S1), stage 2 (BAEEM_S2), and stage 3 (BAEEM_S3). The co-impacts of energy efficiency measures and end-of-pipe technology is achieved through a soft-linkage of ECSC with the GAINS, whereby the output of ECSC is exogenously passed to the GAINS model as an input, to project emissions of greenhouse gases and air pollutants with and without end-of-pipe controls. The integrated scenarios are constructed. They have been named BL combined with air pollutant controls (BLAP), stage 1 (BAEEM_AP_S1), stage 2 (BAEEM_AP_S2), and stage 3 (BAEEM_AP_S3).

The production of the Chinese iron and steel industry has increased very fast in the past three decades because of urbanization. Considering this factor, MIIT of China (2011) assumed that the demand of steel will continue to rise but at a lower growth rate (3.5 % per year) in the 12^{th} Five-Year Plan and reach saturation in 2020. In addition, many studies have shown that the growth rate of the demand for steel will decline drastically between 2020–2025, because the saturation of downstream demand occurs (e.g., building industry), which means that steel production and demand will remain steady. The experience from developed countries indicates that the per capita consumption of iron and steel will stabilise after saturated periods. Therefore, we project that future production of pig iron will increase to 718 million tonne and stabilise by 2020. The output will remain unchanged in the following ten years. The historic steel ratio coefficients were used to calculate each process product activity, which are from WenQiang. The future value added was projected based on the Energy Research Institute's (ERI) IPAC model and communication with experts (see Table 1).

The baseline scenario (BL) of Chinese iron and steel industry during 2005–2030 were constructed in GAINS based on the World Energy Outlook 2009 Baseline scenario of IEA. In this scenario, considering the scale effects, we assumed that the annual autonomous energy and steam efficiency improvement rates of each process (i.e. coke making, iron making, steel making, sintering, casting, rolling and finishing) are 0.2 %,

Table 1. Future product activity levels for each process and value added of Chinese iron and steel industry.

	1995	2000	2005	2010	2015	2020	2025	2030
Coke-[Mt]	135	119	255	392	534	555	491	417
Sinter and pellets-[Mt]	114	167	429	642	870	893	893	893
Pig iron-[Mt]	106	129	345	596	699	718	718	718
Steelmaking _ Basic oxygen furnace -[Mt]	66	104	309	542	601	617	617	617
Steelmaking _ Electric arc furnace-[Mt]	13	20	36	54	117	120	120	120
Casting, rolling and finishing -[Mt]	76	117	327	566	703	722	722	722
Value added-[10^9 $]	27	46	131	190	290	354	406	459

and 0.1 %, respectively. The steam autonomous efficiency for other process will be improved by 3 % per year on the basis of the base year. Note that the awareness and professional skills of staff are not include in BL scenario. The detailed fuel consumption, value-added, product activity in the base year was from the latest China Statistical Yearbook, China Energy Statistical Yearbook, and China Steel Yearbook. The results of the BL scenario were input to GAINS to set the baseline for the air pollutants control options (BLAP) scenario. The current and potential implementation rates of end-of-pipe controls are endogenous to the GAINS database. The emission factors are also from the GAINS. More detailed information is available from the GAINS online website (http://gains.iiasa.ac.at/models/index.html).

Before constructing energy efficiency policy scenarios, the ECSC was first developed to estimate the cost-effective energy efficiency measures. In this step, a future energy price of $3.22/GJ was used and assumed to remain unchanged over the study period. The ECSC was drawn in 5-year steps, starting from 2010 and ending 2030, different from Xu (2011) and Hasanbeigi (2013). The former only estimated the cost-effectiveness of energy efficiency measures for 1994 and 2004, and the latter only developed the Conservation Supply Curve (CSC) for the total study period between 2010 and 2030. The main reason is that different outputs of production and implementation rates will generate huge impacts on cumulative energy saving and CO_2 emission reduction.

After making the ECSC, we assumed that the Cost of Conserved Energy (CCE) of energy efficiency measures below $ zero/GJ as stage 1 (BAEEM_S1)[3], which represent economically feasible opportunities. This stage might be achieved through overcoming barriers to implementation of energy efficiency measures, such as strengthening awareness and improving professional skills of staff. The energy efficiency measures with a CCE of below $10/GJ are clarified as stage 2 (BAEEM_S2). In this stage, higher efficiency improvement will be achieved. We assume that all energy efficiency measures will achieve the projecting implementation rates in those periods (see Figure 2). For stage 3 (BAEEM_S3), we assume that all commercially available energy efficiency measures will be fully implemented.

3. CCE is not the investment costs but they are paid back within the life time.

To estimates cost-effectiveness of co-control options of energy efficiency measures and air pollutant control options, the results of BL and energy efficiency policy scenarios were input into GAINS and combined with end-of-pipe options to build the BLAP, BAEEM_AP_S1, BAEEM_AP_S2, and BAEEM_AP_S3 scenarios, respectively. In BLAP scenarios, the implementation rates from WEO-2009 baseline in GAINS, The future implementation rates of end-of-pipe controls for BAEEM_AP_S1, BAEEM_AP_S2 will be gradually higher than BLAP and all end-of-pipe controls will fully implemented in the BAEEM_AP_S3.

As shown in Figure 2, the cost-effective energy saving potential is around 1,303 PJ in 2015, 2,735 PJ in 2020, 3,778 PJ in 2025, and 4,965 PJ in 2030, respectively. The technical energy saving potential is around 1,873 PJ in 2015, 3,833 PJ in 2020, 5,347 PJ in 2025, and 6,893 PJ in 2030, respectively. It means that if costs are not considered, around additional 43 % energy savings can be achieved.

Result and discussion

FUTURE POTENTIAL OF ENERGY SAVING FOR CHINESE IRON AND STEEL INDUSTRY

Figure 3 indicates the results of future energy consumption for the Chinese iron and steel industry from 2005 to 2030 under different scenarios. In the baseline scenario (BL), energy use of Chinese iron and steel industry increases drastically to 2015, and then, the growth rates presents a slightly declining trend, especially from 2020 to 2030. The main reason is that the peak of production output will come because of market saturation determined by China's industrialization process. Another interesting is that the energy consumption ramps from 15,828 PJ in 2010 to 20,727 PJ in 2020, which is about higher 31 %, compared with 2010, however, the production output of pig iron just increases 20 % from 2010 to 2020 (see Table 1). The main reason is that the growth rate of value-added and other processes (i.e. steel making) is much higher than pig iron.

The energy efficiency measures play a key role to reduce future energy consumption of the Chinese iron and steel industry. Energy use increases rapidly until it peaks around 2015 under all energy efficiency policy scenarios. Compared to the peaks energy use in 2015, the energy use declines by 15 %, 19 %, and

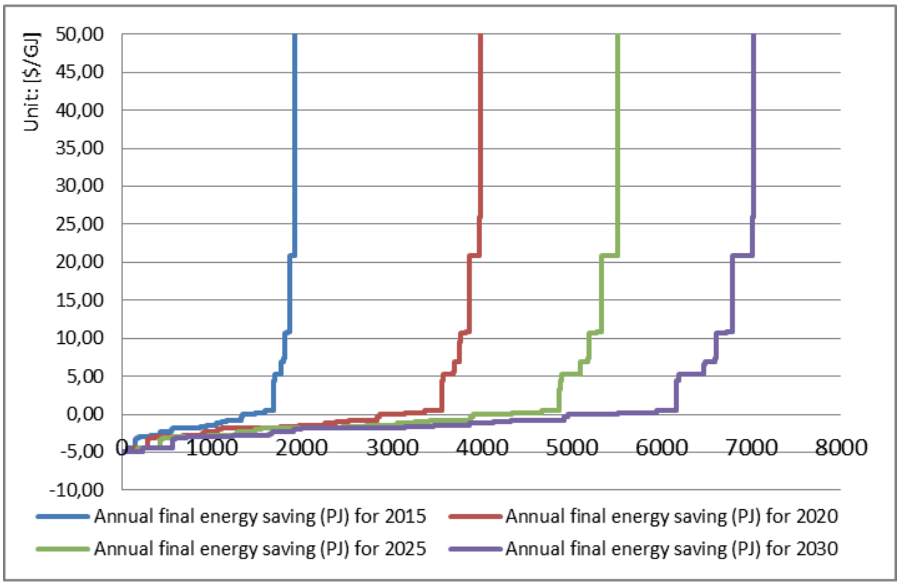

Figure 2. Cumulative energy saving potential (PJ) for the iron and steel industry in China 2010–2030.

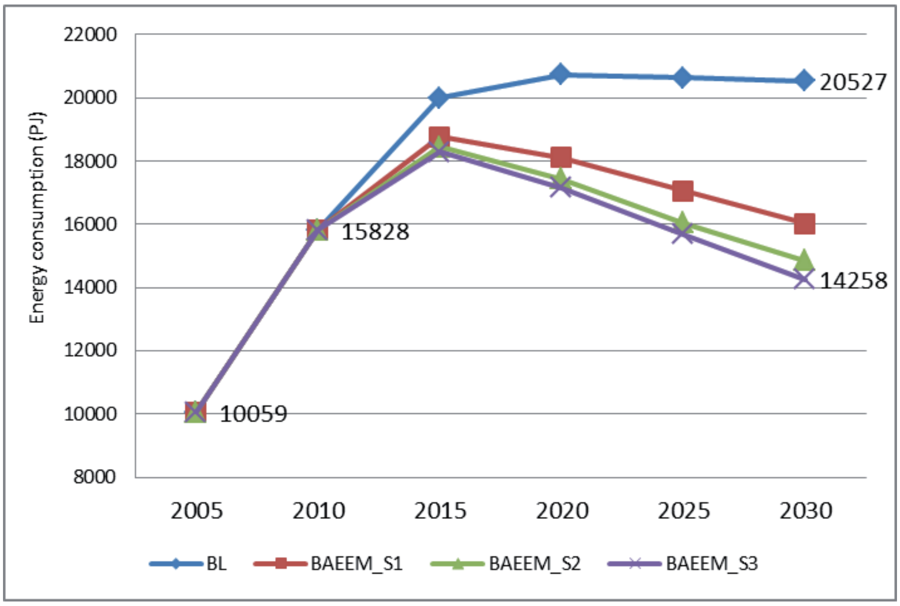

Figure 3. Future energy consumption of Chinese iron and steel under different scenarios.

22 % under BAEEM_S1, BAEEM_S2, and BAEEM_S3, respectively. In 2030, the total reduction of energy use is less 22 % in BAEEM_S1 and 34 % in BAEEM_S3, compared to the BL scenario energy use.

ALL GREENHOUSE GASES EMISSIONS MITIGATION OF CHINESE IRON AND STEEL

Figure 4 shows the level of greenhouse gases emission in Chinese iron and steel industry between 1995 and 2030, for the BL scenario and energy efficiency policy scenarios. For the BL scenario the emission level of greenhouse gases increases rapidly before 2015 and then remains stable to 2030, whereas for all stages of energy efficiency scenarios the emission level of greenhouse gases emission will decrease by 21 % under BAEEM_S1, 28 % under BAEEM_S2, 32 % under BAEEM_S3, compared with the BL scenario in 2030.

AIR POLLUTANTS EMISSIONS REDUCTION OF CHINESE IRON AND STEEL WITHIN AND WITHOUT AIR POLLUTANT CONTROL OPTIONS

The casting, rolling and finishing (CRF) processes are an important contributor to Particulate matter (PM) emission in the iron and steel industry. Table 2–Table 4 depicts the future PM emission level for $PM_{2.5}$, PM_{10}, and PM_{TSP}, respectively. In the following 10 years, the PM emissions increase quickly until it peaks by about 10.6 million to 10.9 million tonnes in 2020 then decrease thereafter. Because the product output of other processes and value added has higher growth rates than pig iron, the increase rate is double than pig iron output from 2010 to 2020. All Energy efficiency measures reduce $PM_{2.5}$ emission less than end-of-pipe controls by 2030 (see Table 2). The energy efficiency measures under scenario BAEEM_S1 can obtain higher emission reductions for PM_{10}, and PM_{TSP} than in the BLAP scenario (see Table 3 and Table 4).

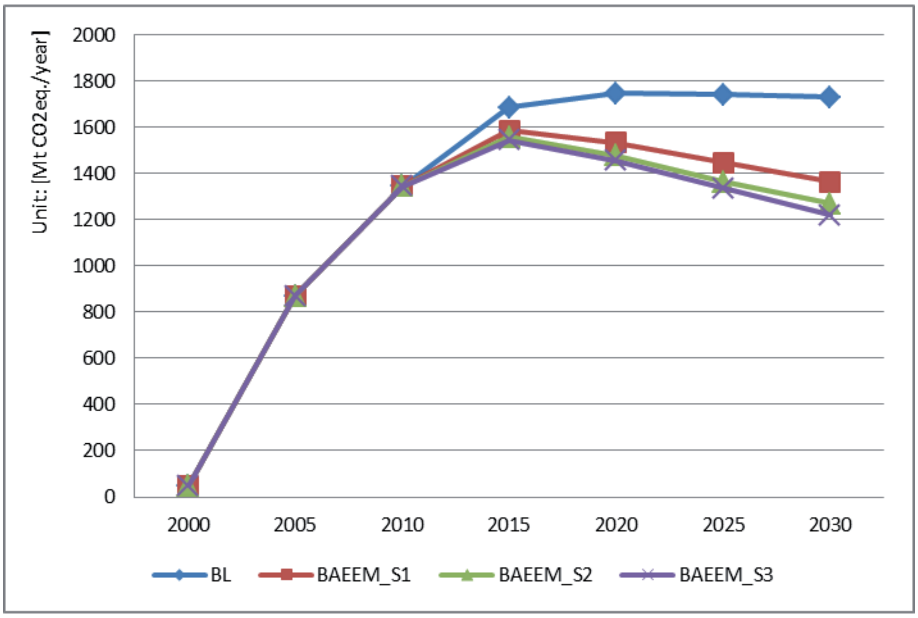

Figure 4. Future emission levels of greenhouse gases in Chinese iron and steel industry under different scenarios.

Table 2. $PM_{2.5}$ emissions of Chinese iron and steel industry under different scenarios. Unit: [kt PM].

Activity	2010	2015	2020	2025	2030
BL	4213	5343	5505	5348	5164
BLAP	4213	5306	5448	5279	5088
BAEEM_S1	4213	5328	5472	5304	5108
BAEEM_S2	4213	5324	5464	5291	5093
BAEEM_S3	4213	5322	5460	5287	5086
BAEEM_AP_S1	4213	4112	4192	4157	4121
BAEEM_AP_S2	4213	4100	4177	4141	4110
BAEEM_AP_S3	4213	4090	4169	4135	4104

Table 3. PM_{10} emissions of Chinese iron and steel industry under different scenarios. Unit: [kt PM].

Activity	2010	2015	2020	2025	2030
BL	5381	6792	6995	6836	6647
BLAP	5381	6750	6926	6750	6553
BAEEM_S1	5381	6764	6934	6753	6542
BAEEM_S2	5381	6756	6918	6729	6515
BAEEM_S3	5381	6752	6912	6720	6501
BAEEM_AP_S1	5381	5518	5618	5569	5519
BAEEM_AP_S2	5381	5500	5593	5541	5496
BAEEM_AP_S3	5381	5485	5581	5531	5485

Table 4. PM_{TSP} emissions of Chinese iron and steel industry under different scenarios. Unit: [kt PM].

Activity	2010	2015	2020	2025	2030
BL	8434	10559	10867	10698	10495
BLAP	8434	10509	10789	10603	10392
BAEEM_S1	8434	10505	10751	10539	10294
BAEEM_S2	8434	10490	10721	10494	10242
BAEEM_S3	8434	10483	10708	10478	10216
BAEEM_AP_S1	8434	9154	9325	9254	9180
BAEEM_AP_S2	8434	9128	9285	9205	9132
BAEEM_AP_S3	8434	9109	9266	9187	9108

Table 5. SO_2 Emissions of Chinese iron and steel industry under different scenarios. Unit: [kt SO_2].

Activity	2010	2015	2020	2025	2030
BL	5279	6798	7033	6975	6904
BLAP	5279	6733	6841	6673	6473
BAEEM_S1	5279	6499	6391	6097	5796
BAEEM_S2	5279	6418	6225	5847	5512
BAEEM_S3	5279	6379	6155	5760	5364
BAEEM_AP_S1	5279	6436	6217	5824	5421
BAEEM_AP_S2	5279	6294	6000	5540	5087
BAEEM_AP_S3	5279	6206	5884	5393	4950

SO_2 emissions from the Chinese iron and steel industry are mainly from sintering and blast furnaces, which account for 58 % and 30 %, respectively. Future potential mitigation of SO_2 emissions in the Chinese iron and steel industry are given in Table 5. Obviously, more cost-effectiveness SO_2 emission reduction can be obtained by implementing energy efficiency measures than end-of-pipe control options. If co-control measures of energy efficiency technologies and end-of-pipe options were adopted, SO2 emission will be further reduces in the future. The interesting result is that the emission levels of SO_2 in 2030 will be lower 2010 levels in BAEEM_AP_S2 scenario and BAEEM_AP_S3 scenario.

In summary, implementing energy efficiency measures not only improves energy efficiency but also reduce SO_2 emissions at a lower cost than end-of-pipe control options (see Figure 3 and Table 5). Conversely, lower co-reduction of energy use and emissions of PM and non-CO_2 is achieved, when comparing with the co-reduction of energy use and SO_2 emission.

FUTURE TRENDS OF INVESTMENT BETWEEN ENERGY EFFICIENCY MEASURES AND END OF PIPE OPTIONS

Figure 5 presents the future trends of energy efficiency investment for Chinese iron and steel industry up to 2030, which is calculated in five year increments based on the cost curves. Overall, the energy efficiency investment per year will increase until it peaks in 2020 and decrease slightly after 2020 under all scenarios. The annual energy efficiency investment in BAEEM_S3 is higher 4.5 times than BAEEM_S2 and 9 times in BAEEM_S1, respectively. According to our results of annual energy efficiency investment in 2010 (see Table 1), the BAEEM_S2 scenario seems easily to be realized in the future, if the government continues to expand the implementation of incentive policies, such as Top-10000 enterprises program, in the 12th Five-Year-Plan.

We have analysed the future investment of end-of-pipe control options to reduce air pollutants emission with GAINS. The results, provided in Figure 6, show that the annual investment of air pollutant control options increases drastically before 2020 and thereafter growing slowly by $19 billion in 2030 under the baseline and air pollutions control options (BLAP) scenario.

In summary, even if energy efficiency measures combined with end-of-pipe controls can obtain best effect to improve energy efficiency and reduce emissions of GHGs and air pollutant, energy efficiency measures are more cost-effective to reduce air pollutant emissions than end-of-pipe controls, especially for SO_2 emission reduction. We also find that some end-of-pipe technology not only cost more but also consume more energy.

Conclusions

In this paper we assessed co-options between energy efficiency measures and end-of-pipe technologies to improve energy efficiency and emissions reduction of GHGs and air pollutants in Chinese iron and steel industry up to the year 2030. Our

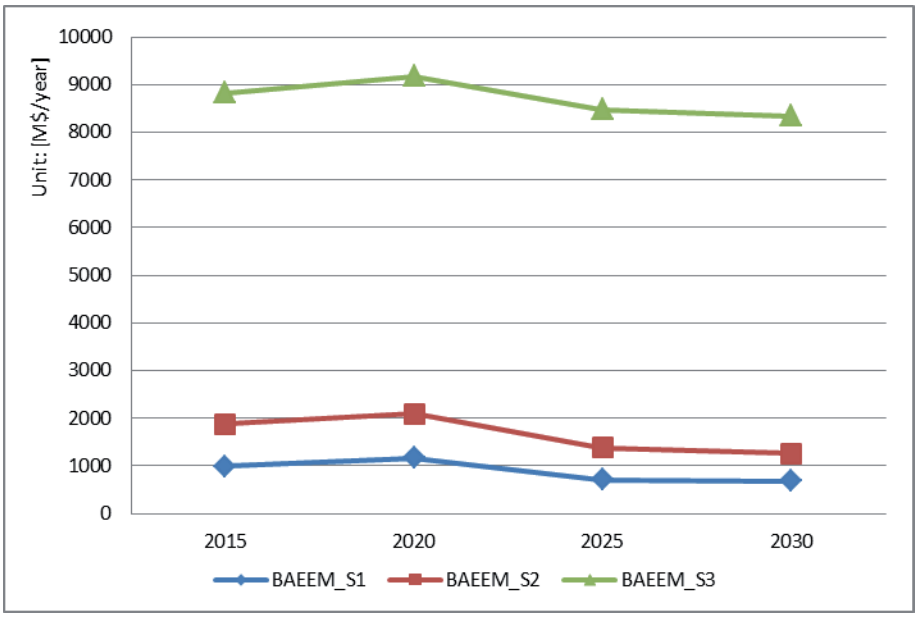

Figure 5. Future trends in energy efficiency investment for in Chinese iron and steel industry under different scenarios.

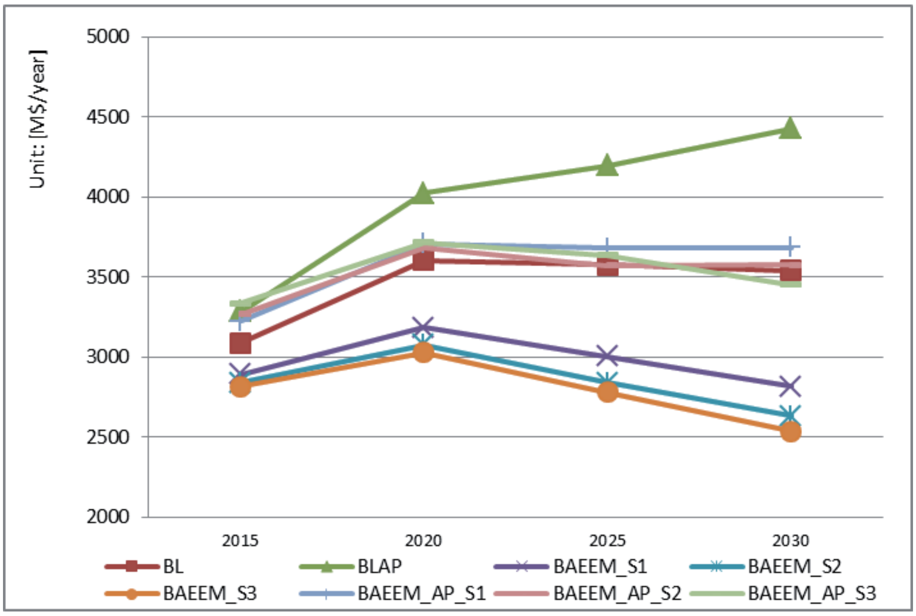

Figure 6. Future annual investments to control air pollutants emission with and without end-of-pipe technology.

analysis builds on earlier studies and provides a more refined analysis by adjusting future major drivers (e.g., production of each process, value-added), adding current implementation rates of each best available energy efficiency measure and making assumptions on their future implementation rate. The lifetime of energy efficiency measure is also updated. And then, co-control options between best available energy efficiency measures and end-of-pipe technologies are introduced through energy conservation supply curve (ECSC) and the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model to estimate the co-benefits between energy efficiency and emissions mitigation of GHGs and air pollutants and its investment.

Scenario analysis results reveal that there are large co-benefits associated with energy efficiency improvements, which include GHG and air pollutant reductions in the Chinese iron and steel industry. In BAAEM_AP_S1 scenario (the energy efficiency measures with a CCE of below $ zero/GJ and within lower implementation rate of end-of-pipe options), the energy saving potential of Chinese iron and steel industry for 2030 is around 5,668 PJ resulting in emissions mitigation of GHGs and air pollutants estimate to 463 Mt CO_2eq, 253 kt of PM, and 1,392 kt of SO_2. The related annual cost of energy efficiency measures and end-of-pipe options is around $1.2 Billion and $2.6 Billion, respectively. The annual cost of energy efficiency measures in BAAEM_S2 scenario (the energy efficiency measures with a CCE of below $10/GJ) are higher $581 million by 2030 than BAAEM_AP_S1, however, the co-effect from energy efficiency measures in BAAEM_S2 scenario can result in decreasing 21 % of GHGs, 3 % of PM, and 20 % of SO_2 by 2030. Improving energy efficiency will also result in reducing emissions of GHGs and can generate higher economic benefits. Therefore, energy efficiency measures in the air quality policy are important option for China.

Finally, the approach of our study used could be applied for other global and national energy industry to estimates the co-benefits between energy efficiency improvement and emissions mitigation of GHGs and air pollutants and its cost.

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