Highlights

- We compared potential technology combinations based on various policy preferences and targets in China’s iron and steel industry using multi-objective analysis.
- Mitigating $PM_{2.5}$ pollution have substantial co-benefits for CO_2 emissions reductions.
- CO_2 emissions reductions correspond to larger financial costs compared to $PM_{2.5}$ pollution reductions.
- It is crucial for China to focus on reducing PM pollution in the short term and prepare for the expected challenges associated with CO_2 reductions in the future.

Word amount: 4873

Multi-objective analysis of the co-mitigation of CO_2 and $PM_{2.5}$ pollution by China's iron and steel industry

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Abstract: China has experienced serious fine particulate matter ($PM_{2.5}$) pollution in recent years, and carbon dioxide (CO_2) emissions must be controlled so that China can keep its pledge to reduce CO_2 emissions by 2030. The iron and steel industry is energy intensive and contributes significantly to $PM_{2.5}$ pollution in China. The simultaneous reduction of CO_2 emissions and $PM_{2.5}$ pollution while minimizing the total mitigation costs remains a crucial issue that must be resolved. Using a multi-objective analysis, we compared potential technology combinations based on various policy preferences and targets. Our results showed that policies designed to mitigate $PM_{2.5}$ pollution have substantial co-benefits for CO_2 emissions reductions. However, policies focused solely on reducing CO_2 emissions fail to effectively reduce $PM_{2.5}$. Furthermore, CO_2 emissions reductions correspond to large financial costs, whereas $PM_{2.5}$ pollution reductions are less expensive. Our results suggest that under limited budgets, decision makers should prioritize $PM_{2.5}$ reductions because CO_2 reductions may be simultaneously achieved. Achieving large decreases in CO_2 emissions will require further technological innovations to reduce the cost threshold. Thus, China should focus on reducing PM pollution in the short term and prepare for the expected challenges associated with CO_2 reductions in the future.

Keywords: multi-objective, iron and steel, $PM_{2.5}$, CO_2 emission reduction, emission control, abatement cost

1. Introduction

Carbon dioxide (CO_2) is a major greenhouse gas (GHG) that has caused rapid increases in temperatures worldwide (Intergovernmental Panel on Climate Change, 2013). As a result of temperature increase, climate change is threatening the existence of human beings (Knutti et al., 2015). To deal with the climate change caused by CO_2 and other GHGs, the Paris Agreement was adopted at the 2015 United Nations Climate Change Conference. The dominant goal of the Paris Agreement is to hold "the increase in the global average temperature to well below 2 °C above preindustrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels" (Rogelj et al., 2016). As the largest emitter of CO_2, accounting for 24% of the global emissions in 2012 (Zhou et al., 2012), China pledged that by 2030, it would decrease its CO_2 emissions per unit gross domestic product (GDP) by 65% compared with the 2005 level (The State Council, 2015). Along with the considerable GHG emissions, hazes have become a severe environmental problem in China. During a haze event, fine particulate matter ($PM_{2.5}$), which is composed of primary $PM_{2.5}$ (Li, Y. et al., 2016) and secondary $PM_{2.5}$ converted from SO_2 and NO_x (Sun et al., 2006), is the major pollutant (Meng et al., 2016). To improve air quality, China's government has taken actions to reduce the precursors of primary and secondary $PM_{2.5}$ emissions (e.g., National Action Plan on Prevention and Control Air Pollution) (The State Council, 2013). However, there exist some challenges to achieve these two goals. The major challenge lies in that the government needs to maintain the development of economy while simultaneously reduce CO_2 emissions and $PM_{2.5}$ pollution. Infrastructure construction has been the major driver of China's rapid growth of economy and emissions, and the economy relies heavily on carbon-intensive industries (e.g., iron and steel, cement and electricity, (Liu et al., 2012). Reducing CO_2 emissions requires high initial capital cost for the adoption of low carbon technology and removing air pollutants calls for extra operation cost (Hou et al., 2011), which may have negative effects on the economy in less developed regions in the short run (Dong and Liang, 2014; Liu et al., 2015; Meng et al., 2017). Thus, it is a challenge to balance the CO_2 and $PM_{2.5}$ reduction while keeping the economic growth.

The iron and steel industry is a major source of CO_2 emissions and $PM_{2.5}$ pollution in China. This industry is energy intensive and consumed 14% of the total energy used in China in 2012 (i.e., 8% of coal, 86% of coke and 10% of electricity) (National Bureau of Statistics of China, 2013). This industry is estimated to account for 10-20% of the CO_2 emissions (Guo and Fu, 2010; Yuan et al., 2012; Zeng et al., 2009) and 5% of the primary $PM_{2.5}$ emissions in China (Lei et al., 2010; Meng et al., 2015). Additionally, the iron and steel industry emitted 10% of China's SO_2 emissions, which are an important precursor of secondary $PM_{2.5}$ (National Bureau of Statistics of China; Ministry of Envrionmental Protection, 2011). Therefore, reducing CO_2 emissions and $PM_{2.5}$ pollution from the iron and steel industry is necessary to mitigate climate change over the long term or resolve the haze problem over the short term (Xu et al., 2014). The Plan for Adjustment and Upgrading of Iron and Steel Industry (Ministry of Industry and Information Technology, 2016) has proposed considerable low carbon technologies, improving the efficiency of energy use and thus reducing the emissions of CO_2 and air pollutants (Dong et al., 2013; Zhang et al., 2013). For example, coke dry quenching helps reduce fossil fuel and electricity consumption, thereby reducing CO_2 emissions and the air pollutants (Ministry of Industry and Information Technology, 2012). Removal devices are also planned to be widely applied to remove air pollutants according to China's 12th Five Year Plan (The State Council, 2011). In addition, carbon capture and storage is a promising technology that can capture and store CO_2 emitted from the blast furnaces (Psarras et al., 2017). Nevertheless, cost factors limit China's capacity to simultaneously reduce CO_2 and $PM_{2.5}$ pollution, and the adoption of technologies to reduce CO_2 and $PM_{2.5}$ is dependent on the cost of the technology. Because of the limitations of budgets, decision makers must minimize costs while focusing on simultaneously reducing $PM_{2.5}$ and CO_2 emissions.

Previous research on China's iron and steel industry has focused on the cost effectiveness of CO_2 reductions and energy conservation. The demand for steel has been used as an indicator to estimate the quantity of CO_2 (Chen et al., 1990; Gao, 2010; Yin and Chen, 2013). The energy efficiency of China's iron and steel industry is far behind the more advanced levels worldwide; therefore, cost-effective technologies have been identified to improve this energy efficiency (Hasanbeigi et al., 2011; He et al., 2013; Lin and Wang, 2015; Ma et al., 2002; 2014; Zhang et al., 2012; Zhang et al., 2007). Additionally, researchers have used different energy models to predict the CO_2 emissions from the iron and steel industry (Chen et al., 2014; Li, L. et al., 2016; Wang et al., 2007; Wen et al., 2014; Xu and Lin, 2016). Research on the co-control of air pollutants and CO_2 indicates that co-control measures are more cost-effective than single reduction measures (Liu et al., 2014; 2016; Mao et al., 2013; 2014). The co-benefit of reducing CO_2 and air pollutants has been studied by Dong (2015) and Kanada (2013).

However, previous research has rarely focused on simultaneously reducing CO_2 and $PM_{2.5}$ pollution while also controlling the cost to China's iron and steel industry. Moreover, environmental assessments of the iron and steel industry are frequently performed by comparing a limited set of predefined scenarios, which introduces added uncertainty to the assessments. This work aims to identify robust optimal strategies for China's iron and steel industry under different policy targets and preferences of decision makers. We combined the detailed technologies and policy preferences and targets with mathematical multi-objective optimization techniques to identify the optimal strategy for simultaneously minimizing CO_2 emissions, $PM_{2.5}$ pollution and abatement costs.

2. Methods and materials

2.1 Available technology options

The technology combinations available to the iron and steel industry included two parts: technology paths and removal technologies. Technology paths refer to the technologies used to produce steel products, whereas removal technologies refer to end-of-pipe pollutant removal technologies. Figure 1 shows the technology paths and removal technologies that are currently available for the iron and steel industry. Technology paths include the blast furnace and basic oxygen furnace technology path (BF-BOF), the electric arc furnace technology path (EAF), the direct reduced iron technology path (DRI) and the carbon capture & storage technology path (CCS). We ruled out the smelt reduced iron technology path because of its high CO_2 emissions and air pollutant emissions (Hu and Jiang, 2001). The BF-BOF is the most widely used technology path in China, and this traditional path includes the coking, sintering, iron-making, steel-making, casting and rolling processes. The alternative technology path for the BF-BOF is the EAF in which scrap instead of iron ore is used to produce crude iron in an electricity arc furnace. Another promising new technology path is the DRI path. Most DRI technologies use natural gas to reduce pellets or sinters, and they then produce direct reduced iron as an alternative to scrap. The *Midrex* technology is currently a widely applied technology in DRI production. The CCS technology path combines carbon capture and storage technology with a blast furnace. The removal processes include $PM_{2.5}$ and SO_2 removal devices. Removing SO_2 is important for reducing $PM_{2.5}$ because it represents an important precursor of $PM_{2.5}$. A high-efficiency particulate matter removal device, such as a fabric filter, should remove primary $PM_{2.5}$. A number of SO_2 removal methods are available, and desulfurization is a general term used to refer to these removal processes (Xing and Lu, 2013; Yanling, 2013). We have classified the technologies used in our analysis in Table 1.

Insert Figure 1

Table 1. A summary of technology options used in this study

Category	Technology	Reference
Traditional process	Coke oven	Hu and Jiang (2001)
	Sintering furnace	Hu and Jiang (2001)
	Blast furnace	Hu and Jiang (2001)
	Electric arc furnace	Hu and Jiang (2001)
	Basic oxygen furnace	Hu and Jiang (2001)
	Casting	Hu and Jiang (2001)
	Hot rolling	Hu and Jiang (2001)
	Cold rolling	Hu and Jiang (2001)
Efficiency improvement	Coke dry quenching	Hu and Jiang (2001)
	Top-pressure recovery turbine	Hu and Jiang (2001)
	Recovery of BOF gas	Hu and Jiang (2001)
	Continuous casting	Hu and Jiang (2001)
System optimization	Direct reduced iron	Baig (2016)
Carbon capture	Carbon capture & storage	Kuramochi et al. (2012)
Pollutant removal	Fabric filter	Ma et al. (2016)
	Desulfurization	Ma et al. (2016)

2.2 Model description

2.2.1 Emission factors and costs for different technology paths

CO_2 emissions are calculated based on energy consumption, and primary $PM_{2.5}$ and SO_2 emissions are calculated based on production processes. The emission factors and the costs of each technology path are calculated as follows:

$$\mathrm{EFC_i} = \sum\nolimits_j \mathrm{CO_2EF_j} \times \mathrm{fuel_{ij}} \tag{1}$$

$$\mathrm{EFP_i} = \sum\nolimits_j \mathrm{PMEF_{ij}} \tag{2}$$

$$\mathrm{EFS_i} = \sum\nolimits_j \mathrm{SO_2EF_{ij}} \tag{3}$$

$$\mathrm{cost_i} = \mathrm{annualized\ cost_i} + \sum\nolimits_j \mathrm{P_j} \times \mathrm{fuel_{ij}} \tag{4}$$

$$\mathrm{anuualized\ cost_i} = \mathrm{capital\ cost_i} \times \frac{\mathrm{d}}{(1-(1+\mathrm{d})^{-\mathrm{n}})} \tag{5}$$

where $\mathrm{EFC_i}$ represents the CO_2 emissions when technology path i produces one ton of finished steel product; $\mathrm{EFP_i}$ represents the primary $PM_{2.5}$ emissions when technology path i produces one ton of finished steel product; $\mathrm{EFS_i}$ represents the SO_2 emissions when technology path i produces one ton of finished steel product; $\mathrm{CO_2EF_j}$ represents the CO_2 emission factor of fuel j in technology path i; $\mathrm{PMEF_{ij}}$ represents the $PM_{2.5}$ emission factor of process j in technology path i; $\mathrm{fuel_{ij}}$ represents the amount of fuel j consumed during the production of one ton of finished steel product using technology path i; $\mathrm{cost_i}$ represents the cost of producing one ton of finished steel product using technology path i; $\mathrm{annualized\ cost_i}$ represents the annual capital investment for producing one ton of finished steel product using technology path i; $\mathrm{P_j}$ represents the price of fuel j; and $\mathrm{capital\ cost_i}$ represents the total capital cost for n years of producing one ton of finished steel product using technology path i. The interest rate d in this paper is set to 10% (Zhang et al., 2014). The variable n is the lifetime of the different technologies. The emission factors and costs of each technology path are shown in Table 2.

Table 2. Emission factors and costs of the technology paths (per ton of finished steel product) and removal technologies (per ton of SO_2 and $PM_{2.5}$)

	CO_2 (including electricity) t/t	**Primary $PM_{2.5}$ kg/t**	**Cost yuan/t**	**SO_2 kg/t**	**Indirect SO_2 from electricity kg/t**	**Indirect primary $PM_{2.5}$ from electricity kg/t**
BF-BOF	2.38	18.18	1954	8.23	0.78	0.05
EAF	0.49	7.09	2043	0.35	0.44	0.03
DRI	1.20	10.25	2575	8.07	0.68	0.05
CCS	0.78	18.18	3129	8.23	1.38	0.09
Desulfurization	1.78		5280			
Fabric filter	14.54		9860			

2.2.2 Multi-objective analysis of CO_2 and $PM_{2.5}$ emissions reductions and cost control in the iron and steel industry

Decision makers have different policy preferences for CO_2 reductions, $PM_{2.5}$ reductions and cost control. Furthermore, decision makers set threshold targets for CO_2 emissions and $PM_{2.5}$ pollution. Moreover, decision makers may be confronted with a limited budget for reducing CO_2 emissions and $PM_{2.5}$ pollution. Therefore, to determine the optimal technology combinations under different conditions, a multi-objective optimization method was designed.

The share of the four technology paths were subject to the following constraints (6):

$$\begin{cases} \sum_{i=1}^{m} r_i = 1 \\ 0 \le r_{1,3,4} \le 1 \\ 0 \le r_2 \le 0.3 \\ 0 \le r_{SO_2} \le 1 \\ 0 \le r_{PM_{2.5}} \le 1 \end{cases} \tag{6}$$

where r_1 represents the share in all the four paths accounted for by the technology path BF-BOF, r_2 represents the EAF share; r_3 represents the DRI share; r_4 represents the CCS share; r_{SO_2} represents the share of desulfurization technology; and $r_{PM_{2.5}}$ represents the share of the $PM_{2.5}$ removal device fabric filter. The maximum value of r_2 is 0.3(Ma et al., 2016).

The SO_2 intensity (SO_2 emissions per ton of finished steel products) is composed of the SO_2 emitted via electricity generation and the SO_2 that is not removed by desulfurization devices.

$$SO_2 = \sum_{i=1}^{4} EFSE_i \cdot r_i + \sum_{i=1}^{4} EFS_i \cdot r_i \cdot r_{SO_2} \cdot (1 - \eta_{SO_2}) + \sum_{i=1}^{4} EFS_i \cdot r_i \cdot (1 - r_{SO_2}) \tag{7}$$

where SO_2 represents the SO_2 intensity, η_{SO_2} represents the removal efficiency of the desulfurization technology, and $EFSE_i$ represents the emission factor of SO_2 emitted from the electricity required to produce one ton of finished steel product using technology path i. In this study , η_{SO_2} is set to 0.95 (Mao et al., 2013).

The $PM_{2.5}$ intensity ($PM_{2.5}$ pollution per ton of finished steel products) is composed of the primary $PM_{2.5}$ emissions from electricity generation, primary $PM_{2.5}$ emissions not removed by a fabric filter and secondary $PM_{2.5}$ converted from SO_2 emissions.

$$PM_{2.5} = \sum_{i=1}^{4} EFPE_i \cdot r_i + \sum_{i=1}^{4} EFP_i \cdot r_i \cdot r_{PM_{2.5}} \cdot (1 - \eta_{PM_{2.5}}) + \sum_{i=1}^{4} EFP_i \cdot r_i \cdot (1 - r_{PM_{2.5}}) + CF \cdot SO_2 \tag{8}$$

where $\mathrm{PM}_{2.5}$ represents the $PM_{2.5}$ intensity, $\eta_{\mathrm{PM}_{2.5}}$ represents the removal efficiency of the fabric filter, EFPE_i represents the emission factor for $PM_{2.5}$ emitted by the electricity required to produce one ton of finished steel product using technology path i, and CF represents the ratio of SO_2 converting to $PM_{2.5}$. In our study, $\eta_{\mathrm{PM2.5}}$ is set to 0.997(Huang et al., 2014) and CF is set to 0.22(Wen, 2015).

The CO_2 intensity (CO_2 emissions per ton of finished steel products) is composed of the CO_2 emitted from electricity generation, the production process and desulfurization device and fabric filter use.

$$\mathrm{CO_2} = \sum \mathrm{EFCE_i} \cdot \mathrm{r_i} + \sum \mathrm{EFTC_i} \cdot \mathrm{r_i} + \mathrm{EFC_{SO_2}} \cdot \sum \mathrm{EFS_i} \cdot \mathrm{r_i} \cdot \mathrm{r_{SO_2}} \cdot \eta_{\mathrm{SO_2}} + \mathrm{EFC_{PM_{2.5}}} \cdot \sum \mathrm{EFP_i} \cdot \mathrm{r_i} \cdot \mathrm{r_{PM_{2.5}}} \cdot \eta_{\mathrm{PM_{2.5}}} \tag{9}$$

where $\mathrm{CO_2}$ represents the CO_2 intensity, $\mathrm{EFCE_i}$ represents the emission factor for CO_2 emitted by the electricity required to produce one ton of finished steel product using technology path i, $\mathrm{EFS_{SO_2}}$ represents the CO_2 emissions from removing 1 kg of SO_2 using a desulfurization device, and $\mathrm{EFP_{PM_{2.5}}}$ represents the CO_2 emissions from removing 1 kg of $PM_{2.5}$ by a fabric filter.

The cost (cost per ton of finished steel products) is composed of the production costs, SO_2 abatement costs, $PM_{2.5}$ abatement costs and carbon tax.

$$\mathrm{cost} = \sum_{i=1}^{4} \mathrm{cost_i} \cdot \mathrm{r_i} + \mathrm{cost_{SO_2}} \cdot \sum_{i=1}^{4} \mathrm{EFS_i} \cdot \mathrm{r_i} \cdot \mathrm{r_{SO_2}} \cdot \eta_{\mathrm{SO_2}} + \mathrm{cost_{PM_{2.5}}} \cdot \sum_{i=1}^{4} \mathrm{EFP_i} \cdot \mathrm{r_i} \cdot \mathrm{r_{PM_{2.5}}} \cdot \eta_{\mathrm{PM_{2.5}}} + \mathrm{t} \cdot \mathrm{CO_2} \tag{10}$$

where cost represents the cost of producing one ton of finished steel product, $\mathrm{cost_{SO_2}}$ denotes the cost of removing 1 kg of SO_2, $\mathrm{cost_{PM_{2.5}}}$ represents the cost of removing 1 kg of $PM_{2.5}$, and t represents the tax rate on one ton of CO_2 emissions. The carbon tax is set to 0 in our study.

The CO_2 and $PM_{2.5}$ intensities and costs are the three parameters to be simultaneously minimized in our multi-objective model. Relative weight factors are used to represent the policy preferences of the decision makers for these three objectives. The use of the relative weight factors in the objective function is presented as follows:

$$\min \mathrm{w_1} \cdot \frac{\mathrm{CO_2} - \mathrm{CO_{2min}}}{\mathrm{CO_{2max}} - \mathrm{CO_{2min}}} + \mathrm{w_2} \cdot \frac{\mathrm{PM_{2.5}} - \mathrm{PM_{2.5min}}}{\mathrm{PM_{2.5max}} - \mathrm{PM_{2.5min}}} + \mathrm{w_3} \cdot \frac{\mathrm{cost} - \mathrm{cost_{min}}}{\mathrm{cost_{max}} - \mathrm{cost_{min}}} \tag{11}$$

$$\begin{cases} \sum_{i=1}^{3} \mathrm{w_i} = 1 \\ \mathrm{w_i} = \frac{\mathrm{n}}{100}, \mathrm{n} = 0,1,2,\cdots,100 \end{cases} \tag{12}$$

where $\mathrm{w_i}$ represents the relative weight factor of an objective; $\mathrm{CO_{2max}}$, $\mathrm{PM_{2.5max}}$ and $\mathrm{cost_{max}}$ represent the largest values for each parameter calculated in the model; and $\mathrm{CO_{2min}}$, $\mathrm{PM_{2.5min}}$, and $\mathrm{cost_{min}}$ represent the smallest values for each parameter calculated in the model. The CO_2 intensity, $PM_{2.5}$ intensity and costs are normalized to eliminate unit-related errors. The value of each relative weight factor is not predefined; rather, these values are assumed to take any possible value between 0 and 1. This weighting method represents all possible combinations of the decision makers' policy preferences.

Decision makers can set threshold targets for CO_2 and $PM_{2.5}$ intensities. These emissions or pollution targets represent the largest allowable emissions or pollution. The cost budget is also likely to be limited to a certain amount. Based on the largest allowable CO_2 emissions, $PM_{2.5}$ pollution or cost budget, the objective function is calculated as follows:

$$\begin{cases} \mathrm{G_1} = \mathrm{CO_2} \\ \mathrm{G_2} = \mathrm{PM_{2.5}} \\ \mathrm{G_3} = \mathrm{cost} \end{cases} \tag{13}$$

$$\mathrm{G_i} \leq \mathrm{Target_i}, \mathrm{i} \in \text{Objectives lower than the target value} \tag{14}$$

$$\min \sum_{\mathrm{j}} \mathrm{w_j} \times \frac{\mathrm{G_j} - \mathrm{G_{jmin}}}{\mathrm{G_{jmax}} - \mathrm{G_{jmin}}}, \mathrm{j} \in \text{ remaining objectives excluding I} \tag{15}$$

$$\begin{cases} \sum_j w_j = 1 \\ w_j = \frac{n}{100}, n = 0,1,2,\cdots,100 \end{cases} \quad (16)$$

where G_i represents the value of objective i and target_i represents the largest allowable value of objective i.

2.3 Data

The energy consumption and lifetime data and the cost of each specific technology in the four paths were obtained from Hu and Jiang (2001) and Baig (2016). Data for the CCS technology path were obtained from the literature (Kuramochi et al., 2012; Ma et al., 2016; Mao et al., 2013). Data for the fabric filter and desulfurization techniques were obtained from Mao et al. (2013). CO_2 emission factors for the energy input were obtained from the Intergovernmental Panel on Climate Change (2006). The emission factors for electricity input were obtained from National Development and Reform Commission (2015) and Mo et al. (2013). The emission factors of $PM_{2.5}$ from production processes were obtained from Lei et al. (2010) and Huang et al. (2014). Emission factors of SO_2 from production processes were obtained from Zhao (2016) and the Handbook of National Pollution Sources (Ministry of Environmental Protection, 2011). The data for energy price were obtained from China's Economic Database from the CEIC (https://www.ceicdata.com/zh-hans/products/china-economic-database).

3. Results and discussion

3.1 Reduction performance based on different policy preferences for CO_2 reductions, $PM_{2.5}$ reductions and cost control

Insert Figure 2

Table 3. Emission factors (per ton of steel product), unit costs (per ton of steel product) and share of the technologies in different technology combinations.

	$PM_{2.5}$ kg/t	CO_2 t/t	Cost yuan/t	BF-BOF	EAF	DRI	CCS	Fabric filter	Desulfurization
1	19.09	2.38	1954	100%	0	0	0	0	0
2	15.55	1.81	1981	70%	30%	0	0	0	0
3	0.80	2.02	2127	70%	30%	0	0	100%	0
4	0.32	2.02	2138	70%	30%	0	0	100%	100%
5	9.98	0.99	2415	0	30%	70%	0	0	0
6	0.74	1.12	2507	0	30%	70%	0	100%	0
7	0.27	1.12	2518	0	30%	70%	0	100%	100%
8	15.67	0.69	2803	0	30%	0	70%	0	0
9	15.19	0.70	2815	0	30%	0	70%	0	100%
10	0.44	0.90	2961	0	30%	0	70%	100%	0

1.BF-BOF; 2.BF-BOF+EAF; 3.BF-BOF+EAF+fabric filter; 4.BF-BOF+EAF+fabric filter+desulfurization;

5. EAF+DRI; 6.EAF+DRI+fabric filter; 7. EAF+DRI+fabric filter+desulfurization;

8.EAF+CCS; 9. EAF+CCS+desulfurization; 10. EAF+CCS+fabric filter+desulfurization

We used relative weight factors to represent the decision maker's policy preferences for CO_2

reductions, $PM_{2.5}$ reductions and cost control. Figure 2 shows the corresponding relationships between the relative weight factors and technology combinations. Table 3 shows the CO_2 intensity, $PM_{2.5}$ intensity and cost of the different technology combinations, and it indicates that the largest and smallest CO_2 intensity, $PM_{2.5}$ intensity and cost are 2.38 kg/t, 19.09 kg/t and 2961 yuan/t and 0.69 kg/t, 0.27 kg/t and 1954 yuan/t, respectively.

The results show that a policy preference for $PM_{2.5}$ reductions alone provides much more co-benefits compared with a policy preference for CO_2 reductions or cost control alone. Our findings indicate that when the $PM_{2.5}$ reduction weight approaches 1 and the CO_2 reduction weight approaches 0, the $PM_{2.5}$ intensity decreases to 0.27 kg/t, the CO_2 intensity (1.12 t/t) is 53% lower than the largest CO_2 intensity, and the costs increase to 2518 kg/t. This reduction performance is the same when the weights of CO_2 reduction, $PM_{2.5}$ reduction and cost control are equal. These results reveal that when the weight of $PM_{2.5}$ reduction is high, CO_2 emissions are also reduced as a co-benefit because the technology paths are altered and removal devices are introduced.

However, when the CO_2 reduction weight approaches 1, the CO_2 intensity is reduced to 0.69 t/t while the $PM_{2.5}$ intensity (15.67 kg/t) is only 18% lower than the largest $PM_{2.5}$ intensity. Additionally, a higher preference for CO_2 reduction induces higher costs. For example, when the weights of CO_2 and $PM_{2.5}$ reduction are both 0.5, the cost is 2961 yuan/t, the $PM_{2.5}$ intensity is 0.44 kg/t and the CO_2 intensity is 0.90 t/t. In contrast, when the weight of $PM_{2.5}$ approaches 1 and the weight of CO_2 reduction approaches 0, the cost decreases to 2518 yuan/t.

Reducing CO_2 and $PM_{2.5}$ emissions simultaneously sacrifices the weight of the cost. When the weight of the cost approaches 1, the CO_2 intensity is 2.38 t/t, and the $PM_{2.5}$ intensity is 19.09 kg/t. Furthermore, when the weight of the cost is higher than approximately 0.5, CO_2 and $PM_{2.5}$ cannot be simultaneously reduced. For example, when the weights of CO_2 reductions and costs are both 0.5, the CO_2 intensity is 43% higher than the smallest intensity, whereas the $PM_{2.5}$ intensity is 35 times higher than the smallest intensity. In contrast, when the weights of $PM_{2.5}$ reductions and costs are both 0.5, the $PM_{2.5}$ intensity decreases to 0.32 kg/t, whereas the CO_2 intensity (2.02 t/t) is only 11% lower than the largest intensity.

3.2 Cost of different CO_2 and $PM_{2.5}$ intensity targets

Insert Figure 3

The emission and pollution targets represent the largest allowable emissions of CO_2 and $PM_{2.5}$, respectively. In the multi-objective model, we use the emission intensity and pollution emission targets to represent the CO_2 and $PM_{2.5}$ targets, respectively. Figure 3 presents the relationships between the costs and the two targets. The blue and red colors represent lower and higher costs, respectively. Setting low CO_2 and $PM_{2.5}$ intensity targets resulted in sharp increases in cost. For example, if the decision makers set the CO_2 and $PM_{2.5}$ intensities to 1 t/t and 1 kg/t, respectively, then the cost would increase to over 2700 yuan/t. This cost is almost 40% higher than the lowest cost estimated by the model. Setting lower $PM_{2.5}$ intensity targets is more cost effective than setting lower CO_2 emission targets. For example, when the $PM_{2.5}$ intensity target decreases by 93% from 15 kg/t to 1 kg/t, the cost increases by approximately 200 yuan/t. However, when the CO_2 intensity target decreases by 50% from 2 kg/t to 1 kg/t, the cost increases by 600 yuan/t. More specifically, when the CO_2 intensity target is 2 t/t and the $PM_{2.5}$ intensity target decreases to 1 kg/t, the cost is approximately 2300 yuan/t. However, when the CO_2 intensity target decreases to 1 t/t and the $PM_{2.5}$ intensity target is 15 kg/t, the cost increases to approximately 2500 yuan/t. Figure 3 shows that the cost could remain constant in the case of a trade-off between the CO_2 and $PM_{2.5}$ intensity targets. To keep the cost unchanged, the CO_2 intensity target would have to be set higher if the $PM_{2.5}$ intensity target is set lower, and vice versa. This trade-off indicates that additional CO_2 emissions reductions may cause additional $PM_{2.5}$ pollution. To avoid considerable cost increases, decision makers should carefully choose threshold targets for CO_2 emissions and $PM_{2.5}$ pollution.

3.3 Reduction performance under a limited budget

To investigate the reduction performance when the budget for CO_2 and $PM_{2.5}$ reductions is limited, we assumed that the cost budget ranges from 2000 yuan/t to 3000 yuan/t. Figure 4 shows the reduction performances under these limited budgets and different policy preferences. Figure 4 (a) shows the CO_2 and $PM_{2.5}$ intensities as calculated under the different budgets and policy preferences, and Figure 4(b) shows the corresponding technology paths and removal devices. When the weight of CO_2 reductions is lower than that of $PM_{2.5}$ reductions, reducing CO_2 emissions requires a higher cost compared with reducing $PM_{2.5}$ pollution. In detail, if the cost budget increases from 2000 yuan/t to 2200 yuan/t, then the $PM_{2.5}$ intensity decreases from 14 kg/t to 0.4 kg/t while the CO_2 intensity increases slightly. Only when the cost budget is higher than 2200 kg/t does the CO_2 intensity decrease with cost budget increases. For the corresponding technology combinations, when $PM_{2.5}$ decreases sharply, the BF-BOF+EAF+fabric filter+desulfurization combination is the optimal technology combination and the share of fabric filter and desulfurization devices keeps increasing. When the CO_2 intensity decreases, the EAF+DRI+CCS+fabric filter+desulfurization combination is the optimal technology combination, and the share of the CCS path increases.

When the ratio of the weight of CO_2 reductions relative to the weight of $PM_{2.5}$ reductions equals 9, a higher budget will not reduce the $PM_{2.5}$ intensity. For example, if the budget is below approximately 2400 yuan/t, then the CO_2 and $PM_{2.5}$ intensities decrease as the budget increases. However, if the cost budget rises above 2400 yuan/t, then the $PM_{2.5}$ intensity increases as the cost budget increases. The lowest intensity for $PM_{2.5}$ is approximately 10 kg/t. When the CO_2 and $PM_{2.5}$ intensities decrease, the BF-BOF+EAF+DRI combination is the optimal technology combination. When the CO_2 intensity decreases and $PM_{2.5}$ intensity increases, the EAF+DRI+CCS combination is the optimal technology combination. Additionally, when the budget increases above 2815 yuan/t, a limited reduction in intensity is observed.

Insert Figure 4

3.4 Uncertainty test

To test the robustness of our results, we ran uncertainty tests on the uncertain parameters in the model. We compared the results of the uncertainty tests with the base scenario as shown in Figure 2. These parameters include the following (detailed information on the settings of these parameters are presented in supplementary information).

(a) SO_2 emission factor. The SO_2 emission factor is uncertain because of the different sulfate contents of iron ore. Thus, we test whether the maximum SO_2 emission factor found in the literature affects our robustness (Ministry of Environmental Protection, 2011).

(b) The ratio of SO_2 conversion to $PM_{2.5}$. This ratio is uncertain because the ratio is influenced by many elements, including humidity, availability of oxidants and temperature. We estimate that the ratio increases by up to 0.8 in the extreme case (Yang et al., 2015).

(c) The maximum ratio of EAF. This maximum ratio is uncertain because the supply of scrap is uncertain. We predict that the maximum ratio might reach 50% according to Ma's estimate (Ma et al., 2016).

(d) The cost to reduce $PM_{2.5}$ and SO_2. The cost to reduce $PM_{2.5}$ and SO_2 is uncertain because of technology improvement. Here, we estimate that the cost to reduce $PM_{2.5}$ decreased by half.

(e) The price of the carbon tax. The carbon tax is tested to identify whether levying a carbon tax would influence $PM_{2.5}$ reduction. We assume that the carbon tax equals 500 yuan/t, an extreme case in our uncertainty test.

(f) The interest rate. Interest rates fluctuate as the economy fluctuates. We assume that the interest decreases to 5% in our uncertainty test.

Figure 5 shows that most parameters have a limited effect on the relationship between the technology combination and policy preference. These results demonstrate that our model and results are robust. The SO_2 emission factor and the ratio of SO_2 conversion to $PM_{2.5}$ has more effect on the robustness of our model compared with the other parameters. Relative to the base scenario, when this ratio is high, the desulfurization devices are more likely to be introduced. However, no parameters influence the conclusion that policy preference on $PM_{2.5}$ pollution reductions alone brings co-benefit in CO_2 emission reductions.

Insert Figure 5

4. Policy implications

The multi-objective study of China's iron and steel industry provides valuable insights to China's policymaking on both climate and air pollution mitigation. To achieve deep CO_2 and $PM_{2.5}$ reduction, the iron and steel industry in China should move away from coal-based technology and enhance the application of cleaner technologies. For instance, direct reduced iron is a promising technology that can significantly reduce both CO_2 and $PM_{2.5}$ emissions. To further reduce CO_2 intensity (i.e. by 65%), carbon capture & storage technology is required to capture CO_2 emissions from the blast furnace. However, it is also urgent to lower the cost of cleaner and low carbon technologies. High capital investment and limited resource supply (e.g., natural gas) are the major barriers to commercialize the application of carbon capture & storage and direct reduced iron technologies in China, which cannot be solved easily. Our study indicates that, currently, much more efforts should be made on $PM_{2.5}$ reduction, which will simultaneously address both air pollution and CO_2 reduction with a lower abatement cost, while in the long run, more priority should be paid to CO_2 reduction.

Several factors may influence the accuracy of our results. The desulfurization of SO_2 from iron and steel industry is a major source of uncertainties in our study. SO_2 is an important precursor of $PM_{2.5}$, and plays a critical role in serious haze events. Thus, SO_2 emitted from iron and steel industry may contribute greatly to the formation of secondary $PM_{2.5}$ when the oxidation of the atmosphere increases in autumn and winter. For example, an increase in the supply of scrap will considerably lower the cost for CO_2 mitigation, and greatly reduce the $PM_{2.5}$ emissions. In addition, the development of shale gas is another critical factor. If the supply of shale gas increases substantially, the limits to apply direct reduced iron technology would also be minimized accordingly. Due to increasing investment in the research of cleaner technology, the capital investment cost for cleaner technology may experience a sharp decrease. This decrease in the cost may considerably promote the commercialization of cleaner technology, including carbon capture & storage technology and direct reduced iron.

5. Conclusions

Previous research has predefined limited scenarios to study China's iron and steel industry. These predefined scenarios represent subjective definitions of the decision makers' policy preferences and targets. However, a considerable number of possible combinations are available for policy preferences and targets. To provide a comprehensive analysis of these combinations, we used a multi-objective model and considered several different combinations of policy preferences and targets.

When decisions are made based only on the policy preferences of decision makers, weighting more on CO_2 reduction can efficiently reduce CO_2 emissions but fail to lower $PM_{2.5}$ pollution. Conversely, weighting more on $PM_{2.5}$ reductions can simultaneously reduce both $PM_{2.5}$ pollution and CO_2 emissions when the direct reduced iron technology and removal devices are used. Furthermore, facilities are capable of achieving these reductions even when the decisions are solely made for $PM_{2.5}$ reductions.

Facing a fixed abatement budget, setting lower CO_2 emission targets could induce more $PM_{2.5}$ pollution and vice versa. To resolve this dilemma, $PM_{2.5}$ mitigation should be prioritized because $PM_{2.5}$ abatement cost is much less than that of CO_2. Therefore, for China's steel industry, under the constraints of a limited cost budget, policy making towards $PM_{2.5}$ reductions would result in more benefits than focused on CO_2 reduction.

The above analyses are based on the assumption that the advanced technologies (e.g., DRI) will be applied extensively in China. Thus, reducing the cost of these advanced technologies in China is necessary for the co-control of CO_2 emissions and $PM_{2.5}$ pollution, and reducing the cost of low-carbon technology is critically important. While reducing $PM_{2.5}$ pollution is relatively feasible in the short term, reducing CO_2 emissions requires considerable abatement costs. For the iron and steel industry, reducing CO_2 emissions per GDP by 65% will be a rather difficult task. Thus, policy making should focus on co-control strategies for $PM_{2.5}$ and CO_2.

Acknowledgement

This work was supported by funding from the National Natural Science Foundation of China under award nos. 41571130010, 41671491, and 41390240; National Key Research and Development Program of China 2016YFC0206202; and the 111 Project (B14001).

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Supplemantary material for

Multi-objective analysis of the co-mitigation of CO_2 and $PM_{2.5}$ pollution by China's iron and steel industry

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The author declares no competing financial interest

List of Tables

Table S1. Parameters used in the uncertainty tests

	Base	Uncertainty test
SO_2 emission factor in sintering	2.4	7.5
Conversion rate of SO_2	0.22	0.8
The maximum ratio of EAF	30%	50%
The cost to reduce $PM_{2.5}$	9860	5000
Carbon tax	0	500
interest rate	10%	5%

Table S2. Annualized investment and lifetime of technology under 10% interest rate

device	annualized investment yuan/t	Lifetime year
coke oven	75.32	30
sintering furnace	42.29	20
TRT blast furnace+pulverized coal injection	102.19	20
BOF furnace	70.48	20
electric arc furnace	71.06	20
DRI	152.7	20
CCS	546.2	20
Casting	42.29	20
Hot rolling	58.73	20
Cold rolling	85.16	20

Word amount: 4873

Multi-objective analysis of the co-mitigation of CO_2 and $PM_{2.5}$ pollution by China's iron and steel industry

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Abstract: China has experienced serious fine particulate matter ($PM_{2.5}$) pollution in recent years, and carbon dioxide (CO_2) emissions must be controlled so that China can keep its pledge to reduce CO_2 emissions by 2030. The iron and steel industry is energy intensive and contributes significantly to $PM_{2.5}$ pollution in China. The simultaneous reduction of CO_2 emissions and $PM_{2.5}$ pollution while minimizing the total mitigation costs remains a crucial issue that must be resolved. Using a multi-objective analysis, we compared potential technology combinations based on various policy preferences and targets. Our results showed that policies designed to mitigate $PM_{2.5}$ pollution have substantial co-benefits for CO_2 emissions reductions. However, policies focused solely on reducing CO_2 emissions fail to effectively reduce $PM_{2.5}$. Furthermore, CO_2 emissions reductions correspond to large financial costs, whereas $PM_{2.5}$ pollution reductions are less expensive. Our results suggest that under limited budgets, decision makers should prioritize $PM_{2.5}$ reductions because CO_2 reductions may be simultaneously achieved. Achieving large decreases in CO_2 emissions will require further technological innovations to reduce the cost threshold. Thus, China should focus on reducing PM pollution in the short term and prepare for the expected challenges associated with CO_2 reductions in the future.

Keywords: multi-objective, iron and steel, $PM_{2.5}$, CO_2 emission reduction, emission control, abatement cost

Comment [h1]: We add the key word

1. Introduction

Carbon dioxide (CO_2) is a major greenhouse gas (GHG) that has caused rapid increases in temperatures worldwide (Intergovernmental Panel on Climate Change, 2013). As a result of temperature increase, climate change is threatening the existence of human beings (Knutti et al., 2015). To deal with the climate change caused by CO_2 and other GHGs, the Paris Agreement was adopted at the 2015 United Nations Climate Change Conference. The dominant goal of the Paris Agreement is to hold "the increase in the global average temperature to well below 2 °C above preindustrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels" (Rogelj et al., 2016). As the largest emitter of CO_2, accounting for 24% of

Comment [h2]: Background information about the Post Paris era the global emissions in 2012 (Zhou et al., 2012), China pledged that by 2030, it would decrease its CO_2 emissions per unit gross domestic product (GDP) by 65% compared with the 2005 level (The State Council, 2015). Along with the considerable GHG emissions, hazes have become a severe environmental problem in China. During a haze event, fine particulate matter ($PM_{2.5}$), which is composed of primary $PM_{2.5}$ (Li, Y. et al., 2016) and secondary $PM_{2.5}$ converted from SO_2 and NO_x (Sun et al., 2006), is the major pollutant (Meng et al., 2016). To improve air quality, China's government has taken actions to reduce the precursors of primary and secondary $PM_{2.5}$ emissions (e.g., National Action Plan on Prevention and Control Air Pollution) (The State Council, 2013). However, there exist some challenges to achieve these two goals. The major challenge lies in that the government needs to maintain the development of economy while simultaneously reduce CO_2 emissions and $PM_{2.5}$ pollution. Infrastructure construction has been the major driver of China's rapid growth of economy and emissions, and the economy relies heavily on carbon-intensive industries (e.g., iron and steel, cement and electricity, (Liu et al., 2012). Reducing CO_2 emissions requires high initial capital cost for the adoption of low carbon technology and removing air pollutants calls for extra operation cost (Hou et al., 2011), which may have negative effects on the economy in less developed regions in the short run (Dong and Liang, 2014; Liu et al., 2015; Meng et al., 2017). Thus, it is a challenge to balance the CO_2 and $PM_{2.5}$ reduction while keeping the economic growth.

Comment [h3]: New challenges for China

The iron and steel industry is a major source of CO_2 emissions and $PM_{2.5}$ pollution in China. This industry is energy intensive and consumed 14% of the total energy used in China in 2012 (i.e., 8% of coal, 86% of coke and 10% of electricity) (National Bureau of Statistics of China, 2013). This industry is estimated to account for 10-20% of the CO_2 emissions (Guo and Fu, 2010; Yuan et al., 2012; Zeng et al., 2009) and 5% of the primary $PM_{2.5}$ emissions in China (Lei et al., 2010; Meng et al., 2015). Additionally, the iron and steel industry emitted 10% of China's SO_2 emissions, which are an important precursor of secondary $PM_{2.5}$ (National Bureau of Statistics of China; Ministry of Envrionmental Protection, 2011). Therefore, reducing CO_2 emissions and $PM_{2.5}$ pollution from the iron and steel industry is necessary to mitigate climate change over the long term or resolve the haze problem over the short term (Xu et al., 2014). The Plan for Adjustment and Upgrading of Iron and Steel Industry (Ministry of Industry and Information Technology, 2016) has proposed considerable low carbon technologies, improving the efficiency of energy use and thus reducing the emissions of CO_2 and air pollutants (Dong et al., 2013; Zhang et al., 2013). For example, coke dry quenching helps reduce fossil fuel and electricity consumption, thereby reducing CO_2 emissions and the air pollutants (Ministry of Industry and Information Technology, 2012). Removal devices are also planned to be widely applied to remove air pollutants according to China's 12th Five Year Plan (The State Council, 2011). In addition, carbon capture and storage is a promising technology that can capture and store CO_2 emitted from the blast furnaces (Psarras et al., 2017). Nevertheless, cost factors limit China's capacity to simultaneously reduce CO_2 and $PM_{2.5}$ pollution, and the adoption of technologies to reduce CO_2 and $PM_{2.5}$ is dependent on the cost of the technology. Because of the limitations of budgets, decision makers must minimize costs while focusing on simultaneously reducing $PM_{2.5}$ and CO_2 emissions.

Comment [h4]: Modify the proportion

Comment [h5]: Update information for iron and steel industry

Previous research on China's iron and steel industry has focused on the cost effectiveness of CO_2 reductions and energy conservation. The demand for steel has been used as an indicator to estimate the quantity of CO_2 (Chen et al., 1990; Gao, 2010; Yin and Chen, 2013). The energy efficiency of China’s iron and steel industry is far behind the more advanced levels worldwide; therefore, cost-effective technologies have been identified to improve this energy efficiency (Hasanbeigi et al., 2011; He et al., 2013; Lin and Wang, 2015; Ma et al., 2002; 2014; Zhang et al., 2012; Zhang et al., 2007). Additionally, researchers have used different energy models to predict the CO_2 emissions from the iron and steel industry (Chen et al., 2014; Li, L. et al., 2016; Wang et al., 2007; Wen et al., 2014; Xu and Lin, 2016). Research on the co-control of air pollutants and CO_2 indicates that co-control measures are more cost-effective than single reduction measures (Liu et al., 2014; 2016; Mao et al., 2013; 2014). The co-benefit of reducing CO_2 and air pollutants has been studied by Dong (2015) and Kanada (2013).

Comment [h6]: Add new literatures the reviewer suggested

However, previous research has rarely focused on simultaneously reducing CO_2 and $PM_{2.5}$ pollution while also controlling the cost to China’s iron and steel industry. Moreover, environmental assessments of the iron and steel industry are frequently performed by comparing a limited set of predefined scenarios, which introduces added uncertainty to the assessments. This work aims to identify robust optimal strategies for China’s iron and steel industry under different policy targets and preferences of decision makers. We combined the detailed technologies and policy preferences and targets with mathematical multi-objective optimization techniques to identify the optimal strategy for simultaneously minimizing CO_2 emissions, $PM_{2.5}$ pollution and abatement costs.

2. Methods and materials

2.1 Available technology options

The technology combinations available to the iron and steel industry included two parts: technology paths and removal technologies. Technology paths refer to the technologies used to produce steel products, whereas removal technologies refer to end-of-pipe pollutant removal technologies. Figure 1 shows the technology paths and removal technologies that are currently available for the iron and steel industry. Technology paths include the blast furnace and basic oxygen furnace technology path (BF-BOF), the electric arc furnace technology path (EAF), the direct reduced iron technology path (DRI) and the carbon capture & storage technology path (CCS). We ruled out the smelt reduced iron technology path because of its high CO_2 emissions and air pollutant emissions (Hu and Jiang, 2001). The BF-BOF is the most widely used technology path in China, and this traditional path includes the coking, sintering, iron-making, steel-making, casting and rolling processes. The alternative technology path for the BF-BOF is the EAF in which scrap instead of iron ore is used to produce crude iron in an electricity arc furnace. Another promising new technology path is the DRI path. Most DRI technologies use natural gas to reduce pellets or sinters, and they then produce direct reduced iron as an alternative to scrap. The *Midrex* technology is currently a widely applied technology in DRI production. The CCS technology path combines carbon capture and storage technology with a blast furnace. The removal processes include $PM_{2.5}$ and SO_2 removal devices. Removing SO_2 is important for reducing $PM_{2.5}$ because it represents an important precursor of $PM_{2.5}$. A high-efficiency particulate matter removal device, such as a fabric filter, should remove primary $PM_{2.5}$. A number of SO_2 removal methods are available, and desulfurization is a general term used to refer to these removal processes (Xing and Lu, 2013; Yanling, 2013). We have classified the technologies used in our analysis in Table 1.

Comment [h7]: A summary and classification of technology

Insert Figure 1

Table 1. A summary of technology options used in this study

Category	Technology	Reference
Traditional process	Coke oven	Hu and Jiang (2001)
	Sintering furnace	Hu and Jiang (2001)
	Blast furnace	Hu and Jiang (2001)
	Electric arc furnace	Hu and Jiang (2001)
	Basic oxygen furnace	Hu and Jiang (2001)
	Casting	Hu and Jiang (2001)
	Hot rolling	Hu and Jiang (2001)
	Cold rolling	Hu and Jiang (2001)
Efficiency improvement	Coke dry quenching	Hu and Jiang (2001)
	Top-pressure recovery turbine	Hu and Jiang (2001)
	Recovery of BOF gas	Hu and Jiang (2001)
	Continuous casting	Hu and Jiang (2001)
System optimization	Direct reduced iron	Baig (2016)
Carbon capture	Carbon capture & storage	Kuramochi et al. (2012)
Pollutant removal	Fabric filter	Ma et al. (2016)
	Desulfurization	Ma et al. (2016)

2.2 Model description

2.2.1 Emission factors and costs for different technology paths

CO_2 emissions are calculated based on energy consumption, and primary $PM_{2.5}$ and SO_2 emissions are calculated based on production processes. The emission factors and the costs of each technology path are calculated as follows:

$$\mathrm{EFC_i} = \sum_j \mathrm{CO_2EF_j} \times \mathrm{fuel_{ij}} \tag{1}$$

$$\mathrm{EFP_i} = \sum_j \mathrm{PMEF_{ij}} \tag{2}$$

$$\mathrm{EFS_i} = \sum_j \mathrm{SO_2EF_{ij}} \tag{3}$$

$$\mathrm{cost_i} = \mathrm{annualized\ cost_i} + \sum_j \mathrm{P_j} \times \mathrm{fuel_{ij}} \tag{4}$$

$$\mathrm{anuualized\ cost_i} = \mathrm{capital\ cost_i} \times \frac{\mathrm{d}}{(1-(1+\mathrm{d})^{-\mathrm{n}})} \tag{5}$$

where $\mathrm{EFC_i}$ represents the CO_2 emissions when technology path i produces one ton of finished steel product; $\mathrm{EFP_i}$ represents the primary $PM_{2.5}$ emissions when technology path i produces one ton of finished steel product; $\mathrm{EFS_i}$ represents the SO_2 emissions when technology path i produces one ton of finished steel product; $\mathrm{CO_2EF_j}$ represents the CO_2 emission factor of fuel j in technology path i; $\mathrm{PMEF_{ij}}$ represents the $PM_{2.5}$ emission factor of process j in technology path i; $\mathrm{fuel_{ij}}$ represents the amount of fuel j consumed during the production of one ton of finished steel product using technology path i; $\mathrm{cost_i}$ represents the cost of producing one ton of finished steel product using technology path i; $\mathrm{annualized\ cost_i}$ represents the annual capital investment for producing one ton of finished steel product using technology path i; $\mathrm{P_j}$ represents the price of fuel j; and $\mathrm{capital\ cost_i}$ represents the total capital cost for n years of producing one ton of finished steel product using technology path i. The interest rate d in this paper is set to

10% (Zhang et al., 2014). The variable n is the lifetime of the different technologies. The emission factors and costs of each technology path are shown in Table 2.

Table 2. Emission factors and costs of the technology paths (per ton of finished steel product) and removal technologies (per ton of SO_2 and $PM_{2.5}$)

	CO_2 (including electricity) t/t	**Primary $PM_{2.5}$ kg/t**	**Cost yuan/t**	**SO_2 kg/t**	**Indirect SO_2 from electricity kg/t**	**Indirect primary $PM_{2.5}$ from electricity kg/t**
BF-BOF	2.38	18.18	1954	8.23	0.78	0.05
EAF	0.49	7.09	2043	0.35	0.44	0.03
DRI	1.20	10.25	2575	8.07	0.68	0.05
CCS	0.78	18.18	3129	8.23	1.38	0.09
Desulfurization	1.78		5280			
Fabric filter	14.54		9860			

2.2.2 Multi-objective analysis of CO_2 and $PM_{2.5}$ emissions reductions and cost control in the iron and steel industry

Decision makers have different policy preferences for CO_2 reductions, $PM_{2.5}$ reductions and cost control. Furthermore, decision makers set threshold targets for CO_2 emissions and $PM_{2.5}$ pollution. Moreover, decision makers may be confronted with a limited budget for reducing CO_2 emissions and $PM_{2.5}$ pollution. Therefore, to determine the optimal technology combinations under different conditions, a multi-objective optimization method was designed.

The share of the four technology paths were subject to the following constraints (6):

$$\begin{cases} \sum_{i=1}^{m} r_i = 1 \\ 0 \le r_{1,3,4} \le 1 \\ 0 \le r_2 \le 0.3 \\ 0 \le r_{SO_2} \le 1 \\ 0 \le r_{PM_{2.5}} \le 1 \end{cases} \tag{6}$$

where r_1 represents the share in all the four paths accounted for by the technology path BF-BOF, r_2 represents the EAF share; r_3 represents the DRI share; r_4 represents the CCS share; r_{SO_2} represents the share of desulfurization technology; and $r_{PM_{2.5}}$ represents the share of the $PM_{2.5}$ removal device fabric filter. The maximum value of r_2 is 0.3(Ma et al., 2016).

The SO_2 intensity (SO_2 emissions per ton of finished steel products) is composed of the SO_2 emitted via electricity generation and the SO_2 that is not removed by desulfurization devices.

$$SO_2 = \sum_{i=1}^{4} EFSE_i \cdot r_i + \sum_{i=1}^{4} EFS_i \cdot r_i \cdot r_{SO_2} \cdot (1 - \eta_{SO_2}) + \sum_{i=1}^{4} EFS_i \cdot r_i \cdot (1 - r_{SO_2}) \tag{7}$$

where SO_2 represents the SO_2 intensity, η_{SO_2} represents the removal efficiency of the desulfurization technology, and $EFSE_i$ represents the emission factor of SO_2 emitted from the electricity required to produce one ton of finished steel product using technology path i. In this study, η_{SO_2} is set to 0.95 (Mao et al., 2013).

The $PM_{2.5}$ intensity ($PM_{2.5}$ pollution per ton of finished steel products) is composed of the primary $PM_{2.5}$ emissions from electricity generation, primary $PM_{2.5}$ emissions not removed by a fabric filter and secondary $PM_{2.5}$ converted from SO_2 emissions.

$$PM_{2.5} = \sum_{i=1}^{4} EFPE_i \cdot r_i + \sum_{i=1}^{4} EFP_i \cdot r_i \cdot r_{PM_{2.5}} \cdot (1 - \eta_{PM_{2.5}}) + \sum_{i=1}^{4} EFP_i \cdot r_i \cdot (1 - r_{PM_{2.5}}) + CF \cdot SO_2 \tag{8}$$

where $PM_{2.5}$ represents the $PM_{2.5}$ intensity, $\eta_{PM_{2.5}}$ represents the removal efficiency of the fabric filter, $\mathrm{EFPE_i}$ represents the emission factor for $PM_{2.5}$ emitted by the electricity required to produce one ton of finished steel product using technology path i, and CF represents the ratio of SO_2 converting to $PM_{2.5}$. In our study, $\eta_{PM2.5}$ is set to 0.997(Huang et al., 2014) and CF is set to 0.22(Wen, 2015).

The CO_2 intensity (CO_2 emissions per ton of finished steel products) is composed of the CO_2 emitted from electricity generation, the production process and desulfurization device and fabric filter use.

$$\mathrm{CO_2} = \sum \mathrm{EFCE_i} \cdot \mathrm{r_i} + \sum \mathrm{EFTC_i} \cdot \mathrm{r_i} + \mathrm{EFC_{SO_2}} \cdot \sum \mathrm{EFS_i} \cdot \mathrm{r_i} \cdot \mathrm{r_{SO_2}} \cdot \eta_{\mathrm{SO_2}} + \mathrm{EFC_{PM_{2.5}}} \cdot \sum \mathrm{EFP_i} \cdot \mathrm{r_i} \cdot \mathrm{r_{PM_{2.5}}} \cdot \eta_{\mathrm{PM_{2.5}}} \tag{9}$$

where $\mathrm{CO_2}$ represents the CO_2 intensity, $\mathrm{EFCE_i}$ represents the emission factor for CO_2 emitted by the electricity required to produce one ton of finished steel product using technology path i, $\mathrm{EFS_{SO_2}}$ represents the CO_2 emissions from removing 1 kg of SO_2 using a desulfurization device, and $\mathrm{EFP_{PM_{2.5}}}$ represents the CO_2 emissions from removing 1 kg of $PM_{2.5}$ by a fabric filter.

The cost (cost per ton of finished steel products) is composed of the production costs, SO_2 abatement costs, $PM_{2.5}$ abatement costs and carbon tax.

$$\mathrm{cost} = \sum_{\mathrm{i}=1}^{4} \mathrm{cost_i} \cdot \mathrm{r_i} + \mathrm{cost_{SO_2}} \cdot \sum_{\mathrm{i}=1}^{4} \mathrm{EFS_i} \cdot \mathrm{r_i} \cdot \mathrm{r_{SO_2}} \cdot \eta_{\mathrm{SO_2}} + \mathrm{cost_{PM_{2.5}}} \cdot \sum_{\mathrm{i}=1}^{4} \mathrm{EFP_i} \cdot \mathrm{r_i} \cdot \mathrm{r_{PM_{2.5}}} \cdot \eta_{\mathrm{PM_{2.5}}} + \mathrm{t} \cdot \mathrm{CO_2} \tag{10}$$

where cost represents the cost of producing one ton of finished steel product, $\mathrm{cost_{SO_2}}$ denotes the cost of removing 1 kg of SO_2, $\mathrm{cost_{PM_{2.5}}}$ represents the cost of removing 1 kg of $PM_{2.5}$, and t represents the tax rate on one ton of CO_2 emissions. The carbon tax is set to 0 in our study.

The CO_2 and $PM_{2.5}$ intensities and costs are the three parameters to be simultaneously minimized in our multi-objective model. Relative weight factors are used to represent the policy preferences of the decision makers for these three objectives. The use of the relative weight factors in the objective function is presented as follows:

$$\min \mathrm{w_1} \cdot \frac{\mathrm{CO_2} - \mathrm{CO_2}_{\mathrm{min}}}{\mathrm{CO_2}_{\mathrm{max}} - \mathrm{CO_2}_{\mathrm{min}}} + \mathrm{w_2} \cdot \frac{\mathrm{PM_{2.5}} - \mathrm{PM_{2.5}}_{\mathrm{min}}}{\mathrm{PM_{2.5}}_{\mathrm{max}} - \mathrm{PM_{2.5}}_{\mathrm{min}}} + \mathrm{w_3} \cdot \frac{\mathrm{cost} - \mathrm{cost_{min}}}{\mathrm{cost_{max}} - \mathrm{cost_{min}}} \tag{11}$$

$$\begin{cases} \sum_{\mathrm{i}=1}^{3} \mathrm{w_i} = 1 \\ \mathrm{w_i} = \frac{\mathrm{n}}{100}, \mathrm{n} = 0,1,2,\cdots,100 \end{cases} \tag{12}$$

where $\mathrm{w_i}$ represents the relative weight factor of an objective; $\mathrm{CO_2}_{\mathrm{max}}$, $\mathrm{PM_{2.5}}_{\mathrm{max}}$and $\mathrm{cost_{max}}$ represent the largest values for each parameter calculated in the model; and $\mathrm{CO_2}_{\mathrm{min}}$, $\mathrm{PM_{2.5}}_{\mathrm{min}}$, and $\mathrm{cost_{min}}$ represent the smallest values for each parameter calculated in the model. The CO_2 intensity, $PM_{2.5}$ intensity and costs are normalized to eliminate unit-related errors. The value of each relative weight factor is not predefined; rather, these values are assumed to take any possible value between 0 and 1. This weighting method represents all possible combinations of the decision makers' policy preferences.

Decision makers can set threshold targets for CO_2 and $PM_{2.5}$ intensities. These emissions or pollution targets represent the largest allowable emissions or pollution. The cost budget is also likely to be limited to a certain amount. Based on the largest allowable CO_2 emissions, $PM_{2.5}$ pollution or cost budget, the objective function is calculated as follows:

$$\begin{cases} \mathrm{G_1} = \mathrm{CO_2} \\ \mathrm{G_2} = \mathrm{PM_{2.5}} \\ \mathrm{G_3} = \mathrm{cost} \end{cases} \tag{13}$$

$$\mathrm{G_i} \le \mathrm{Target_i}, \mathrm{i} \in \text{Objectives lower than the target value} \tag{14}$$

$$\min \sum_{\mathrm{j}} \mathrm{w_j} \times \frac{\mathrm{G_j} - \mathrm{G_{jmin}}}{\mathrm{G_{jmax}} - \mathrm{G_{jmin}}}, \mathrm{j} \in \text{ remaining objectives excluding I} \tag{15}$$

$$\begin{cases} \sum_{\mathrm{j}} \mathrm{w_j} = 1 \\ \mathrm{w_j} = \frac{\mathrm{n}}{100}, \mathrm{n} = 0,1,2,\cdots,100 \end{cases} \tag{16}$$

where G_i represents the value of objective i and $target_i$ represents the largest allowable value of objective i.

2.3 Data

The energy consumption and lifetime data and the cost of each specific technology in the four paths were obtained from Hu and Jiang (2001) and Baig (2016). Data for the CCS technology path were obtained from the literature (Kuramochi et al., 2012; Ma et al., 2016; Mao et al., 2013). Data for the fabric filter and desulfurization techniques were obtained from Mao et al. (2013). CO_2 emission factors for the energy input were obtained from the Intergovernmental Panel on Climate Change (2006). The emission factors for electricity input were obtained from National Development and Reform Commission (2015) and Mo et al. (2013). The emission factors of $PM_{2.5}$ from production processes were obtained from Lei et al. (2010) and Huang et al. (2014). Emission factors of SO_2 from production processes were obtained from Zhao (2016) and the Handbook of National Pollution Sources (Ministry of Environmental Protection, 2011). The data for energy price were obtained from China's Economic Database from the CEIC (https://www.ceicdata.com/zh-hans/products/china-economic-database).

3. Results and discussion

3.1 Reduction performance based on different policy preferences for CO_2 reductions, $PM_{2.5}$ reductions and cost control

Insert Figure 2

Table 3. Emission factors (per ton of steel product), unit costs (per ton of steel product) and share of the technologies in different technology combinations.

	$PM_{2.5}$ kg/t	CO_2 t/t	Cost yuan/t	BF-BOF	EAF	DRI	CCS	Fabric filter	Desulfurization
1	19.09	2.38	1954	100%	0	0	0	0	0
2	15.55	1.81	1981	70%	30%	0	0	0	0
3	0.80	2.02	2127	70%	30%	0	0	100%	0
4	0.32	2.02	2138	70%	30%	0	0	100%	100%
5	9.98	0.99	2415	0	30%	70%	0	0	0
6	0.74	1.12	2507	0	30%	70%	0	100%	0
7	0.27	1.12	2518	0	30%	70%	0	100%	100%
8	15.67	0.69	2803	0	30%	0	70%	0	0
9	15.19	0.70	2815	0	30%	0	70%	0	100%
10	0.44	0.90	2961	0	30%	0	70%	100%	0

1.BF-BOF; 2.BF-BOF+EAF; 3.BF-BOF+EAF+fabric filter; 4.BF-BOF+EAF+fabric filter+desulfurization;

5. EAF+DRI; 6.EAF+DRI+fabric filter; 7. EAF+DRI+fabric filter+desulfurization;

8.EAF+CCS; 9. EAF+CCS+desulfurization; 10. EAF+CCS+fabric filter+desulfurization

We used relative weight factors to represent the decision maker's policy preferences for CO_2 reductions, $PM_{2.5}$ reductions and cost control. Figure 2 shows the corresponding relationships between the relative weight factors and technology combinations. Table 3 shows the CO_2 intensity,

$PM_{2.5}$ intensity and cost of the different technology combinations, and it indicates that the largest and smallest CO_2 intensity, $PM_{2.5}$ intensity and cost are 2.38 kg/t, 19.09 kg/t and 2961 yuan/t and 0.69 kg/t, 0.27 kg/t and 1954 yuan/t, respectively.

The results show that a policy preference for $PM_{2.5}$ reductions alone provides much more co-benefits compared with a policy preference for CO_2 reductions or cost control alone. Our findings indicate that when the $PM_{2.5}$ reduction weight approaches 1 and the CO_2 reduction weight approaches 0, the $PM_{2.5}$ intensity decreases to 0.27 kg/t, the CO_2 intensity (1.12 t/t) is 53% lower than the largest CO_2 intensity, and the costs increase to 2518 kg/t. This reduction performance is the same when the weights of CO_2 reduction, $PM_{2.5}$ reduction and cost control are equal. These results reveal that when the weight of $PM_{2.5}$ reduction is high, CO_2 emissions are also reduced as a co-benefit because the technology paths are altered and removal devices are introduced.

However, when the CO_2 reduction weight approaches 1, the CO_2 intensity is reduced to 0.69 t/t while the $PM_{2.5}$ intensity (15.67 kg/t) is only 18% lower than the largest $PM_{2.5}$ intensity. Additionally, a higher preference for CO_2 reduction induces higher costs. For example, when the weights of CO_2 and $PM_{2.5}$ reduction are both 0.5, the cost is 2961 yuan/t, the $PM_{2.5}$ intensity is 0.44 kg/t and the CO_2 intensity is 0.90 t/t. In contrast, when the weight of $PM_{2.5}$ approaches 1 and the weight of CO_2 reduction approaches 0, the cost decreases to 2518 yuan/t.

Reducing CO_2 and $PM_{2.5}$ emissions simultaneously sacrifices the weight of the cost. When the weight of the cost approaches 1, the CO_2 intensity is 2.38 t/t, and the $PM_{2.5}$ intensity is 19.09 kg/t. Furthermore, when the weight of the cost is higher than approximately 0.5, CO_2 and $PM_{2.5}$ cannot be simultaneously reduced. For example, when the weights of CO_2 reductions and costs are both 0.5, the CO_2 intensity is 43% higher than the smallest intensity, whereas the $PM_{2.5}$ intensity is 35 times higher than the smallest intensity. In contrast, when the weights of $PM_{2.5}$ reductions and costs are both 0.5, the $PM_{2.5}$ intensity decreases to 0.32 kg/t, whereas the CO_2 intensity (2.02 t/t) is only 11% lower than the largest intensity.

3.2 Cost of different CO_2 and $PM_{2.5}$ intensity targets

Insert Figure 3

The emission and pollution targets represent the largest allowable emissions of CO_2 and $PM_{2.5}$, respectively. In the multi-objective model, we use the emission intensity and pollution emission targets to represent the CO_2 and $PM_{2.5}$ targets, respectively. Figure 3 presents the relationships between the costs and the two targets. The blue and red colors represent lower and higher costs, respectively. Setting low CO_2 and $PM_{2.5}$ intensity targets resulted in sharp increases in cost. For example, if the decision makers set the CO_2 and $PM_{2.5}$ intensities to 1 t/t and 1 kg/t, respectively, then the cost would increase to over 2700 yuan/t. This cost is almost 40% higher than the lowest cost estimated by the model. Setting lower $PM_{2.5}$ intensity targets is more cost effective than setting lower CO_2 emission targets. For example, when the $PM_{2.5}$ intensity target decreases by 93% from 15 kg/t to 1 kg/t, the cost increases by approximately 200 yuan/t. However, when the CO_2 intensity target decreases by 50% from 2 kg/t to 1 kg/t, the cost increases by 600 yuan/t. More specifically, when the CO_2 intensity target is 2 t/t and the $PM_{2.5}$ intensity target decreases to 1 kg/t, the cost is approximately 2300 yuan/t. However, when the CO_2 intensity target decreases to 1 t/t and the $PM_{2.5}$ intensity target is 15 kg/t, the cost increases to approximately 2500 yuan/t. Figure 3 shows that the cost could remain constant in the case of a trade-off between the CO_2 and $PM_{2.5}$ intensity targets. To keep the cost unchanged, the CO_2 intensity target would have to be set higher if the $PM_{2.5}$ intensity target is set lower, and vice versa. This trade-off indicates that additional CO_2 emissions reductions may cause additional $PM_{2.5}$ pollution. To avoid considerable cost increases, decision makers should carefully choose threshold targets for CO_2 emissions and $PM_{2.5}$ pollution.

3.3 Reduction performance under a limited budget

To investigate the reduction performance when the budget for CO_2 and $PM_{2.5}$ reductions is limited, we assumed that the cost budget ranges from 2000 yuan/t to 3000 yuan/t. Figure 4 shows the reduction performances under these limited budgets and different policy preferences. Figure 4 (a) shows the CO_2 and $PM_{2.5}$ intensities as calculated under the different budgets and policy preferences, and Figure 4(b) shows the corresponding technology paths and removal devices. When the weight of CO_2 reductions is lower than that of $PM_{2.5}$ reductions, reducing CO_2 emissions requires a higher cost compared with reducing $PM_{2.5}$ pollution. In detail, if the cost budget increases from 2000 yuan/t to 2200 yuan/t, then the $PM_{2.5}$ intensity decreases from 14 kg/t to 0.4 kg/t while the CO_2 intensity increases slightly. Only when the cost budget is higher than 2200 kg/t does the CO_2 intensity decrease with cost budget increases. For the corresponding technology combinations, when $PM_{2.5}$ decreases sharply, the BF-BOF+EAF+fabric filter+desulfurization combination is the optimal technology combination and the share of fabric filter and desulfurization devices keeps increasing. When the CO_2 intensity decreases, the EAF+DRI+CCS+fabric filter+desulfurization combination is the optimal technology combination, and the share of the CCS path increases.

When the ratio of the weight of CO_2 reductions relative to the weight of $PM_{2.5}$ reductions equals 9, a higher budget will not reduce the $PM_{2.5}$ intensity. For example, if the budget is below approximately 2400 yuan/t, then the CO_2 and $PM_{2.5}$ intensities decrease as the budget increases. However, if the cost budget rises above 2400 yuan/t, then the $PM_{2.5}$ intensity increases as the cost budget increases. The lowest intensity for $PM_{2.5}$ is approximately 10 kg/t. When the CO_2 and $PM_{2.5}$ intensities decrease, the BF-BOF+EAF+DRI combination is the optimal technology combination. When the CO_2 intensity decreases and $PM_{2.5}$ intensity increases, the EAF+DRI+CCS combination is the optimal technology combination. Additionally, when the budget increases above 2815 yuan/t, a limited reduction in intensity is observed.

Insert Figure 4

3.4 Uncertainty test

To test the robustness of our results, we ran uncertainty tests on the uncertain parameters in the model. We compared the results of the uncertainty tests with the base scenario as shown in Figure 2. These parameters include the following (detailed information on the settings of these parameters are presented in supplementary information).

Comment [h8]: Detailed information is in the supplementary information

(a) SO_2 emission factor. The SO_2 emission factor is uncertain because of the different sulfate contents of iron ore. Thus, we test whether the maximum SO_2 emission factor found in the literature affects our robustness (Ministry of Environmental Protection, 2011).

(b) The ratio of SO_2 conversion to $PM_{2.5}$. This ratio is uncertain because the ratio is influenced by many elements, including humidity, availability of oxidants and temperature. We estimate that the ratio increases by up to 0.8 in the extreme case (Yang et al., 2015).

(c) The maximum ratio of EAF. This maximum ratio is uncertain because the supply of scrap is uncertain. We predict that the maximum ratio might reach 50% according to Ma's estimate (Ma et al., 2016).

(d) The cost to reduce $PM_{2.5}$ and SO_2. The cost to reduce $PM_{2.5}$ and SO_2 is uncertain because of technology improvement. Here, we estimate that the cost to reduce $PM_{2.5}$ decreased by half.

(e) The price of the carbon tax. The carbon tax is tested to identify whether levying a carbon tax would influence $PM_{2.5}$ reduction. We assume that the carbon tax equals 500 yuan/t, an extreme case in our uncertainty test.

(f) The interest rate. Interest rates fluctuate as the economy fluctuates. We assume that the interest decreases to 5% in our uncertainty test.

Figure 5 shows that most parameters have a limited effect on the relationship between the technology combination and policy preference. These results demonstrate that our model and results are robust. The SO_2 emission factor and the ratio of SO_2 conversion to $PM_{2.5}$ has more effect on the robustness of our model compared with the other parameters. Relative to the base scenario, when this ratio is high, the desulfurization devices are more likely to be introduced. However, no parameters influence the conclusion that policy preference on $PM_{2.5}$ pollution reductions alone brings co-benefit in CO_2 emission reductions.

Comment [h9]: Add a new graph

Insert Figure 5

4. Policy implications

The multi-objective study of China's iron and steel industry provides valuable insights to China's policymaking on both climate and air pollution mitigation. To achieve deep CO_2 and $PM_{2.5}$ reduction, the iron and steel industry in China should move away from coal-based technology and enhance the application of cleaner technologies. For instance, direct reduced iron is a promising technology that can significantly reduce both CO_2 and $PM_{2.5}$ emissions. To further reduce CO_2 intensity (i.e. by 65%), carbon capture & storage technology is required to capture CO_2 emissions from the blast furnace. However, it is also urgent to lower the cost of cleaner and low carbon technologies. High capital investment and limited resource supply (e.g., natural gas) are the major barriers to commercialize the application of carbon capture & storage and direct reduced iron technologies in China, which cannot be solved easily. Our study indicates that, currently, much more efforts should be made on $PM_{2.5}$ reduction, which will simultaneously address both air pollution and CO_2 reduction with a lower abatement cost, while in the long run, more priority should be paid to CO_2 reduction.

Comment [h10]: Policy implications for iron and steel industry

Several factors may influence the accuracy of our results. The desulfurization of SO_2 from iron and steel industry is a major source of uncertainties in our study. SO_2 is an important precursor of $PM_{2.5}$, and plays a critical role in serious haze events. Thus, SO_2 emitted from iron and steel industry may contribute greatly to the formation of secondary $PM_{2.5}$ when the oxidation of the atmosphere increases in autumn and winter. For example, an increase in the supply of scrap will considerably lower the cost for CO_2 mitigation, and greatly reduce the $PM_{2.5}$ emissions. In addition, the development of shale gas is another critical factor. If the supply of shale gas increases substantially, the limits to apply direct reduced iron technology would also be minimized accordingly. Due to increasing investment in the research of cleaner technology, the capital investment cost for cleaner technology may experience a sharp decrease. This decrease in the cost may considerably promote the commercialization of cleaner technology, including carbon capture & storage technology and direct reduced iron.

Comment [h11]: Analysis of uncertainty test

5. Conclusions

Previous research has predefined limited scenarios to study China’s iron and steel industry. These predefined scenarios represent subjective definitions of the decision makers’ policy preferences and targets. However, a considerable number of possible combinations are available for policy preferences and targets. To provide a comprehensive analysis of these combinations, we used a multi-objective model and considered several different combinations of policy preferences and targets.

When decisions are made based only on the policy preferences of decision makers, weighting more on CO_2 reduction can efficiently reduce CO_2 emissions but fail to lower $PM_{2.5}$ pollution. Conversely, weighting more on $PM_{2.5}$ reductions can simultaneously reduce both $PM_{2.5}$ pollution and CO_2 emissions when the direct reduced iron technology and removal devices are used. Furthermore, facilities are capable of achieving these reductions even when the decisions are solely made for $PM_{2.5}$ reductions.

Facing a fixed abatement budget, setting lower CO_2 emission targets could induce more $PM_{2.5}$ pollution and vice versa. To resolve this dilemma, $PM_{2.5}$ mitigation should be prioritized because $PM_{2.5}$ abatement cost is much less than that of CO_2. Therefore, for China’s steel industry, under the constraints of a limited cost budget, policy making towards $PM_{2.5}$ reductions would result in more benefits than focused on CO_2 reduction.

The above analyses are based on the assumption that the advanced technologies (e.g., DRI) will be applied extensively in China. Thus, reducing the cost of these advanced technologies in China is necessary for the co-control of CO_2 emissions and $PM_{2.5}$ pollution, and reducing the cost of low-carbon technology is critically important. While reducing $PM_{2.5}$ pollution is relatively feasible in the short term, reducing CO_2 emissions requires considerable abatement costs. For the iron and steel industry, reducing CO_2 emissions per GDP by 65% will be a rather difficult task. Thus, policy making should focus on co-control strategies for $PM_{2.5}$ and CO_2.

Acknowledgement

This work was supported by funding from the National Natural Science Foundation of China under award nos. 41571130010, 41671491, and 41390240; National Key Research and Development Program of China 2016YFC0206202; and the 111 Project (B14001).

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Figure caption

Figure 1 Technology paths and removal technologies in the iron and steel industry

Figure 2. Technology combinations that correspond to different relative weight factors for CO_2 and $PM_{2.5}$ reductions and cost control. The different colors refer to distinct technology combinations.

Figure 3. Unit cost of different CO_2 and $PM_{2.5}$ intensity targets. Costs increase when the color changes from blue to red.

Figure 4. (a) CO_2 and $PM_{2.5}$ intensity under the different budgets and relative weight factors. (b) Share of technology under the different budgets and relative weight factors. In Figure 4(a), the color of the lines indicates the amount of the budget.

Figure 5. The uncertainty tests on several key parameters in the multi-objective optimization model: (a) the base; (b) SO_2 emission factor; (c) SO_2 to sulfate conversion rate; (d) maximum EAF; (e) cost of $PM_{2.5}$ reduction; (f) carbon tax; (g) interest rate (detailed settings of each parameter are given in Table S1 in the supporting information)

Figure 1

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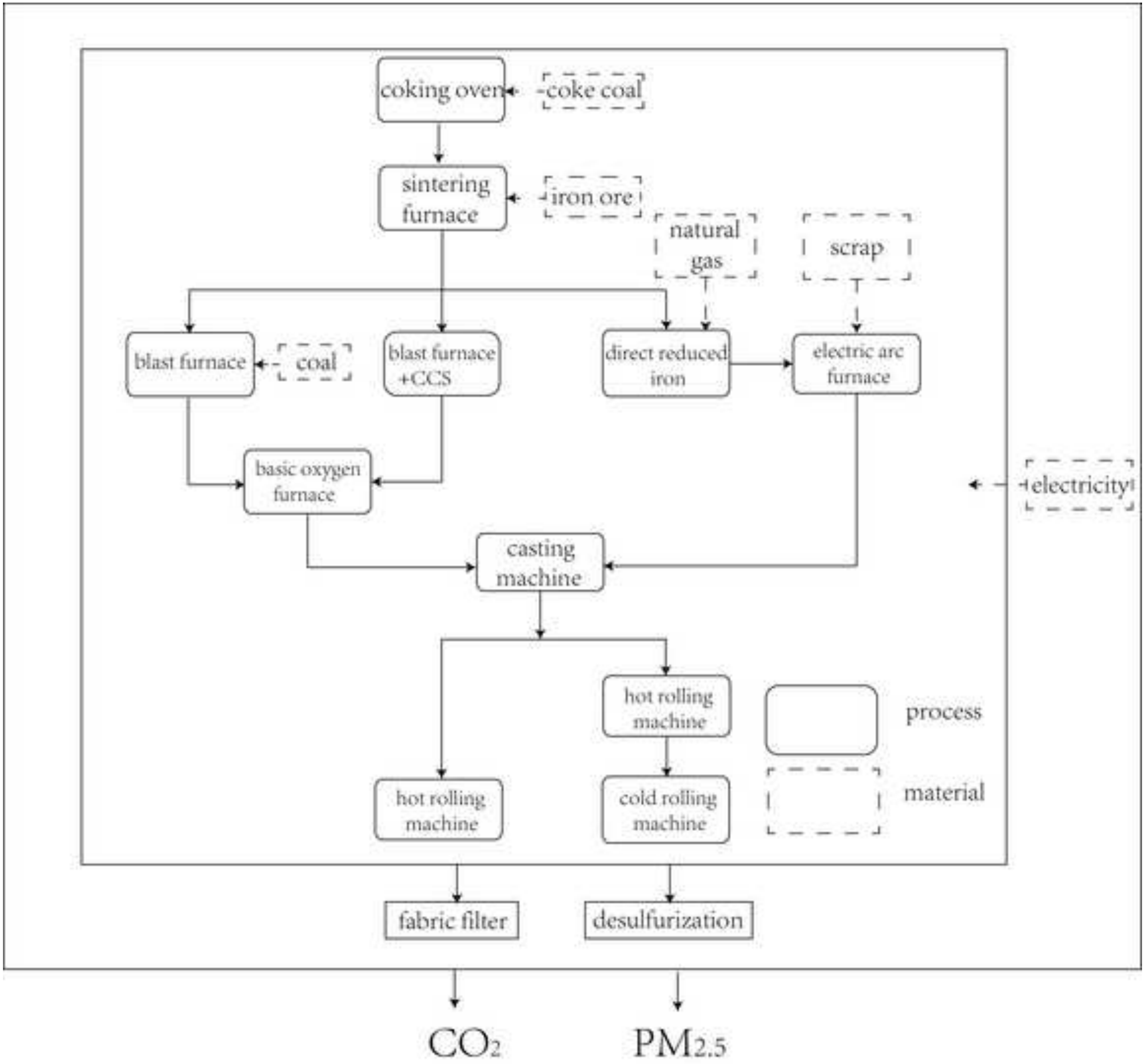

Figure 2

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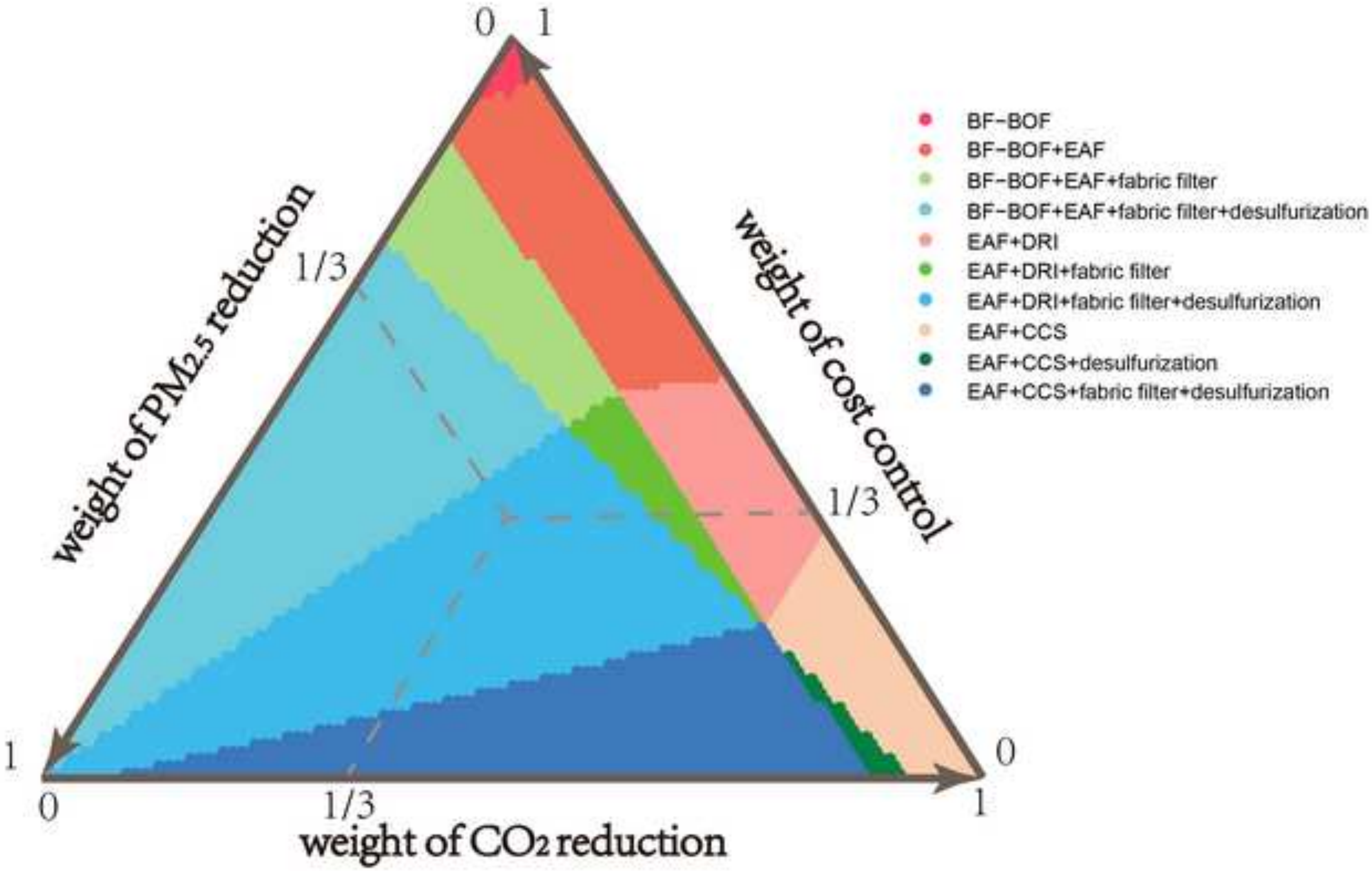
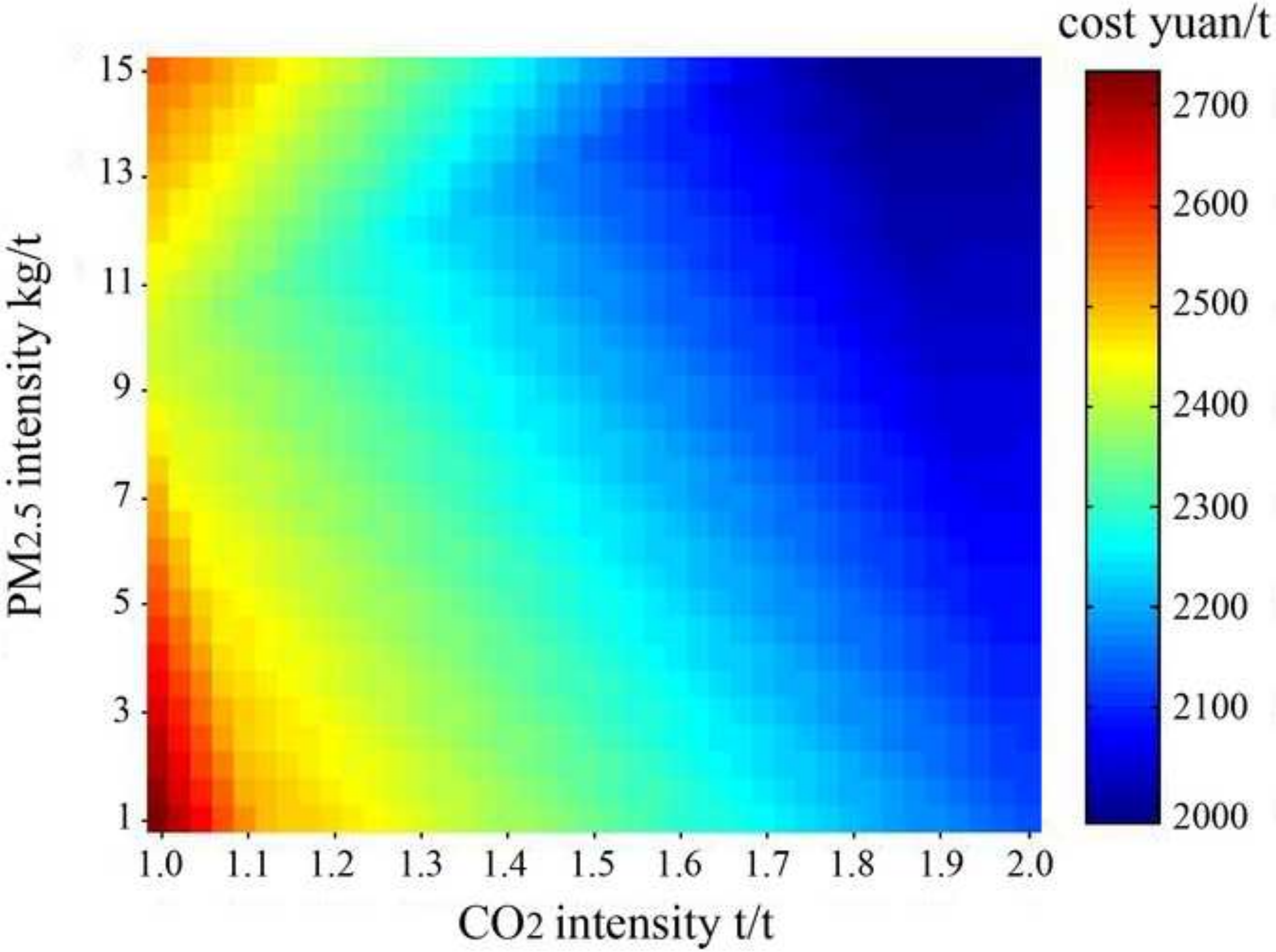


Figure 3


cost yuan/t
2700
2600
2500
2400
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2100
2000
PM2.5 intensity kg/t
15
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11
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1
1.0
1.1
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CO2 intensity t/t

Figure 4

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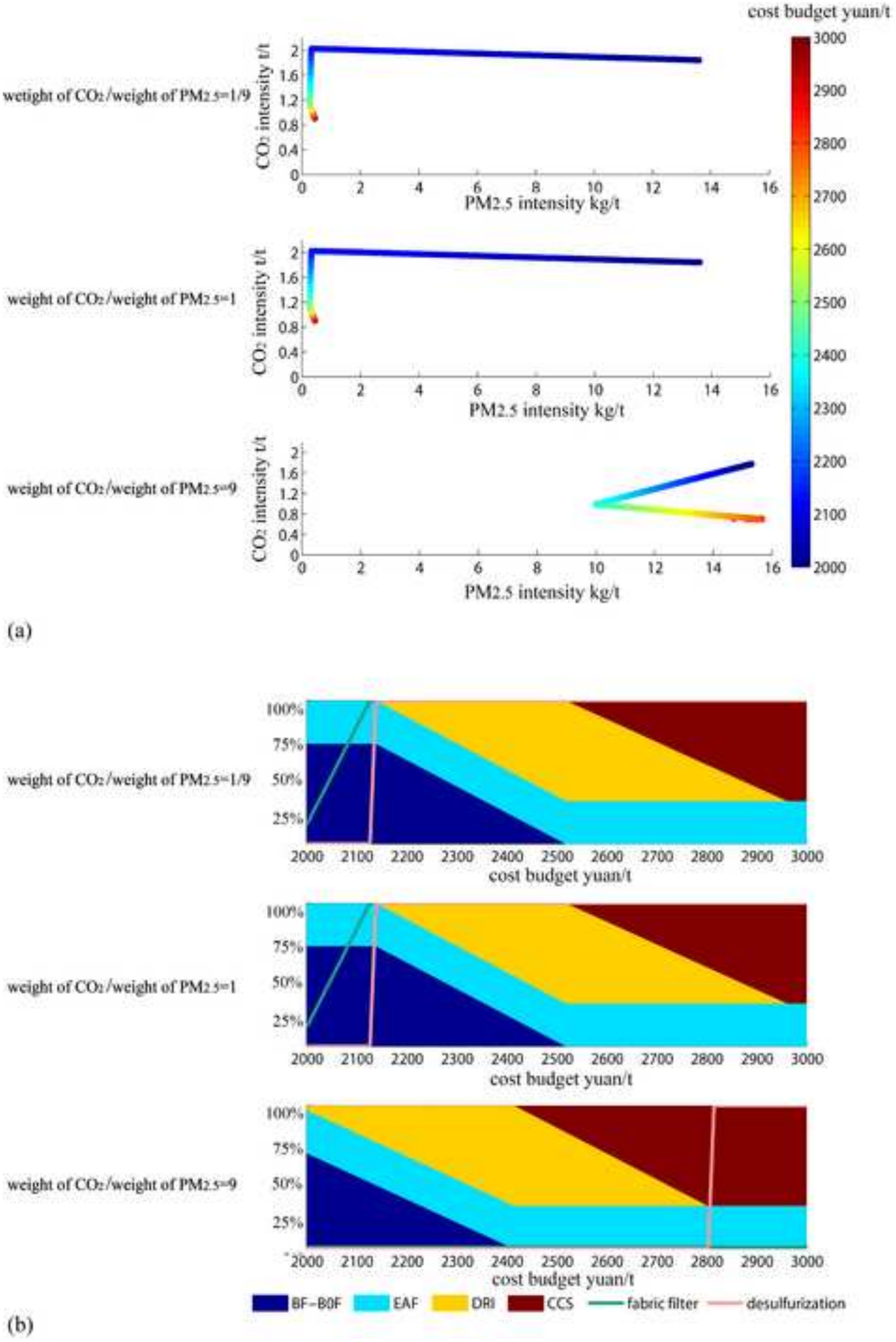
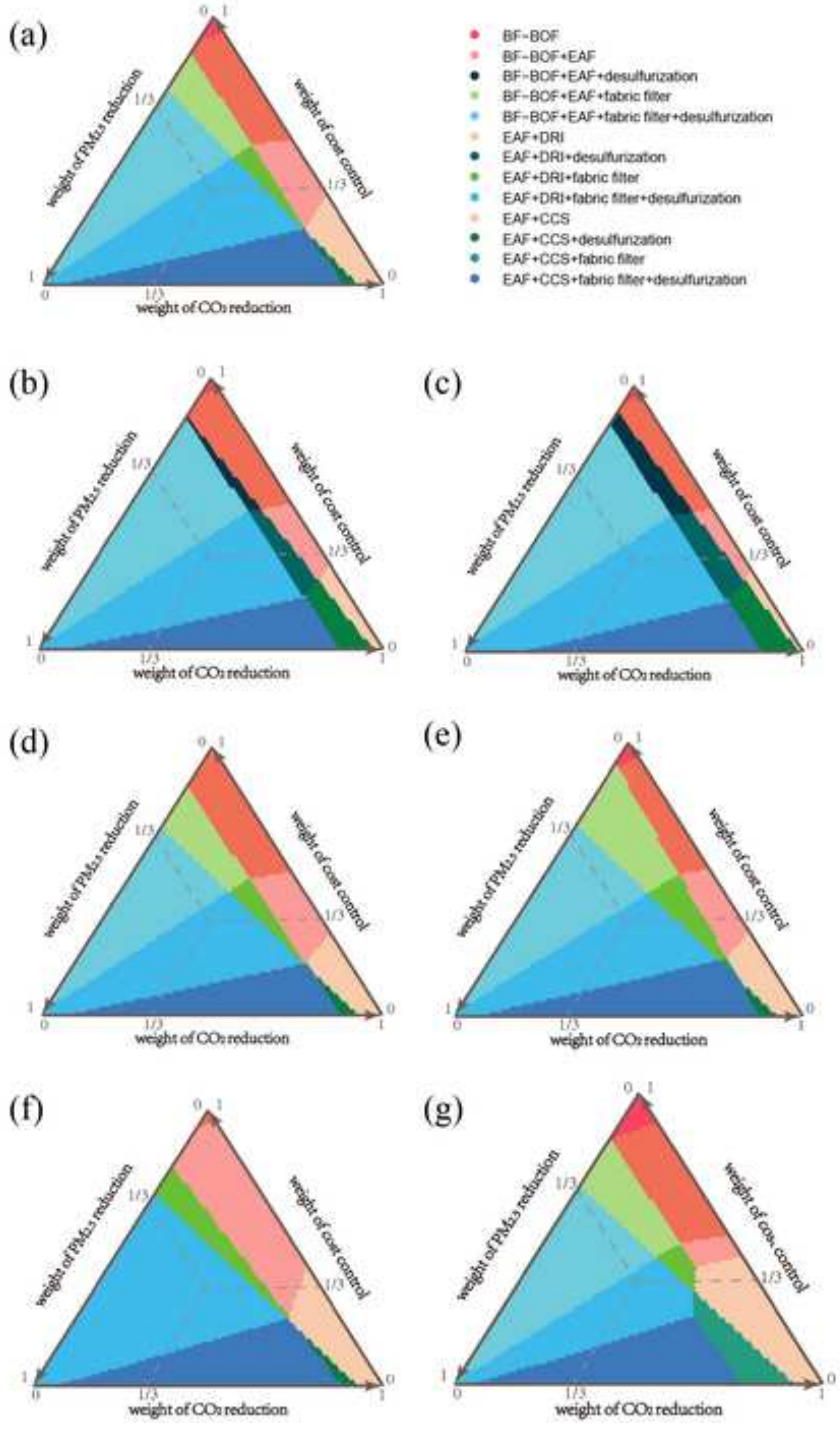


Figure 5


(a)
(b)
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(d)
(e)
(f)
(g)
weight of $PM_{2.5}$ reduction
weight of cost control
weight of CO_2 reduction
0
1
1/3
● BF−BOF
● BF−BOF+EAF
● BF−BOF+EAF+desulfurization
● BF−BOF+EAF+fabric filter
● BF−BOF+EAF+fabric filter+desulfurization
● EAF+DRI
● EAF+DRI+desulfurization
● EAF+DRI+fabric filter
● EAF+DRI+fabric filter+desulfurization
● EAF+CCS
● EAF+CCS+desulfurization
● EAF+CCS+fabric filter
● EAF+CCS+fabric filter+desulfurization

Table 1

Table 1. A summary of technology options used in our model

Category	Technology	Reference
Traditional process	Coke oven	Hu and Jiang (2001)
	Sintering furnace	Hu and Jiang (2001)
	Blast furnace	Hu and Jiang (2001)
	Electric arc furnace	Hu and Jiang (2001)
	Basic oxygen furnace	Hu and Jiang (2001)
	Casting	Hu and Jiang (2001)
	Hot rolling	Hu and Jiang (2001)
	Cold rolling	Hu and Jiang (2001)
Efficiency improvement	Coke dry quenching	Hu and Jiang (2001)
	Top-pressure recovery turbine	Hu and Jiang (2001)
	Recovery of BOF gas	Hu and Jiang (2001)
	Continuous casting	Hu and Jiang (2001)
System optimization	Direct reduced iron	Baig (2016)
Carbon capture	Carbon capture & storage	Kuramochi et al. (2012)
Pollutant removal	Fabric filter	Ma et al. (2016)
	Desulfurization	Ma et al. (2016)

Table 2

Table 1. Emission factors and costs of the technology paths (per ton of finished steel product) and removal technologies (per ton of SO_2 and $PM_{2.5}$)

	CO_2 (including electricity) t/t	Primary $PM_{2.5}$ kg/t	Cost yuan/t	SO_2 kg/t	Indirect SO_2 from electricity kg/t	Indirect primary $PM_{2.5}$ from electricity kg/t
BF-BOF	2.38	18.18	1954	8.23	0.78	0.05
EAF	0.49	7.09	2043	0.35	0.44	0.03
DRI	1.20	10.25	2575	8.07	0.68	0.05
CCS	0.78	18.18	3129	8.23	1.38	0.09
Desulfurization	1.78		5280			
Fabric filter	14.54		9860			

Table 3

Table 2. Emission factors (per ton of steel product), unit costs (per ton of steel product) and share of the technologies in different technology combinations.

	$PM_{2.5}$ kg/t	CO_2 t/t	Cost yuan/t	BF-BOF	EAF	DRI	CCS	Fabric filter	Desulfurization
1	19.09	2.38	1954	100%	0	0	0	0	0
2	15.55	1.81	1981	70%	30%	0	0	0	0
3	0.80	2.02	2127	70%	30%	0	0	100%	0
4	0.32	2.02	2138	70%	30%	0	0	100%	100%
5	9.98	0.99	2415	0	30%	70%	0	0	0
6	0.74	1.12	2507	0	30%	70%	0	100%	0
7	0.27	1.12	2518	0	30%	70%	0	100%	100%
8	15.67	0.69	2803	0	30%	0	70%	0	0
9	15.19	0.70	2815	0	30%	0	70%	0	100%
10	0.44	0.90	2961	0	30%	0	70%	100%	0

1.BF-BOF; 2.BF-BOF+EAF; 3.BF-BOF+EAF+fabric filter; 4.BF-BOF+EAF+fabric filter+desulfurization;

5. EAF+DRI; 6.EAF+DRI+fabric filter; 7. EAF+DRI+fabric filter+desulfurization;

8.EAF+CCS; 9. EAF+CCS+desulfurization; 10. EAF+CCS+fabric filter+desulfurization