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RESEARCH ARTICLE

Analyzing and forecasting CO_2 emission reduction in China’s steel industry

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Abstract Recent measures of carbon dioxide emissions from the steel industry of China have indicated a high rate of total CO_2 emissions from the industry, even compared to the rest of the world. So, CO_2 emission reduction in China’s steel industry was analyzed, coupling the whole process and scenarios analysis. First, assuming that all available advanced technologies are almost adopted, this study puts forward some key potential-sectors and explores an optimal technical route for reducing CO_2 emissions from the Chinese steel industry based on whole process analysis. The results show that in the stages of coking, sintering, and iron making, greater potential for reducing emissions would be fulfilled by taking some technological measures. If only would above well-developed technologies be fulfill, the CO_2 emissions from 5 industry production stages would be reduced substantially, and CO_2 emissions per ton of steel could be decreased to 1.24 (ton/ton-steel) by 2020. At the same time, the scenarios analysis indicates that if mature carbon-reducing technologies are adopted, and if the difference between steel output growth rate and the GDP growth rate could be controlled below 3%, CO_2 emissions from China’s steel industry would approach the goal of reducing CO_2 emissions per GDP unit by 40%–45% of the 2005 level by 2020. This indicates that the focus of carbon dioxide emissions reduction in China lies in policy adjustments in order to enhance technological application, and lies in reasonably controlling the pace of growth of GDP and steel output.

Keywords CO_2 emission, whole-process, scenario analysis, Chinese steel industry, ecological industry

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1 Introduction

In 2009, China experienced rapid growth (13.51%) in the Gross Domestic Product (GDP). This was associated with increased production from the steel industry. In the same year, CO_2 emissions from the steel industry were approximately 1.2 billion tons, accounting for 16% of China’s total CO_2 emissions (National Bureau of Statistics, 2010). At the United Nations (UN) Climate Change Conference in 2009, China promised to cut CO_2 emissions per GDP unit by 40%–45% of the 2005 level by 2020 (The United Nations Climate Change Conference, 2009). Associated with this commitment, CO_2 emissions from the steel industry in China are also required to decrease from 2005 levels by 40%–45%. CO_2 emissions have not only become a focus in China, they have also gained widespread interest worldwide because of the role that CO_2 emissions play in global warming.

Internationally, reducing CO_2 emissions from the steel industry using various methods has been studied extensively (Worrell et al., 1997; Fan et al., 2007; İpek Tunç et al., 2007; Agnolucci et al., 2009). In Japan and Germany, the analysis of CO_2 emission reductions was attempted using a steel strategic process model and a top-down analysis (Worrell et al., 2001; Kim and Worrell, 2002; Ozawa et al., 2002). Recently, Lawrence Berkeley National Laboratory forecasted CO_2 emission reduction potentials based on steel quantities and product and energy structures (Jürgen, 2010). Also, a number of CO_2 emission reduction strategies have been developed for other industries, such as the Japanese petrochemical industry (Gielen et al., 2002; Gielen, 2003), and the European Union’s (EU) and Thailand’s cement industries (Hasanbeigi et al., 2010; Moya et al., 2011).

In China, studies of CO_2 emission reduction strategies for the steel and other industries, and different regions and cities have been performed. Some different methods were used to study a low-carbon model at the regional and city-levels, including 30 provincial capital cities in China and so on (Chen and Chen, 2011; Zhang et al., 2011a, b; Feng et al., 2013). Some studies analyzed CO_2 emission reduction mechanisms and source of greenhouse gas emissions in China (Price et al., 2002; Chen and Zhang, 2010; Li et al., 2012; Wu et al., 2012). The potential and future state for reducing CO_2 emissions were analyzed and forecasted in China's other industries including the synthetic ammonia industry (Zhang et al., 2012b), corn ethanol production (Yang and Chen, 2013), and Macao's gaming industry (Li et al., 2014). Studies have identified CO_2 emission reduction mechanisms and the potential for the steel industry's using energy-saving system theory (Lu et al., 1996; Sun, 1998; Hu et al., 2006; Oda et al., 2007; Sun et al., 2011; Hasanbeigi et al., 2013) and also based on energy policy perspectives (Xia et al., 2011). Using life cycle inventories and an analytical framework, a number of main factors were proposed including a model of energy consumption (Sha et al., 2008), research technologies transfer (Ang, 2009), and the relationships among CO_2 reduction practices, determinants, and performance (Zhang et al., 2012a).

In regulations of carbon emission and control, China had already drawn up some laws such as the Electricity Law of the People's Republic of China, the Law of the People's Republic of China on the Coal Industry, and the Law of the People's Republic of China on Conserving Energy, which were some important laws on low-carbon emissions and were carried out in the 1990s (Standing Committee of the National People's Congress, 1995, 1996, 1997). Soon afterwards some more major laws such as the Law of the People's Republic of China on Promoting Clean Production, the Renewable Energy Law of the People's Republic of China, and the Circular Economy Promotion Law of the People's Republic of China, which promoted low-carbon economic development, seriously required improving product technologies, and adjusting energy structures and related measures. Recently some laws on low-carbon development were revised according to requirements and changes of economy and societal development (Standing Committee of the National People's Congress, 2002, 2005, 2008; Zhao, 2012).

Some studies have been performed on the prediction of CO_2 emissions from the Chinese steel industry, mainly based energy consumption, energy-technologies, and related policy changes (Yang and Liu, 2002; Wang et al., 2007; Wen et al., 2014).These studies have provided some suggestions for reducing CO_2 emissions from China, but China's iron and steel industries are significantly different from those in other countries, particularly because of the rapid development of the steel industry and the application mechanisms for CO_2 emission reduction technologies.

In China the steel industry is undergoing extensive growth. In 2011, steel output from China was 685 million tons, accounting for 45.5% of global steel output (National Bureau of Statistics, 2012). From 2000 to 2007, the growth rate of steel production peaked at 21.7% (National Bureau of Statistics, 2012), which further increased the proportion of CO_2 emissions from the steel industry to total Chinese CO_2 emissions. Another characteristic of the Chinese steel industry was that it was a low-benefit, high-pollution industry and there had been no substantial decrease in CO_2 emissions over the past 20 years. Presently, CO_2 emissions per ton of steel range from 2–5 t/t-s (t-s means t-steel) in China, while in more developed countries this value was approximately 1.7 t/t-s using traditional blast furnace processes in 2008, and only 0.4 t/t-s when the electric furnace process was used (Polenske and McMichael, 2002). The other side of this story is that numerous well-developed energy-saving and carbon-reducing technologies are not adopted due to an absence of related governmental incentives. For example, current policy is inadequate in punishment and constraint for CO_2 emissions from companies, and it is lacking in rewards for carbon-reducing. Furthermore, the high annual amount of steel output has also caused this situation to deteriorate.

2 Theory and methodology

Now, integrating the characters and needs of the Chinese steel industry, we will analyze some major factors that influence CO_2 emission reduction based on an evolution equation (see Eq. (1)).

$$\begin{aligned} T_{ns} &= \frac{C_{ns}}{IG_{ns}} = \frac{P_{ns}\times\dfrac{C_{ns}}{P_{ns}}}{IG_{ns}} = \frac{P_{ns}\times c_{t-s}}{IG_s} \\ &= \frac{P_{0s}(1+p)^n\times c_{t-s}}{IG_{ns}} = \frac{P_{0s}(1+p)^n\times c_{t-s}}{IG_{0s}(1+g_s)} \\ &= \frac{P_{0s}(1+g+x)^n\times c_{t-s}}{IG_{0s}(1+g_s)}, \end{aligned} \tag{1}$$

where, T_{ns} represents the carbon emissions intensity of n year, namely, CO_2 emissions per unite steel output; C_{ns} is CO_2 emission in the Chinese steel industry; IG_{ns} represents the value of the steel industry in n year; P_{ns} demonstrates crude steel output; $c_{t\text{-}s}$ refers to CO_2 emissions per ton steel; p represents the average annual growth rate of steel output; g_s represents the average annual growth rate of IG_s; IG_{0s} and P_{0s} represent the GDP value of the steel industry and crude steel output in the base year, respectively; g represents the average annual growth rate of GDP; x is the relationship variable between the growth rate of crude steel and the growth rate of GDP (that is, $p = g + x$), which will then be used below to establish the scenario model (Song et al., 2011).

According to Eq. (1), CO_2 emission in the steel industry was affected by the growth rate of crude steel output, CO_2 emissions per ton steel, and economic development rate.

At the micro-scale, CO_2 emissions per ton steel (ct-s) were analyzed using whole-process analysis to accurately identify major sectors and corresponding technologies that would be easily implemented. At the macro-scale, crude steel output in China was analyzed using scenario analysis in order to obtain total CO_2 emissions from the Chinese steel industry, and to highlight suggestions for coordinating relationships between national economic (g) and steel industry developments (p).

2.1 Whole-process analysis

Similar to material flow analysis, whole-process analysis considers the internal relationships and external factors governing different production stages in the whole production process of certain products, and determines the main factors affecting the product over the whole process (Lu, 2006; Gao et al., 2011).

As shown in Fig. 1, Stages 1, 2, …, n represent different production stages in the steel industry; while α, β, γ and δ represent technologies or factors that have impacts on energy savings and carbon reduction during certain production stages of the steel industry. The production process can be divided into several stages that could be affected by different external or internal factors. By comparing the effects of those factors during all stages of the whole process, whole-process analysis can identify the major factors that will provide the most benefit if they are implemented. In general, from whole-process analysis, the work flow of steel production can be divided into six stages: coking, sintering, iron making, steel making, steel rolling, and end-treatment. Data from 2009 showed that CO_2 emissions from the Chinese steel industry came mostly from coking (4%), sintering (6%), and iron-making (46%) in the production process (Zhang, 2009).

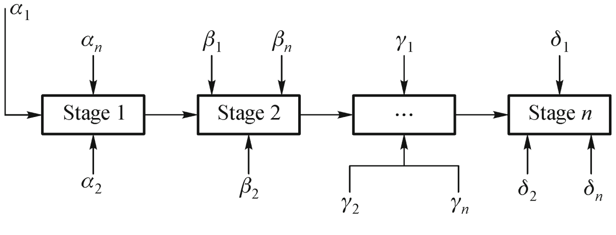

Fig. 1 Model of whole-process analysis.

In each stage, diverse carbon reduction technologies can be applied. For instance, Coke Dry Quenching (CDQ) and Coal Moisture Control (CMC) can be applied in the coking stage. CO_2 emissions can be reduced by 105 kg/t if CDQ is adopted. However, in China CDQ was used by only 40% of the steel industry. CMC can reduce CO_2 emissions by 48 kg/t, but was only used by 10% of the industry. In the sintering stage, the sensible heat from the sintering mine was far from being used fully, causing resource waste and an increase in CO_2 emissions. If sensible heat recovery technology were fully adopted, CO_2 emissions could be reduced by 11 kg/t-s. In the iron-making stage, the main energy-saving technology was Top Gas Recovery Turbine (TRT), which potentially reduces CO_2 emissions by 30 kgCO_2/t-iron (Lu et al., 1996; Sun, 1998; Oda et al., 2007; Sha et al., 2008; Sun et al., 2011). In the steel-making stage, converter gas recovery and electric furnace steel can both achieve considerable carbon reductions. In the steel-rolling stage, regenerative heating furnaces and rolling-slab hot charging can be used to save energy. Finally, in the end-treatment stage, the focus is on enhancing the full usage of resources. For example, technologies including by-product gas generation, blast furnace cement, slag cement, and vegetation carbon-fixation can all reduce CO_2 emissions significantly.

Overall, matured-technologies that can fulfill the potential for CO_2 emission reductions in the Chinese steel industry include CDQ, CMC, sinter residual-heat recovery, arc-furnace steel and blast furnace cement, and so on, as shown in Fig. 2. Also, in the figure, the unit of t-ps refers to the unit of weight of plastic scrap.

2.2 Scenario analysis

Scenario analysis describes possible future scenarios and forms an overall estimate by linking all related predictions produced under different scenarios. This analysis can provide a whole-view description and allow for timely adjustments if the monitored factors change. In this study, steel output and CO_2 emissions per ton of steel were analyzed and predicted in order to calculate the potential for reductions of CO_2 emissions from the Chinese steel industry.

The scenario model was established based on four scenarios. In each scenario, changes in two parameters (GDP and steel output growth rates) at different stages produced a model for the future.

In scenarios I and II, the time stages used were 2010–2015 and 2016–2020, respectively. The parameters g_1 and g_2 represent the annual average GDP growth rate from 2010 to 2015 and from 2016 to 2020, respectively. In each of the four scenarios, p represents the average annual growth rate of steel output from 2010 to 2020. In order to analyze the outcomes more accurately and to analyze the effect from steel output on carbon-emissions in scenarios III and IV, time stage was extended to include three stages (2000–2010, 2011–2015, and 2016–2020). At the same time, in the results, the time of controlling steel output should be discussed. In both scenarios, g_0 represents the actual GDP growth rate in the 2000–2010 stage, and g_1 and g_2 are the same as in scenarios I and II. At the same time, we assumed g_s and g were constant in all scenarios, considering that the economy of industries should keep in step with the general economy in China. The scenario model was set up as shown in Fig. 3.

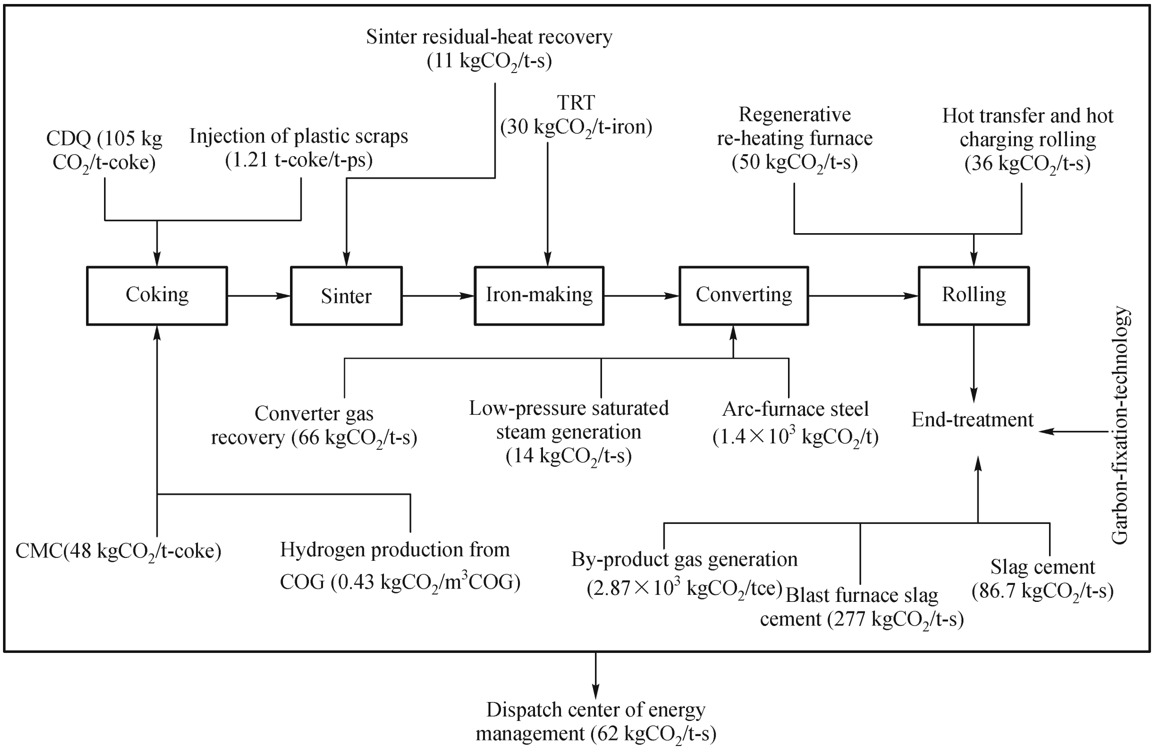

Fig. 2 Technical route and key points for CO_2 emission reduction in the steel industry.

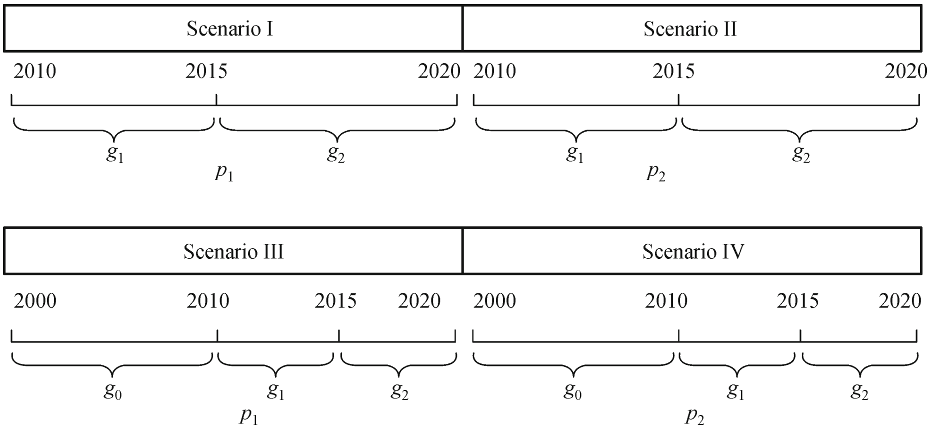

Fig. 3 Model of scenario analyses.

3 Results and discussion

3.1 Improving the use of carbon-reducing technologies

From whole-process analyses, achieving carbon reductions in the Chinese steel industry requires the widespread use of carbon-reducing technologies. Based on statistics for the use of related technologies (Song et al., 2011) and understanding the energy savings for typical steel enterprises, the highest usage-rate of these technologies could be ensured (Table 1).

According to the technical route shown in Fig. 2 and the usage shown in Table 1, this study predicted CO_2 emissions per unit product from different stages of steel production and predicted CO_2 emissions per ton of steel for typical steel enterprises in China by 2020.

Table 2 shows that in agreement with the technical route and the expected usage, the CO_2 emissions per unit of steel can be significantly reduced by 2020. In Table 2, virtual CO_2 emissions were calculated using CO_2 emissions minus the carbon-fixation per ton of steel, which can be obtained from Eq. (2):

$$CF_{\text{steel}} = (V_a \times C_v)/P, \tag{2}$$

Table 1 CO_2 reduction forecasts and usage of CO_2 emissions reduction technologies in the steel industry

Technologies	2005		2010		2015		2020	
	CO_2 reduction effect /(kg·(t-s)$^{-1}$)	Usage rate/%	CO_2 reduction effect /(kg·(t-s)$^{-1}$)	Usage rate/%	CO_2 reduction effect /(kg·(t-s)$^{-1}$)	Usage rate/%	CO_2 reduction effect /(kg·(t-s)$^{-1}$)	Usage rate/%
CDQ	6.678	15.9	16.8	40.0	29.408	70.0	37.808	90.0
CMC	0	0	1.92	10	3.84	20.0	7.68	40.0
TRT	22.5	75.0	24	80.0	26.78	90.0	29.63	100
Converter gas recovery	24.75	37.5	29.7	45.0	53.66	66.7	76.73	90.0
Regenerative re-heating furnace	5	10.0	12.5	25.0	20	40.0	30	60.0
Hot transfer and hot charging rolling	10.8	30.0	16.2	45.0	21.6	60.0	28.8	80.0
Sinter residual-heat recovery	1.1	10	2.2	20	3.3	30	5.5	50
Low-pressure saturated steam generation	0.42	3	1.4	10	2.1	15	2.8	20
Dispatch center of energy management	4.03	6.5	9.3	15	18.6	30	37.2	60
Blast furnace slag cement	277.5	75	221.6	80	249.3	90	277	100
Slag cement	6.936	8	13.005	15	17.336	20	21.676	25
Arc-furnace steel	163.8	11.7	182	13	210	15	280	20

Table 2 CO_2 emissions per product in different process of steel enterprises

Year	Coking /(kg·t^{-1})	Sintering /(kg·t^{-1})	Iron-making/(kg·t^{-1})	Converting/(kg·t^{-1})	Rolling /(kg·t^{-1})	CO_2 emission /(t·(t-s)$^{-1}$)	Carbon-fixation per ton steel/(t·(t-s)$^{-1}$)	Virtual CO_2 emissions/(t·(t-s)$^{-1}$)
2005	366.47	162.05	1139.30	89.75	221.88	1.979	0.168	1.812
2020	279.91	136.99	1023.75	8.08	143.75	1.237	0.039	1.198

where, CF_{steel} is the carbon-fixation per ton of steel; V_a represents the area of green vegetation (approximately 100,000 km^2); C_v is the amount of CO_2 emissions from the steel industry absorbed by green vegetation per square kilometers (15,047 t/km^2) which occupy 30% in total absorption capacity; and P is the crude steel output.

Table 2 shows that the reduction of virtual CO_2 emissions per ton of product in every stage was particularly obvious in the converter steel-making stage, which should be targeted for further application of converter gas and steam recovery technologies. These results also demonstrate that a huge potential for CO_2 emission reductions exists in converter steel making and iron-making.

Overall, some policies are required to guarantee the application of technologies for saving energy or reducing CO_2 emissions. For example, rules and regulations could be established for punishing or constraining CO_2 emissions from companies that would provide rewards for reducing carbon emissions. Another policy that could be adopted is economic encouragement, where the government cuts taxes if a steel company accomplishes its task of reducing CO_2 emissions, guaranteeing that the company's benefits far outweigh their costs. Finally, more technologies for saving energy or reducing CO_2 emissions should be publicized by government departments.

3.2 Establishing a scenario model

The four scenarios used in the scenario model described in Section 2.2 were:

Scenario I: According to the 12th Five-year Plan Scheme for China, g_1 and g_2 were 7% and 4%, respectively. Based on the industrialization experiences of the United States and Japan, p_1 is normally 3% higher than the GDP growth rate, that is to say, $p_1 = g + 3\%$.

Scenario II: Values of g_1 and g_2 were the same as those in scenario I. The gap between p_2 and g was 7% based on the situation in China over the past decade, that is, $p_2 = g + 7\%$.

Scenario III: The parameter g_0 was the actual GDP growth rate in China from 2000 to 2010 (China Steel Industry Association Code, 2010) and the values of g_1 and g_2 were the same as those in scenario I. The growth rate of steel output (p) from 2000 to 2020 was calculated based on $p_1 = g + 3\%$, which was matched based on the empirical relationship between p and g from some developed countries, especially for use during the process of industrialization in countries such as the United States, Japan, and Germany, etc.

Scenario IV: The parameter g_0 was the actual GDP growth rate in China from 2000 to 2010 and the values of

g_1 and g_2 were the same as those in scenario I. The growth rate of steel output (p) from 2010 to 2020 was calculated based on $p_2 = g + 7\%$. The scenario from 2011 to 2020 was analyzed in the same way as scenario II.

In the four scenarios, the gross value of the steel industry output was obtained from its proportion to the GDP. Based on the different scenarios presented, CO_2 emissions per unit of steel and crude steel production, and CO_2 emissions from the steel industry per unit of gross value, the calculated results from the four scenarios are presented in Table 3. In Table 3, the index of "decreased rate compared with 2005" represents the decreased rate of CO_2 emissions from the steel industry per unit of gross value in each year compared with 2005. Negative signs indicate that CO_2 emissions increased.

As shown in Table 3 and Figs. 4 and 5, in scenario I, CO_2 emissions per unit output values from the steel industry in 2010, 2015, and 2020 were reduced by 25.56%, 26.30%, and 33.99%, respectively, when compared with the values in 2005. Under these scenarios, a large gap would still exist for the 40%–45% emissions reduction committed to by China (State Council Office, 2009). In 2020 the crude steel production would be up to 1,415.61 million tons which would make environment, resources, and energy more deteriorated or depleted. The main cause of this shortfall would be the extensive growth of steel output in China, and it is found that the current mode of steel industry development is an unfeasible path for China.

In scenario II, CO_2 emissions per unit GDP output values for the steel industry in 2010, 2015, and 2020 were 5.358, 6.342, and 6.824 tons of CO_2 per thousand dollars, respectively. CO_2 emissions per unit GDP output would increase, which could be attributed to unsuccessful energy-saving technologies and the rapid growth of the economy. In 2020, CO_2 emissions from the steel industry would decrease by 5.19%, which is not compatible with the commitment of China to widespread energy-saving technologies and the reduction of CO_2 emissions. These results are also related to the extensive rapid growth of the economy in China, which produced much more crude steel to support the rising economy. Scenario II is an unfeasible path for the Chinese steel industry in the future.

In scenario III, CO_2 emissions per unit GDP output value for the steel industry in 2010, 2015, and 2020 were reduced by 17.92%, 18.74%, and 27.22%, respectively, when compared with 2005. Although this result still is not in agreement with the goals of CO_2 emission reductions in China, it is closer to the goal than that in scenario II, and the crude steel production would be 998.78 million tons, which is less than that in scenario I. In scenario III, the objective of reducing carbon will be approached under the condition where some major measure should be carried out as early possible, including controlling steel output, and strengthening carbon emission management.

In scenario IV, CO_2 emissions per unit output values for the steel industry in 2010 and 2020 were decreased by 2.53% and 11.26%, respectively. CO_2 emissions in 2015 actually increased by 15.37% compared with 2005. Under this scenario, the goals set for CO_2 emission reductions could not be met by the end of 2020.

Overall, to achieve the goal of 40%–45% reduction in CO_2 emissions by 2020, differences between the steel

Table 3 CO_2 emissions forecast of the Chinese steel industry

Scenario	Year	Index				
		GDP /(10^{12}\$)	Crude steel production /(10^6 t)	CO_2 emissions per ton steel/($t \cdot (t\text{-}s)^{-1}$)	CO_2 emission per unit gross value of steel industry output/($t \cdot 10^{-3}$ \$)	Decrease rate compared to 2005/%
Scenario I	2005	2.26	353.2	1.812	7.198	
	2010	5.36	626.7	1.513	5.358	25.56
	2015	7.52	1009.31	1.384	5.305	26.30
	2020	9.15	1415.61	1.198	4.751	33.99
Scenario II	2005	2.26	353.2	1.812	7.197	
	2010	5.36	626.7	1.513	5.358	25.56
	2015	7.52	1206.66	1.384	6.342	11.89
	2020	9.15	2033.29	1.198	6.824	5.19
Scenario III	2005	2.26	226.02	1.812	4.606	
	2010	5.36	442.17	1.513	3.78	17.92
	2015	7.52	712.12	1.384	3.743	18.74
	2020	9.15	998.78	1.198	3.352	27.22
Scenario IV	2005	2.26	269.29	1.812	5.488	
	2010	5.36	625.65	1.513	5.349	2.53
	2015	7.52	1204.64	1.384	6.331	– 15.37
	2020	9.15	1445.18	1.198	4.85	11.62

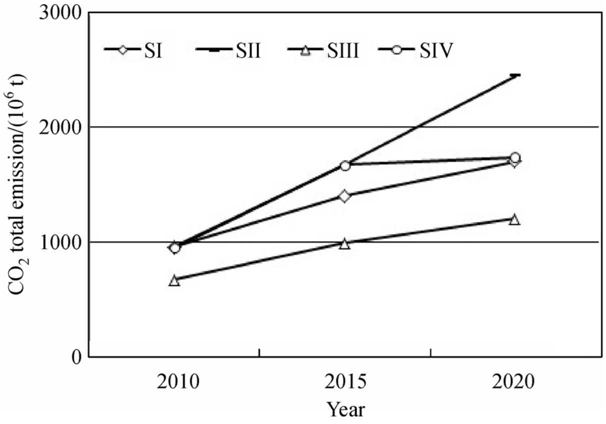

Fig. 4 CO_2 total emissions of the Chinese steel industry from 2010 to 2020.

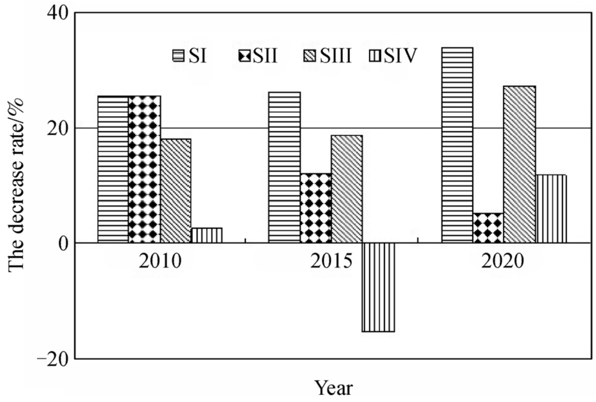

Fig. 5 The decrease rate for CO_2 emissions per unit GDP of the steel industry in China from 2010 to 2020.

output growth rate and the GDP growth rate should be maintained below 3%. In scenario I and scenario III CO_2 emissions per unit output values for the steel industry in 2020 were decreased by 33.99% and 27.22%, respectively. Both scenarios were close to the goal, but in scenario I the steel output of China would reach 1,415.61 million tons by 2020, which does not meet the requirement of environmental capacity; and in scenario III, the steel output of China would reach 998.78 million tons by 2020, which would be corresponding to the request for economic development at present. Therefore, scenario III has the highest feasibility for the Chinese steel industry. To ensure the achievement of this scenario, China should control steel output immediately and take economic or administrative measures to enhance usage technologies for reducing carbon.

4 Conclusions

Based on the calculations and analyses presented, two measures should be introduced in the Chinese steel industry to reduce CO_2 emissions. These measures are the reduction of CO_2 emissions per unit of steel output, and controlling the rapid growth rate of the economy in China. This study applied whole-process and scenario analyses to forecast CO_2 emission reduction potentials for the Chinese steel industry.

Whole-process analysis indicated that the main technologies with potential to reduce CO_2 emissions in the future were CDQ, CMC, sinter residual-heat recovery, arc-furnace steel, and blast furnace cement. Scenario analysis showed that the difference between the steel output growth rate and the GDP growth rate should be maintained below 3%, and that the growth of the GDP and steel output should be slowed reasonably. Both results indicate that these measures can not only help to approach the goal of 40%–45% less CO_2 emissions by 2020 (compared with 2005) as committed to by China, they would also provide for economic development in the steel industry, where China's steel output is expected to reach 998.78 million tons by 2020.

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