PEER-REVIEWED PAPER

Why the energy use of Chinese steel industry may peak as early as 2015?

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Keywords
decomposition, energy consumption, iron and steel industry, technology structure, energy intensity forecast

Abstract
The iron and steel industry accounted for approximately 27 % of China's primary energy use for the manufacturing industry in 2010. This study aims to analyze influential factors that affected the energy use of steel industry in the past in order to quantify the likely effect of those factors in the future. This study analyzes the energy use trends of China's key medium- and large-sized steel enterprises during 2000–2030. In addition, the study uses a refined Logarithmic Mean Divisia Index decomposition analysis to quantify the effects of various factors in shaping energy consumption trends in the past and in the future. The result of our forecast shows the final energy use of the key steel enterprises peaks in year 2020 under scenario 1 and 2 (low and medium scrap usage) and in 2015 under scenario 3 (high scrap usage). The three scenarios produced for the forward-looking decomposition analysis for 2010–2030 show that contrary to the experience during 2000–2010, the structural (activity share of each process route) effect and the pig iron ratio (the ratio of pig iron used as feedstock in each process route) effect plays an important role in reducing final energy use during 2010–2030.

Introduction
Production of iron and steel is an energy-intensive manufacturing process. In 2010, the iron and steel industry accounted for around 27 % of primary energy consumption of Chinese manufacturing (NBS, 2011). The energy efficiency of steel production has a direct impact on overall energy consumption and related emissions of carbon dioxide (CO_2) and other air pollutants.

China is a developing country and is currently in the process of industrialization. The iron and steel industry, as a pillar industry for Chinese economic development, has grown rapidly along with the national economy. Starting in the 1990s, the industry development accelerated, with crude steel production in 1996 exceeding more than 100 million metric tonnes (Mt). Since then, steel production in China has continued to increase rapidly, and China has been the world's largest crude steel producer for 16 continuous years. The average annual growth rate of crude steel production was around 18 % between 2000 and 2010. China's steel production in 2010 consumed around 461 TWh of electricity and 14,872 PJ of fuel (NBS, 2011), and represented 47 % of the world steel production in that year (worldsteel, 2011). For this reason, the development path of China's iron and steel sector will greatly affect future energy demand of not only China.

The Chinese iron and steel industry has made much progress in reducing energy use, starting from energy saving of individual equipment and process energy conservation in the 1980s to systematic energy conservation via process optimization in the 1990s and 2000s. The promotion and application of energy-saving technologies has become an important step for increasing energy efficiency and reducing energy consumption of steel enterprises in China, especially during the 11th Five Year Plan (FYP) (2006–2010) and 12th FYP (2011–2015) (Hasanbeigi et al. 2011).

Throughout this paper all the data presented are for the key medium- and large-sized steel enterprises unless it is noted otherwise. This is primarily because of the fact that process-level energy intensity data that are used in this study are only available for the key medium- and large-sized steel enterprises and not for the entire steel industry. The key medium-sized steel enterprises have 300–2,000 employees with product sales revenue of 30–300 million RMB per year and total assets of 40–400 million RMB. The key large-sized steel enterprises have more than 2,000 employees with product sales revenue of more than 300 million RMB per year and total assets of more than 400 million RMB (SETC/SPC/MoF/NBS, 2003).

It should be noted that the key medium- and large-sized steel enterprises do not represent China's total iron and steel industry. They accounted for 80 and 87 % of the total China's crude steel production in 2005 and 2010, respectively. Also, the key medium- and large-sized steel enterprises do not include small steel enterprises that are often less energy efficient. Thus, the aggregate energy intensity of the key medium- and large-sized steel enterprises tends to be lower than the energy intensity of the entire Chinese steel industry.

This study first analyzes China's key medium- and large-sized steel enterprises' past energy use trends since 2000 and also makes projections for energy use and production up to 2030 for key medium- and large-sized steel enterprises. Then, it uses refined decomposition analysis to quantify the effects of various factors in shaping energy consumption trends in the past and in the near future. Many energy analysts have employed decomposition analysis since the early 1990s. By indexing certain drivers to a base year value, this analysis approach shows how energy consumption would have changed had all other factors been held constant. Decomposition analysis is used to understand the drivers of energy use as well as to measure and monitor the performance of energy-related policies. Most countries of the Organization for Economic Cooperation and Development (OECD) use decomposition analysis to understand their energy use and assess the progress of their energy policies.

Methodology

Since the energy intensity data by process for various years, which are used in this analysis, are only reported for the key medium- and large-sized steel enterprises, all the analyses below are done for these enterprises only. Two major steel production routes, i.e. BF-BOF route and EAF route, are included in this analysis. The share of other types of steel production in China is minimal.

DECOMPOSITION ANALYSIS METHOD

A decomposition analysis separates the effects of key components on energy end-use trends over time. Three main components that are usually considered in a decomposition analysis are: 1) aggregate activity, 2) sectoral structure, and 3) energy intensity. Different studies have used different mathematical techniques for decomposition analysis. Liu and Ang (2003) explain eight different methods for decomposing the aggregate energy intensity of industry into the impacts associated with aggregate activity, sectoral structure, and energy intensity. They argue that the choice of method can be influenced by limitations such as the data set (e.g., whether or not there are negative values) and the number of factors in the decomposition. Ang et al. (2010) propose the use of the Logarithmic Mean Divisia Index (LMDI) method, which is recognized as superior in comparative studies such as Liu and Ang (2003).

In this study, however, we are conducting the decomposition analysis for the iron and steel industry only and not for the entire manufacturing sector. Thus, the decomposition formulas and the factors to be considered must be modified. Based on the availability of the data and important factors that influence steel production energy use, we modified the LMDI decomposition formulas as described below. We considered four major factors that could influence the steel production energy use and we developed the decomposition analysis formulas based on these factors. The factors are:

- *Activity*: Represents the total crude steel production.
- *Structure*: Represents the activity share of each process route (BF-BOF or EAF route).
- *Pig iron ratio*: The ratio of pig iron used as feedstock in each process route. This is especially important for the EAF process because the higher the pig iron ratio in the feedstock of the EAF, the higher the energy intensity of EAF steel production.
- *Energy intensity*: Represents energy use per tonne of crude steel.

Total energy use of the iron and steel industry, then, is represented by:

$$Et = \sum_i E_{PI,i,t} + \sum_i E_{Oth,i,t} \quad (1)$$

Where:

i process route (BF-BOF or EAF route)

t year

$E_{PI,i,t}$ Energy use for production of pig iron used for steel production in process route i in year t,

$E_{Oth,i,t}$ Total energy use for steel production minus the energy use for production of pig iron used for steel production in process route i in year t

Using the basic LMDI decomposition analysis method, we can derive Eq. 2 from Eq. 1:

$$Et = \sum_i Q_{Crude,t} \frac{Q_{Crude,i,t}}{Q_{Crude,t}} \frac{Q_{PI,i,t}}{Q_{Crude,i,t}} \frac{E_{PI,i,t}}{Q_{PI,i,t}} + \sum_i Q_{Crude,t} \frac{Q_{Crude,i,t}}{Q_{Crude,t}} \frac{E_{Oth,i,t}}{Q_{Crude,i,t}} \quad (2)$$

Where:

$Q_{crude,t}$ total crude steel production in year t,

$Q_{crude,i,t}$ crude steel production by process route i in year t

$Q_{PI,i,t}$ pig iron used by process route i in year t

The aggregate change in total final energy consumption of the key medium- and large-sized steel enterprises can be calculated using Eq. 3.

$$\Delta E_{tot} = E^T - E^0 = (\Delta E_{act.PI} + \Delta E_{Str.PI} + \Delta E_{ratio.PI} + \Delta E_{int.PI}) + (\Delta E_{act.Oth} + \Delta E_{Str.Oth} + \Delta E_{int.Oth}) \quad (3)$$

Where:
T last year of the period
T=0 base year of the period
E total final energy consumption of the key medium- and large-sized steel enterprises
ΔE_{tot} aggregate change in total final energy consumption of the key medium- and large-sized steel enterprises

The subscripts "*act*", "*str*", "*ratio*", and "*int*" denote the effects associated with the overall activity level, structure of steel industry (BF-BOF vs. EAF steelmaking), ratio of pig iron used as feedstock to EAF and BOF, and process energy intensity, respectively. To further simplify Eq. 3, we will have:

$$\Delta E_{tot} = \Delta E_{act} + \Delta E_{str} + \Delta E_{ratio} + \Delta E_{int} \quad (4)$$

$$\Delta E_{act} = \Delta E_{act.PI} + \Delta E_{act.Oth} \quad (5)$$

$$\Delta E_{Str} = \Delta E_{Str.PI} + \Delta E_{Str.Oth} \quad (6)$$

$$\Delta E_{shar} = \Delta E_{ratio.PI} \quad (7)$$

$$\Delta E_{int} = \Delta E_{int.PI} + \Delta E_{int.Oth} \quad (8)$$

$$\Delta \text{Eact. PI} = \sum_i \frac{E^T_{PI,i} - E^0_{PI,i}}{\ln E^T_{PI,i} - \ln E^0_{PI,i}} \ln\left(\frac{Q^T_{crude}}{Q^0_{crude}}\right) \quad (9)$$

$$\Delta \text{Estr. PI} = \sum_i \frac{E^T_{PI,i} - E^0_{PI,i}}{\ln E^T_{PI,i} - \ln E^0_{PI,i}} \ln\left(\frac{St^T_i}{St^0_i}\right) \quad (10)$$

$$\Delta \text{Eratio. PI} = \sum_i \frac{E^T_{PI,i} - E^0_{PI,i}}{\ln E^T_{PI,i} - \ln E^0_{PI,i}} \ln\left(\frac{Ra^T_{PI,i}}{Ra^0_{PI,i}}\right) \quad (11)$$

$$\Delta \text{Eint. PI} = \sum_i \frac{E^T_{PI,i} - E^0_{PI,i}}{\ln E^T_{PI,i} - \ln E^0_{PI,i}} \ln\left(\frac{I^T_{PI,i}}{I^0_{PI,i}}\right) \quad (12)$$

$$\Delta \text{Eact. Oth} = \sum_i \frac{E^T_{Oth,i} - E^0_{Oth,i}}{\ln E^T_{Oth,i} - \ln E^0_{oth,i}} \ln\left(\frac{Q^T_{crude}}{Q^0_{crude}}\right) \quad (13)$$

$$\Delta \text{Estr. Oth} = \sum_i \frac{E^T_{Oth,i} - E^0_{Oth,i}}{\ln E^T_{Oth,i} - \ln E^0_{Oth,i}} \ln\left(\frac{St^T_i}{St^0_i}\right) \quad (14)$$

$$\Delta \text{Estr. Oth} = \sum_i \frac{E^T_{Oth,i} - E^0_{Oth,i}}{\ln E^T_{Oth,i} - \ln E^0_{Oth,i}} \ln\left(\frac{I^T_{Oth,i}}{I^0_{Oth,i}}\right) \quad (15)$$

$$Q_{crude} = \sum_i Q_{crude,i} \text{: total activity level} \quad (16)$$

$$St_i = \frac{Q_{crude,i}}{Q_{crude}} \text{: activity share of process route i} \quad (17)$$

$$Ra_i = \frac{Q_{PI,i}}{Q_{crude,i}} \text{: ratio of pig iron used as feedstock in process route i} \quad (18)$$

$$I_{PI,i} = \frac{E_{PI,i}}{Q_{PI,i}} \text{: energy intensity associated with the pig iron used in process route i} \quad (19)$$

$$I_{Oth,i} = \frac{E_{Oth,i}}{Q_{crude,i}} \text{: energy intensity associated with all other processes in process route i except the pig iron used} \quad (20)$$

Where:
i process route (BF-BOF or EAF route)
T last year of the period
T=0 base year of the period
$E_{PI,i,t}$ Energy use for production of pig iron used for steel production in process route i in year t
$E_{Oth,i,t}$ Total energy use for steel production minus the energy use for production of pig iron used for steel production in process route i in year t
$Q_{crude,t}$ total crude steel production in year t
$Q_{crude,i,t}$ crude steel production by process route i in year t
$Q_{PI,i,t}$ pig iron used by process route i in year t

In this study we conduct a retrospective decomposition analysis of the key medium- and large-sized Chinese steel enterprises using historical data from 2000 to 2010. In addition, we conduct a prospective decomposition analysis for the periods of 2010–2015, 2015–2020, and 2020–2030 using forecast data calculated based on the method explained below.

HISTORICAL FINAL ENERGY INTENSITY OF THE KEY MEDIUM- AND LARGE-SIZED STEEL ENTERPRISES

In this study the final energy intensity of the BF-BOF and EAF steel production routes are calculated separately. Further, the energy use for the production of pig iron used in each steel making route is calculated separately in order to be used in the decomposition analysis (see Eq. 1). The final energy intensities are calculated by a bottom-up approach using the sub-processes energy intensities mostly provided in *China Steel Yearbooks* (EBCSY 2001–2011). Table 1 shows the final energy intensity of major iron and steel production sub-processes. It should be noted that this table only includes the major sub-processes and does not include all sub-processes in the steel plants. For example, several sub-processes such as steam generation, oxygen production, and some finishing processes, etc. are missing. We categorized all these sub-processes that are missing as "Auxiliary" and we accounted for the energy intensity for this category below when calculating the energy intensity of the complete process.

Having the data from Table 1, the final energy intensity of the complete EAF and BF-BOF steel production line can be calculated (Table 2). Because of the space constraint, the details of the calculation are not presented here and can be found in Hasanbeigi et al. (2013). Finally, we can calculate the combined final energy intensity of key medium- and large-sized Chinese steel enterprises from the following equation:

$$EI = EI_{BF\text{-}BOF} * Sh_{BOF} + EI_{EAF} * Sh_{EAF} \quad (21)$$

Where:
Sh_{BOF} and Sh_{EAF} are the share of Bf-BOF and EAF routes from total steel production in key medium- and large-sized Chinese steel enterprises in each year, respectively.

Also, further calculation was done using the data from Table 1 and Table 2 to prepare the data for equation 9–20.

Table 1. Final energy intensity of the main steel-making processes in key medium- and large-sized Chinese steel enterprises (2000–2010) (EBCSY 2001–2011; Zhang and Wang 2006).

Year	Coking (GJ/t coke)	Sintering (GJ/t sinter)	Pelletizing (GJ/t pellet)	Iron making (BF) (GJ/t pig iron)	BOF (GJ/t crude steel)	EAF (GJ/t crude steel)	Rolling (GJ/t finished steel)
2000	4.3	1.8	1.1	13.5	0.3	3.2	2.5
2001	4.1	1.8	1.1	13.1	0.3	2.8	2.3
2002	4.0	1.7	1.1	13.2	0.3	2.7	2.1
2003	4.0	1.7	1.1	13.5	0.3	2.6	2.1
2004	3.8	1.7	1.1	13.5	0.3	2.5	2.0
2005	3.8	1.7	1.1	13.2	0.3	2.4	1.9
2006	3.6	1.6	1.0	12.7	0.3	2.4	1.9
2007	3.6	1.6	0.9	12.5	0.2	2.4	1.8
2008	3.5	1.6	0.9	12.5	0.2	2.4	1.7
2009	3.3	1.6	0.9	12.0	0.1	2.2	1.7
2010	3.1	1.5	0.9	12.0	0.0	2.2	1.8

Table 2. Final energy intensities (GJ/t crude steel) calculated for key medium- and large-sized Chinese steel enterprises (2000–2010).

Year	Final energy intensity of complete EAF route	Final energy intensity of complete BF-BOF route	Combined Final energy intensity of key enterprises
2000	11.1	21.5	20.3
2001	10.3	20.8	19.3
2002	11.0	20.6	19.2
2003	10.8	20.8	19.2
2004	11.7	20.7	19.4
2005	12.8	20.2	19.4
2006	13.4	19.5	18.9
2007	12.8	19.0	18.4
2008	12.4	19.0	18.5
2009	13.4	18.5	18.1
2010	12.2	18.1	17.7

FORECASTING ENERGY INTENSITY OF THE KEY MEDIUM- AND LARGE-SIZED STEEL ENTERPRISES

Similar steps as described in above were taken to forecast the final energy intensity of key medium- and large-sized Chinese steel enterprises in 2015, 2020, and 2030. However, instead of using the process energy intensities given in Table 1, we used the "advanced value of energy intensity from national standard"[1] given by China's Ministry of Industry and Information Technology (MIIT) and also in "GB 21256-2007: The norm of energy consumption per unit product of major processes of crude steel manufacturing" as the basis for our assumptions for energy intensity of each of the main steel-making processes (MIIT 2010; Standards Press of China, 2007). Table 3 shows the assumed energy intensities for each process in 2030. We assume that the energy intensity of steel-making processes in key medium- and large-sized Chinese steel enterprises in 2030 will be equal to the "advanced value of energy intensity from national standard." Then, we assumed that the reduction in energy intensity of processes between 2010 and 2030 will be linear and based on the calculated the energy intensity for each process in 2015 and 2020.

Once we have the final energy intensities of steel-making processes, the calculations to determine the energy intensities of BF-BOF and EAF steel-making in 2015, 2020, and 2030 are similar to those described in the previous section. Several other assumptions were made before calculating the future energy intensities. The most important assumptions were the pig iron feed ratio in EAF production and the share of EAF steel production within total steel production in the future. Several drivers can influence these two factors such as the steel scrap availability, the retirement rate of the BF-BOF plants and the construction rate of the new EAF plants, the future steel demand and production in China, etc. There are varying forecasts for all of the aforementioned drivers in different studies (McKinsey & Co. 2009; Hatch. 2012; Valle 2013; Wang et al. 2013; Zhu et al. 2012), which make it difficult to determine one absolute number for the pig iron ratio in EAF and the EAF share. Therefore, we decided to develop three different scenarios to address this issue and to capture the effect of different assumption of the final results. Total steel production is kept constant across the three scenarios. The three scenarios are as follows:

- Scenario 1: Low scrap usage: the share of EAF steel production grows slower and the pig iron feed ratio in EAF drops slower than other scenarios
- Scenario 2: Medium scrap usage: the rate of growth in the share of EAF steel production and the drop in the pig iron feed ratio in EAF production is medium (between scenario 1 and 3)
- Scenario 3: High scrap usage: the share of EAF steel production grows faster and the pig iron feed ratio in EAF production drops faster than other scenarios.

Table 4 presents the values for pig iron feed ratio in EAF and the EAF steel production share in the future under different scenarios. It also presents the assumptions on the share of sinter and pellet from total iron ore used in the future.

1. From *The Norms of Energy Consumption per Unit of Product for Major Processes of Crude Steel Manufacturing* published by Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China (AQSIQ), which gives the values for minimum energy consumption per unit of production for existing plants, newly constructed plants, and advanced level (AQSIQ 2007).

Table 3. Energy intensity of main steel-making processes assumed for 2030 (MIIT 2010: Standards Press of China 2007).

	Coking (GJ/t coke)	Sintering (GJ/t sinter)	Pelletizing (GJ/t pellet)	Ironmaking (BF) (GJ/t pig iron)	BOF (GJ/t crude steel)	EAF (GJ/t crude steel)	Rolling (GJ/t finished steel)
Advanced value of energy intensity from national standard	3.1	1.4	0.7	11.1	-0.4	2.1	1.6

Table 4. Several assumptions used in calculating the future energy intensities.

Year	Pig iron ratio in EAF (t pig iron/t crude steel)			Share of EAF steel production from total steel production in Key Enterprises			Share of sinter from total iron ore used	Share of pellet from total iron ore used
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3		
2010	0.47	0.47	0.47	7.2 %	7.2 %	7.2 %	85 %	15 %
2015	0.40	0.40	0.40	10 %	10 %	10 %	85 %	15 %
2020	0.35	0.30	0.30	13 %	15 %	18 %	85 %	15 %
2030	0.30	0.20	0.10	20 %	25 %	35 %	85 %	15 %

Using the values in Table 3 and Table 4 and the method explained in above, we calculated the final energy intensities for the BF-BOF and EAF steel production routes in 2015, 2020, and 2030. The results are presented in the section "Final energy intensity, energy use, and crude steel production in key medium- and large-sized steel enterprises" below.

HISTORICAL AND FUTURE PRODUCTION FOR KEY MEDIUM- AND LARGE-SIZED STEEL ENTERPRISES

In the decomposition analysis equations, the production of crude steel by BF-BOF and EAF production routes as well as the amount of pig iron used in EAF and BOF is needed. The pig iron ratio for EAF in different years are available from historical records. We also assumed that the pig iron ratio for BOF is equal to 1 in all years. These ratios can be multiplied by the crude steel production in EAF and BOF production to determine the pig iron used in EAF and BOF steel production, respectively. The historical production data for key enterprises are obtained from various years of the China Steel Yearbook (EBCSY 2001–2011).

Future production data are calculated based on Fridley et al. (2011) which forecasts 804 million tonne (Mt) and 831 Mt steel production in China in 2020 and 2030, respectively, using several assumptions on drivers such as infrastructural and construction demand as well as demand for product steel used in appliances, machinery, and other products for final consumption. The details of their assumptions can be found in Fridley et al. (2011). However, the steel production forecast data in Fridley et al. (2011) is for the entire Chinese steel industry and not for key enterprises. Hence, we could not use those forecast data directly. First, we calculated the average annual growth rate (AAGR) of the steel production in the periods of 2010–2015 (2.1 %), 2015–2020 (1.4 %), 2020–2025 (0.4 %) and 2025–2030 (0.2 %) from Fridley et al. (2011). Then, we used these AAGRs, as shown in Table 5, to calculate the total steel production of key enterprises in 2015, 2020, 2025, and 2030. Following equation is used to calculate the future productions using the AAGRs:

$$P_{(t)} = P_{(t0)} * (1+AAGR_{t0-t})^{(t-t0)} \quad (22)$$

Where:

- $P_{(t)}$ crude steel production in year t
- $P_{(t0)}$ crude steel production in the base year of the period (e.g. 2010 production for the period of 2010–2015 or 2015 production for the period of 2015–2020)
- $AAGR_{t0-t}$ average annual growth rate of crude steel production during the period of t0-t.

After calculating the total steel production of key enterprises, we used the share of EAF steel production from total steel production in key enterprises (Table 4) to calculate the steel production by EAF and BF-BOF production routes under each scenario.

The pig iron ratio for EAF in 2015, 2020, and 2030 (Table 4) is multiplied by the crude steel production by EAF to achieve the pig iron used in EAF. The pig iron ratio for BOF is assumed to be equal to 1.0 in all years. The results for the production of key steel enterprises are presented below.

Results and Discussion

In this section, we first present and analyze the result of historical as well as forecasted final energy intensity and total energy use and crude steel production of Chinese key medium- and large-sized steel enterprises. Then, retrospective and prospective decomposition analysis results are presented.

FINAL ENERGY INTENSITY, ENERGY USE, AND CRUDE STEEL PRODUCTION IN KEY MEDIUM- AND LARGE-SIZED STEEL ENTERPRISES

Figure 1 shows the calculated final energy intensities for BF-BOF and EAF steel production routes in key steel enterprises from 2000 to 2030. It shows that energy intensity of both the BF-BOF route and the combined energy intensity have a declining trend, while the energy intensity of the EAF route has

Table 5. Assumptions on AAGR used to forecast total steel production in key enterprises (Fridley et al. 2011).

	2010–2015 based on 2010 production	2015–2020 based on 2015 production	2020–2025 based on 2020 production	2025–2030 based on 2025 production
AAGR	2.1 %	1.4 %	0.4 %	0.2 %

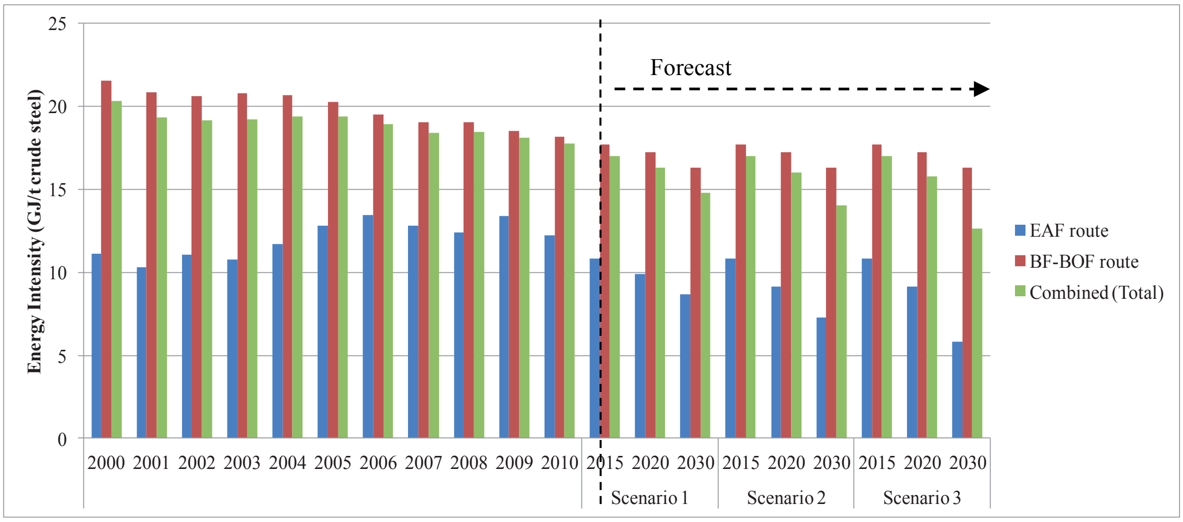

Figure 1. Final energy intensities calculated for key medium- and large-sized Chinese steel enterprises (2000–2030).

an increasing trend between 2001 and 2009 and then decreasing up to 2030. The increasing trend of the EAF route energy intensity is primarily because of upwards trend of pig iron ratio in EAF production as a feedstock in this period.

Table 6 shows the calculated steel production and pig iron used in EAF and BF-BOF routes in key medium- and large-sized Chinese steel enterprises between 2000 and 2030. Figure 2 illustrates the total crude steel production by the EAF and BF-BOF production routes in key enterprises under different scenarios. Since the retrospective decomposition analysis is conducted for the periods of 2000–2005 and 2006–2010, we only present the historical production data for these years. Figure 2 shows clearly that scenario 1 and scenario 3 have the lowest and highest overall EAF steel production between 2010 and 2030, respectively. The total steel produced by the key steel enterprises are the same across the scenarios and only the share of EAF steel production varies among the scenarios. One important point is that under all scenarios, the total annual crude steel production of key Chinese steel enterprises (and most likely the entire Chinese steel industry) is assumed to peak in 2030. Also, the AAGR of crude steel production in key steel enterprises in the periods of 2000–2005 and 2006–2010 were 19 % and 12 %, respectively, which are far higher than the future AAGR of crude steel production between 2010 and 2030 given in Table 5. The decomposition analysis results presented in the next section show how the lower AAGR of steel production in the future contributes to the changes in the total energy use trend of the steel industry.

Figure 3 shows the total final energy use in key medium- and large-sized Chinese steel enterprises under each scenario during 2000–2030. The interesting result shown in Figure 3 is that the total final energy use of the key Chinese steel enterprises (and most likely the entire Chinese steel industry) peaks in 2020 under scenario 1 and scenario 2 and in 2015 under scenario 3. In addition, the percentage change in final energy use between 2010 and 2030 is equal to +2 %, -3 %, and -13 % under scenario 1, 2, and 3, respectively (Figure 3). This is a very important finding that deserves further investigation. The decomposition analysis results presented in the next section will show what contributed (changes in steel production, EAF share of total production, pig iron ratio in EAF production, and energy intensity of steel production) to the reduction in the final energy use and its peak under each scenario.

Another important finding is that the share of final energy use by the EAF production route in the total final energy use by key enterprises in 2030 is 12 %, 13 %, and 16 % under scenario 1, 2, and 3, respectively, while in 2030 the EAF route accounts for 20 %, 25 %, and 35 % of total steel production of key steel enterprise under scenario 1, 2, and 3, respectively. However, it should be noted that if the energy use in the EAF production route is converted from final to primary energy (by taking into account the power generation and transmission and distribution losses), the EAF production route will account for a higher share of total primary energy use in the key steel enterprises.

DECOMPOSITION OF KEY MEDIUM- AND LARGE-SIZED STEEL ENTERPRISES' ENERGY USE

We conducted separate decomposition analysis for each of the three scenarios explained in order to show how different assumptions regarding the crude steel production forecast will affect the prospective decomposition results. A LMDI decomposition analysis was performed for the Chinese key medium- and large-sized steel enterprises for five time periods: 2000–2005, 2006–2010, 2010–2015, 2015–2020, and 2020–2030. These five periods were chosen based on the Chinese government Five Year Plan periods. Each FYP period is associated with a set of Government policies that affect manufacturing

Table 6. Annual crude steel production and pig iron used in EAF and BF-BOF steel production routes in key medium- and large-sized Chinese steel enterprises under each scenario.

			Scenario 1			Scenario 2			Scenario 3		
		2010	2015	2020	2030	2015	2020	2030	2015	2020	2030
Annual crude steel production (10^6 t crude steel)	BF-BOF Route	514,6	553,1	572,7	544,3	553,1	559,5	510,3	553,1	539,8	442,3
	EAF Route	39,7	61,5	85,6	136,1	61,5	98,7	170,1	61,5	118,5	238,1
	Total Key Steel Enterprises	554,3	614,6	658,3	680,4	614,6	658,3	680,4	614,6	658,3	680,4
Annual pig iron use (10^6 t pig iron)	BF-BOF Route	514,6	553,1	572,7	544,3	553,1	559,5	510,3	553,1	539,8	442,3
	EAF Route	18,8	24,6	29,9	40,8	24,6	29,6	34,0	24,6	35,5	23,8
	Total Key Steel Enterprises	533,4	577,7	602,7	585,1	577,7	589,2	544,3	577,7	575,3	466,1

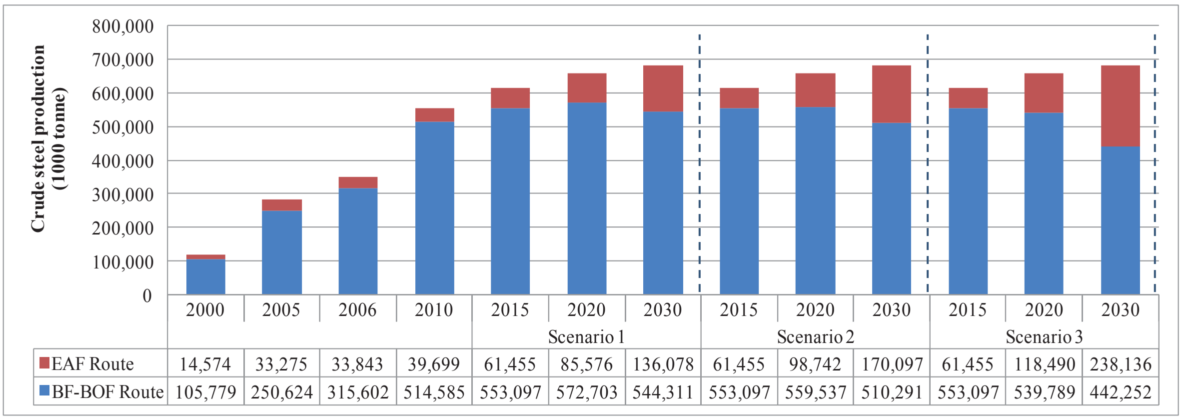

Figure 2. Total crude steel production by EAF and BF-BOF steel production routes in key enterprises under different scenarios (2000–2030).

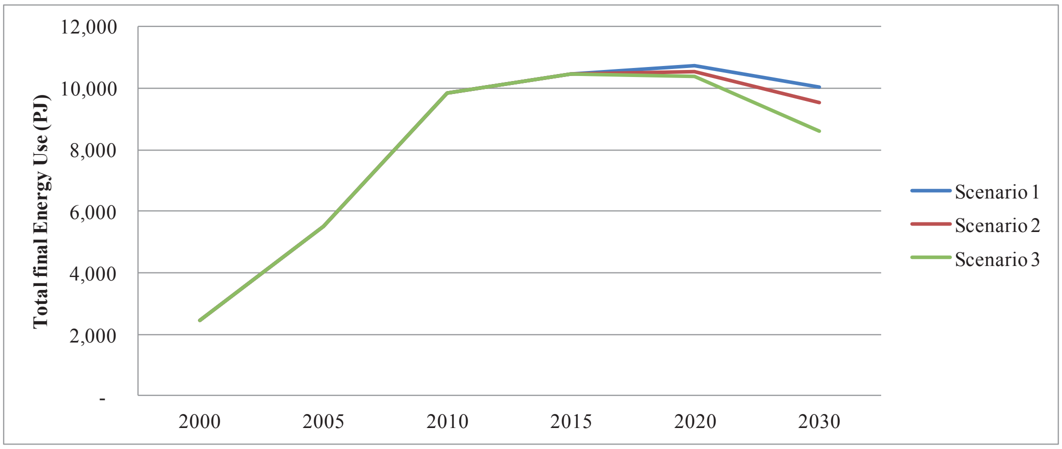

Figure 3. Total final energy use in key medium- and large-sized Chinese steel enterprises under each scenario (2000–2030).

energy intensity. Starting in the 11th FYP, specific policies, programs, incentives, and targets were established with the stated intent of reducing China's overall energy intensity and a substantial share of these were focused on reducing manufacturing energy intensity, especially in the energy-intensive sectors like iron and steel industry.

Figures 4 show the results of the decomposition analysis of total final energy use of key medium- and large-sized steel enterprises for during the 10th and 11th FYP, separately. Figure 4 shows that in both periods the activity and intensity effects were the two dominant influences working against each other to drive energy use upward (activity effect) or downward (intensity effect). The intensity effect during the 10th FYP (2000–2005) is the smaller compared to the 11th FYP because of a very small decline in combined final energy intensity of key enterprises during this period (see Figure 1). This was due to the sudden boom in steel production capacity and construction of steel plants in China and the rapid increase in production with-

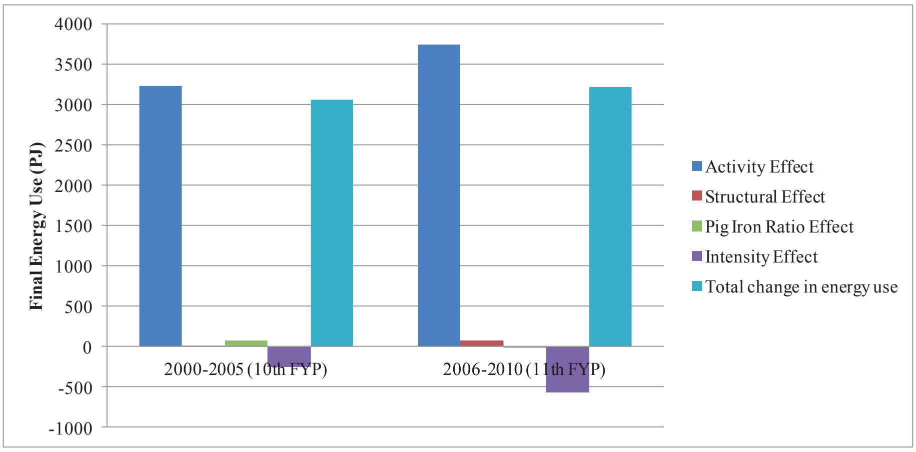

Figure 4. Results of retrospective decomposition of final energy use of key medium- and large-sized steel enterprises during the 10th and 11th Five Year Plans.

out enough attention to energy efficiency. During the 11th FYP, in an attempt to control the energy intensity of manufacturing, the Chinese government implemented series of policies and programs to reduce the energy intensity of manufacturing sectors, especially the energy-intensive industries like the steel industry. Programs like the "Top-1000 Enterprises Energy Saving Program" and the "10 Key Energy Saving Projects Program" implemented during the 11th FYP substantially helped to control the energy intensity of the manufacturing (Price et al. 2011).

Figures 5 to 7 show the results of the prospective decomposition analysis for 2010–2030 (the 12th, 13th, and 14th plus 15th Five Year Plan periods). The differences between the three scenarios and the primary reasons for such differences are summarized below. Overall, the future activity effects are almost similar across the scenarios due to the similar steel production forecast for all three scenarios (see Table 6).

Contrary to 10th and 11th FYP periods, the structural effect is negative (i.e. reducing the final energy use) during 2010–2030 because of our assumption of the increase in the EAF share of steel production in this period. The structural effect is the smallest in scenario 1 and largest in scenario 3 because of lower EAF steel production share in scenario 1 and higher share in scenario 3. If China wants to adjust the structure of its steel industry and move towards less energy-intensive and lower polluting steel manufacturing, the shift from BF-BOF steel production to EAF steel production is essential. However, steel scrap availability, the scrap price, and the retirement rate of the BF-BOF plants (most of which were built after 2000) limits the ability of China to increase its EAF steel production significantly in the short term. Even in the current EAF steel production, the share of pig iron used as feedstock in EAF instead of scrap in China is among the highest in the world. The pig iron use in EAF increases the total energy and CO_2 emissions footprint of the steel produced by EAFs because of the high energy used for pig iron production. As the Chinese economy becomes more mature there will be more recycled scrap available which will make it possible for China to produce more steel by EAFs and less by BF-BOF and also to decrease the use of pig iron as feedstock in EAFs.

The pig iron ratio effect reduces the final energy use during 2010–2030. This reduction is the smallest in scenario 1 and largest in scenario 3 because of higher pig iron ratio used as EAFs feedstock in scenario 1 and lower ratio in scenario 3. Also, the pig iron ratio effect increases as the share of EAF steel production from total steel production by key enterprises increases from scenario 1 to scenario 3.

During 2010–2030, the intensity effect is almost in the same range across all three scenarios, with scenario 1 having slightly greater (in negative value) energy intensity effect. This is mainly because we assumed a similar energy intensity reduction rate during the 12th FYP, 13th FYP, and 14th plus 15th FYP periods for all three scenarios. The slight differences between intensity effects across scenarios comes from the differences in absolute energy use in key enterprises in 2015, 2020, and 2030 under each scenario which is the result of different assumptions for the EAF share of steel production in each scenario. As can be seen in Eq. 12 and Eq. 15, absolute energy use in each production route ($E_{PI,i}$ or $E_{Oth,i}$) plays a role in the calculation of the intensity effect in addition to the energy intensity of the production route. Nonetheless, the intensity effect plays a significant role in reducing final energy use of steel manufacturing during the 12th FYP, 13th FYP, and 14th plus 15th FYP periods. This is primarily because of reduction in energy intensities of production processes in 2020 and 2030. While the realization of such energy intensity reduction is uncertain and remains to be seen in the future, the aggressive policies of the Chinese government to reduce the energy use per unit of product of the energy intensive sectors, especially the steel sector, are a promising sign that the Chinese steel industry in moving towards those energy intensity targets. The "Top-1000 Enterprises Energy Saving Program" and the "10 Key Energy Saving Projects Program" implemented during the 11th FYP have both been extended to the 12th FYP with the Top 1000 program expanding to the "Top-10,000 Enterprises Energy Saving Program". These programs along with other policies and incentives in the coming years will be helping to reduce the energy intensity of the steel industry in China; hence we see a strong intensity effect in the decomposition analysis.

There are number of limitations and sources of uncertainty in this study and most other studies that try to forecast the future production for manufacturing sectors as well as their future energy intensities. For example, the projected AAGRs for steel production, the energy intensity reduction rates, pig

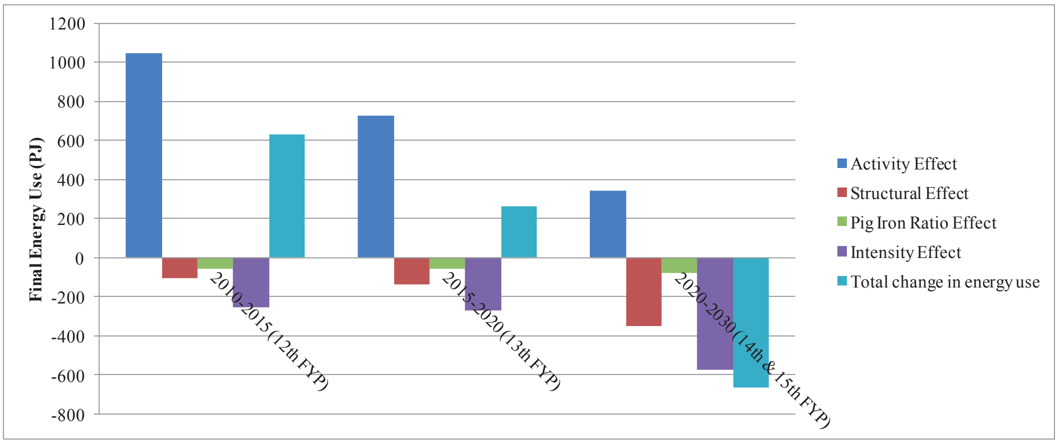

Figure 5. Scenario 1. Results of prospective decomposition of final energy use of key medium- and large-sized steel enterprises during the 12th, 13th, and 14th plus 15th Five Year Plans.

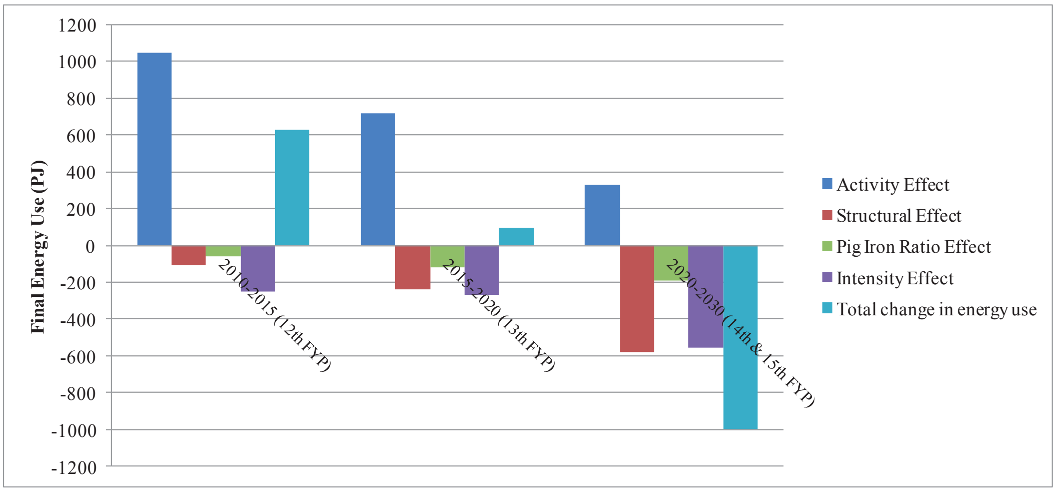

Figure 6. Scenario 2. Results of prospective decomposition of final energy use of key medium- and large-sized steel enterprises during the 12th, 13th, and 14th plus 15th Five Year Plans.

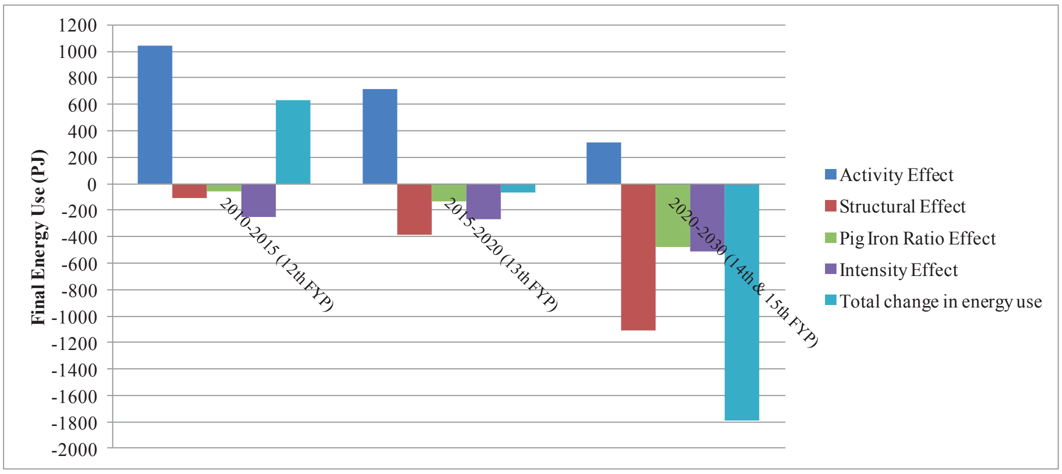

Figure 7. Scenario 3. Results of prospective decomposition of final energy use of key medium- and large-sized steel enterprises during the 12th, 13th, and 14th plus 15th Five Year Plans.

iron feed ratio in EAFs, and the EAF steel production share between 2010 and 2030 are sources of uncertainty. Even so, the scenario development and decomposition analysis in this study can help to understand how changes in these influential factors can affect overall energy consumption of key medium- and large-sized steel enterprises in the future. Therefore, the result of such studies should be reviewed and interpreted with caution keeping in mind the limitations and uncertainties.

Conclusions

In this study, a bottom-up analysis of the energy use of key medium- and large-sized Chinese steel enterprises is performed using data at the process level. Both retrospective and prospective analyses are conducted in order to assess the impact of factors that influence the energy use of the steel industry in the past (2000–2010) and estimate the likely impact in the future (2010–2030). Throughout this paper all of the data presented are for the key medium- and large-sized steel enterprises unless it is mentioned otherwise. The aggregate energy intensity of the key medium- and large-sized steel enterprises tends to be lower than the energy intensity of the entire Chinese steel industry. We focus the analysis on the key medium- and large-sized steel enterprises because the energy intensity data by process for various years, which are used in our analysis, are only reported for the key medium- and large-sized steel enterprises in China.

The results of our analysis shows that although total annual crude steel production of key Chinese steel enterprises (and most likely entire Chinese steel industry) is assumed to peak in 2030 under all scenarios, total final energy use of the key Chinese steel enterprises (and most likely the entire Chinese steel industry) peaks earlier, i.e. in year 2020 under scenario 1 and scenario 2 and in 2015 under scenario 3. Energy intensity reduction of the production processes and structural shift from BF-BOF to EAF steel production plays the most significant role in the final energy use reduction. The decomposition analysis results show what contributed to the reduction in the final energy use and its peak under each scenario.

The retrospective decomposition analysis described in this paper shows that energy intensity reduction was almost the only factor that helped to reduce final energy use in Chinese key steel enterprises between 2000 and 2010. The structural effect and the pig iron ratio effect played a minor role and even increased the energy demand between 2000 and 2010.

The three scenarios produced for the forward looking (prospective) decomposition analysis for 2010–2030 show the future activity effects are almost similar across the scenarios because of the similar steel production forecast for all three scenarios. Contrary to 10th and 11th FYP periods, the structural effect is negative (i.e. reducing the final energy use) during 2010–2030 because of the increase in the EAF share of steel production in this period. Similarly, the pig iron ratio effect reduces the final energy use of key steel enterprises because of reduction in the share of pig iron used as feedstock in EAF steel production during this period. Scenario 3 has the largest structural effect and pig iron ratio effect because of higher EAF steel production and lower pig iron use in EAFs in this scenario.

The intensity effect plays a significant role in reducing final energy use of steel manufacturing during 2010–2030. This is primarily because of the energy intensity assumptions for production processes in 2020 and 2030. While the realization of such energy intensity reduction is uncertain and remains to be seen in the future, the aggressive policies by the Chinese government to reduce the energy use per unit of product of the energy intensive sectors, especially the steel sector, are a promising sign that the Chinese steel industry is moving towards those energy intensity targets. The "Top-10,000 Enterprises Energy Saving Program" and the "10 Key Energy Saving Projects Program" along with other policies and incentives in the coming years will significantly help to reduce the energy intensity of the steel industry in China.

References

Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, (AQSIQ). 2007. The norms of energy consumption per unit of product for major processes of crude steel manufacturing. GB 21256-2007 (in Chinese).

Ang, B.W., A.R. Mu, P. Zhou. 2010. "Accounting frameworks for tracking energy efficiency trends." Energy Economics, Volume 32, Issue 5, September 2010: 1209–1219.

Editorial Board of China Steel Yearbook (EBCSY). 2001–2011. China Steel Yearbook-various years. Beijing, China [in Chinese, but some tables in English].

Fridley, D.; Zheng, N.; Zhou, N.; Ke, J.; Hasanbeigi, A.; Price, L., 2011. China Energy and Emission Paths to 2030. Berkeley, CA: Lawrence Berkeley National Laboratory.

Hasanbeigi, A.; J. Zeyi, L. Price. 2013. Analysis of the Past and Future Trends of Energy Use in Key Medium and Large-Sized Chinese Steel Enterprises, 2000–2030. Berkeley, CA: Lawrence Berkeley National Laboratory. LBNL-6380E.

Hasanbeigi, A.; Price, L.; Aden, N.; Zhang C.; Li X.; Shangguan F. 2011. A Comparison of Iron and Steel Production Energy Use and Energy Intensity in China and the U.S. Report LBNL-4836E. Berkeley, CA: Lawrence Berkeley National Laboratory.

Hatch. 2012. Prospects for the Global Scrap Market. Presentation to Alacero 53 Congress. http://www.alacero.org/CongresoAlacero53/Pte201253/P2,%20RichardMcLaughlin.pdf

Liu, F.L.; Ang, B.W. 2003. Eight methods for decomposing the aggregate energy-intensity of industry. Applied Energy 76 (2003) 15–23.

McKinsey & Co. 2009. China's green revolution: Prioritizing technologies to achieve energy and environmental sustainability.

Ministry of Industry and Information Technology (MIIT), 2010. Energy Efficiency Bench-marking Indicators for Main Products/Processes of Steel Industry (in Chinese).

National Bureau of Statistics (NBS), 2011. China Energy Statistical Yearbook 2011. China Statistics Press. Beijing, China.

Price, L., M. D. Levine, N. Zhou, D. Fridley, N. Aden, H. Lu, M. McNeil, N. Zheng, Y. Qin, P. Yowargana. 2011. Assessment of China's Energy-Saving and Emission-

Reduction Accomplishments and Opportunities During the 11th Five Year Plan. Energy Policy, Volume 39, Issue 4, April 2011, Pages 2165–2178.

Standards Press of China, 2007. The norm of energy consumption per unit product of major processes of crude steel manufacturing. GB 21256-2007.

State Economic and Trade Commission (SETC), The State Planning Commission (SPC), The Ministry of Finance (MoF), National Bureau of Statistics (NBS), 2003. Criteria for the classification of large-, medium-, and small- sized enterprises for industry (in Chinese).

Valle, D.D. 2013. BHP Billiton Coal overview. www.bhpbilliton.com/home/investors/reports/Documents/2013/130529_CoalBriefing.pdf

Wang. P., X. Zhang, Z. Jiang. 2013. Long-term scenario forecasts of steel production pathway transformation, energy consumption and emissions in Chinese steel industry. Presentation at the Forum for Energy Efficiency in the Steel Industry. University of Science and Technology Beijing. July 2013.

World Steel Association (worldsteel). 2011. Steel Statistical Yearbook 2011. http://www.worldsteel.org/statistics/statistics-archive/yearbook-archive.html

Zhang, Y. and Wang, W. 2006. Energy structure and energy saving in iron and steel industry. China Metallurgy, Vol 16. No. 10 (in Chinese).

Zhu, J.H., K.K. Lee, W. Ouyang. 2012. China steel – Embracing a new age. https://research.standardchartered.com/configuration/ROW%20Documents/China_steel_%E2%80%93_Embracing_a_new_age_16_09_12_13_19.pdf

Acknowledgements

This work was supported by the China Sustainable Energy Program of the Energy Foundation through the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. We would like to thank David Fridley, Nina Khanna, and Ryan Triolo of the China Energy Group of Lawrence Berkeley National Laboratory for their contributions to this study. We are also thankful to Peng Wang and Fushan Tian of the School of Mechanical Engineering, University of Science and Technology Beijing, China for their research assistance in this study. We are grateful to Zhang Chunxia and Li Xiuping of the China Iron & Steel Research Institute for their valuable comments on an earlier version of the paper.