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A Bottom-up Energy Efficiency Improvement Roadmap for China's Iron and Steel Industry up to 2050

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Contents

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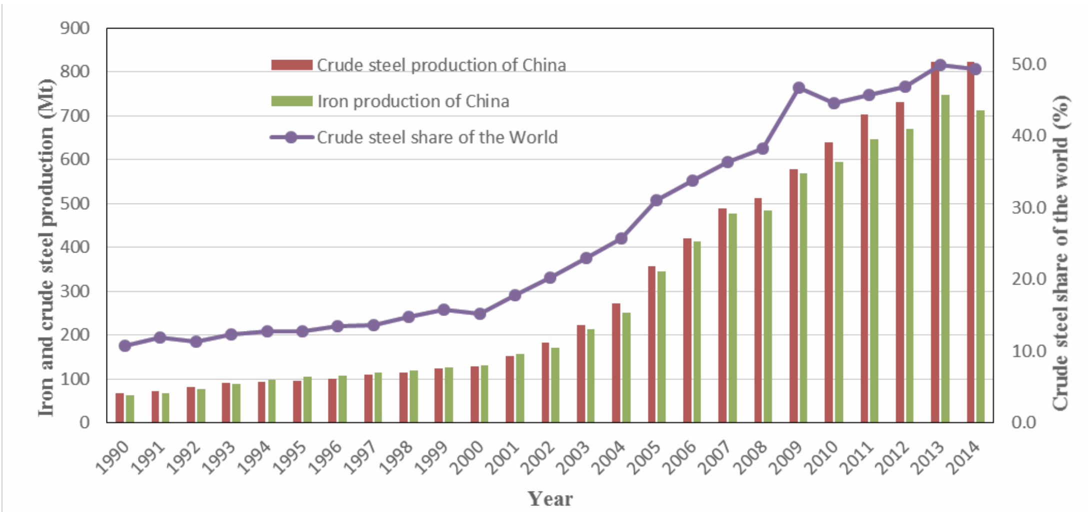
1. Introduction

Iron and steel manufacturing is energy intensive, accounting for more than 5% of the world's annual energy demand (Li and Zhu, 2014). In 2010, iron and steel production consumed 464 million tons (Mt) of standard coal and emitted 1.82 billion tons of carbon dioxide (CO_2) in China (Tian et al., 2013). Iron and steel manufacturing is an important basic industry of the Chinese national economy and plays a major role in China's industrialization and urbanization (Hasanbeigi et al., 2013a). Since the 1990s, China's iron and steel industry has developed rapidly. From 2000 to 2014, crude steel production grew by an annual average of 12.8%. In 2014, China's crude steel production was 822.7 Mt, which represented 49.3% of world crude steel production (Worldsteel, 2015), as shown in Figure 1.



Source: World Steel Association (1991-2015)

Figure 1. China's crude steel production and share of world steel production from 1990 to 2014

With such a high level of steel production and related energy consumption and CO_2 emissions, China's iron and steel industry must play an important role in the national energy savings and emission reduction to face significant challenges in energy use and climate change. However, there are many factors that shape the energy consumption of the China's iron and steel industry, i.e. steel production volume, production structure, energy-efficient technologies, et al., and we will discuss these issues to find the potential of energy savings in this paper.

Many approaches have been used to forecast China's future steel demand (Gao and Wang, 2010; Olsson, 2008; Chen Wenying et al., 2014) and the potential for energy-efficiency improvements and CO_2 emissions reduction. (Hasanbeigi et al., 2013a; Wen et al., 2014). Many models have been created to predict future steel production in China (Xiang and Chen, 2013). These models suggest that China's steel production will grow steadily to a peak and then gradually decrease (Wang et al., 2014). It is also thought that, of the two major types of steel production in China, the share of electric-arc furnace (EAF) production will increase while the share of blast furnace/basic oxygen furnace (BF/BOF) production will decrease. The increasing use of EAFs in steel production is one of the main factors driving changes in the industry's energy consumption and CO_2 emissions (Sheinbaum et al., 2010; Chen et al., 2014; Wang et al.,2014; Wang et al., 2007). (These two types of steel production in China are described in Section 2.1).

Numerous studies have focused on energy savings in the iron and steel industry. Arens et al. (2012) analyzed primary energy use per unit product in the German steel sector from 1991 to 2007. They found that 75% of a decline this energy use measure resulted from a change in industry structure toward more EAF production; only 25% of the reduction in energy use resulted from energy-efficiency improvements. Wen et al. (2014) used the Asian-Pacific Integrated Model to estimate the potential for energy conservation and CO_2 emissions mitigation in China's iron and steel industry from 2010 to 2020. Three scenarios were analyzed; results indicated that adoption of energy-efficient technologies had a much greater impact on energy savings and emissions reductions than structural adjustments in the industry. This study also showed that the same measures have different effects in different countries.

Several studies have focused on deployment of energy-efficient technologies in China's iron and steel industry. Hasanbeigi et al. (2013b) used a bottom-up model to estimate the energy and CO_2 savings from 23 energy-efficient technologies and measures applicable to China's iron and steel manufacturers. Li and Zhu (2014) selected 41 energy-saving technologies and estimated the cost curve of energy savings and CO_2 emissions reduction in China's iron and steel sector. Wen et al. (2014) selected 21 technologies based on resource and energy consumption, pollutant emissions, and technical-economic considerations and estimated the potential for conserving energy and mitigating CO_2 emissions in China's iron and steel industry. Ma et al. (2015) build a new evaluation framework to quantify energy benefits and environmental benefits associated with 36 energy-efficiency measures in China's iron and steel industry. These studies highlight that improvements in energy efficiency and changes in the industry's production structure will both contribute to reduce energy use and CO_2 emissions.

The current study contributes to the literature in this area by examining the future energy and emissions reductions in relation to the penetration of energy-efficient technologies as well as changes in the industry's production structure. Because different technologies have different energy-saving potential, and different penetration rates make different contributions to energy savings, it is challenging for policy makers to fully understand the potential impacts on future energy use of promoting energy-efficient technologies and/or changes in industry production practices. Our analysis is intended to help address this problem.

We undertook a detailed analysis of the impact on energy consumption of energy-efficiency improvements and production structure changes in China's iron and steel industry, using a bottom-up model and scenario analysis to examine 28 energy-efficient technologies in different production processes. The remainder of the paper is organized as follows: Section 2 gives an overview of the development and energy consumption of China's iron and steel industry. Section 3 describes the methodology used for our analysis, including the energy-efficiency and production scenarios. Section 4 discusses our results, and Section 5 presents our recommendations.

2. The China's iron and steel industry

The subsections below describe the production structure and the historical energy consumption of China's iron and steel industry.

2.1 Production structure

Crude steel production in China uses two main processes. The BF/BOF process uses primarily iron ore, and the EAF process uses scrap or pig iron as raw material. Other steel production processes, such as direct reduced iron (DRI) and smelting reduction, are very uncommon in China. Figure 2 shows a simplified version of BF/BOF, EAF, DRI steel-making processes (Arens et al.,2012).

BF/BOF production is the most common process by which steel is produced from iron ore, both in China and worldwide. In China, BF/BOF production accounts for about 90% of crude steel production (Zhang et al.,2013). As shown in Figure 2, BF/BOF production entails many processes (sintering, coke making, iron making, steelmaking and rolling, etc.) More than 70% of the energy used in BF/BOF production in China is generated from coal, which is one reason that BF/BOF production consumes significant energy and generates significant CO_2 emissions.

EAF production accounts for about 30% of steel production worldwide but only about 10% of total steel production in China. Furthermore, Chinese EAF production is supplemented with a high percentage of pig iron which is the reason why Chinese EAF production is more energy intensive than in many other countries (Hasanbeigi et al., 2014; Wang et al., 2014). Use of pig iron as feedstock in EAFs can increase the total energy consumption and CO_2 emissions associated with the steel it is used to produce because of a significant amount of energy is used to produce pig iron.

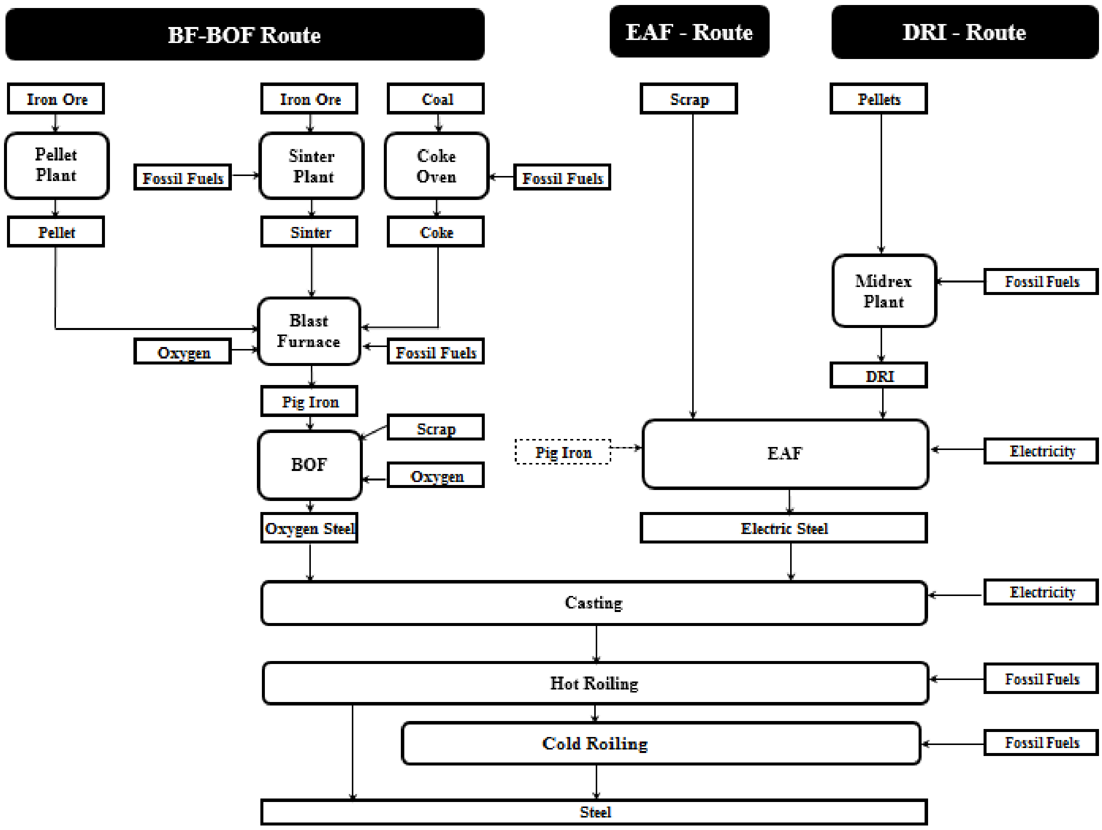


Figure 2. Steel production processes

2.2 Energy consumption

The iron and steel industry is one of the most energy-intensive, resource-intensive, and polluting industries in the world. China's iron and steel industry has developed rapidly, with final energy consumption increasing from 128.7 million tons of coal equivalent (Mtce) in 1996 to 464 Mtce in 2010. As noted above, coal is the dominant energy source for iron and steel production, accounting for about 78.8% of total energy consumption by the iron and steel industry in China in 2010 (Chen et al., 2014). Although the total energy consumption of this industry has increased, the specific energy consumption has decreased during the past decade as energy efficiency and the penetration rate of energy-saving technologies have increased. The energy intensity of China's key steel enterprises decreased from 18.90 gigajoules per ton (GJ/t) of crude steel in 2006 to 17.67 GJ/t of crude steel in 2012. However, there are many small production units in China whose energy consumption is greater than that of larger, more advanced manufacturing facilities. Table 1 shows energy consumption in several major steel industry processes in 2000, 2005, 2010, and 2012. Moreover, the energy intensity of the entire Chinese steel industry is still 15-20% higher than the energy intensity of the industry in the most efficient international steel-producing country because China's steel industry has fewer energy-efficient technologies and a small share of EAF production (Hasanbeigi et al., 2014; Chen et al., 2014).

Table 1. Energy consumption of several key processes in the Chinese steel industry, in GJ/t

	Sintering	Pelleting	Coking	Iron-making	Converter furnace steelmaking	Electric-arc furnace steelmaking	Steel rolling
China 2000 Average	1.80	1.10	4.30	13.50	0.30	3.20	2.50
China 2005 Average	1.90	1.17	4.17	13.39	1.06	2.84	2.22
China 2010 Average	1.54	0.86	3.10	11.95	-0.01	2.17	1.81
China 2012 Average	1.48	0.87	3.10	11.77	-0.16	1.99	1.75
2012 Advanced domestic industry	0.69	0.41	1.80	9.99	-0.63	0.68	0.79
2012 Unimproved domestic industry	1.93	1.60	5.41	13.68	0.91	5.32	4.92

Source: Zhang and Wang (2006), Hasanbeigi et al. (2014), Chen et al. (2014).
The authors converted kilograms of coal equivalent (kgce)/t to GJ/t, using the multiplier 0.02931.

3. Methodology

Bottom-up modeling can predict future energy consumption and manufacturing production based on the production technologies used (Bohringer and Rutherford, 2009). Hasanbeigi et al. (2013a) used bottom-up modeling to analyze future energy-saving and emissions-reduction trends in the iron and steel industry. In our analysis, we use future penetration rates of energy-efficient technologies to generate process energy-intensity data.

3.1 Future energy intensity of China's iron and steel industry

As mentioned in Section 2.1, BF/BOF production and EAF production are the two main steel manufacturing processes in China. We define the energy intensity of each process as final energy use per unit of product. In this study, we back-calculated the 2010 energy intensity based on the energy intensity of the main production processes (Table 1) and the penetration rate of energy-efficient technologies which comes from the references [Hasanbeigi et al. (2013b), Li and Zhu (2014)]. We used the same method to calculate the energy intensity of each production process in 2020, 2030, 2040, and 2050.

$$\Delta E_{j,p} = E_j \cdot \Delta I_{j,p} \tag{1}$$

$$EI_{i,t} = EI_{i,2010} - \Delta E_{j,p} \tag{2}$$

Where

$\Delta E_{j,p}$: energy saving of energy-efficient technology *j* in different periods

E_j: typical energy saving of energy-efficient technology *j*

$\Delta I_{j,p}$:the penetration rate of energy-efficient technology *j* in different periods

$EI_{i,2010}$: the energy intensity of process *i* in 2010

$EI_{i,t}$: the energy intensity of process *i* in the target year.

After determining $EI_{i,t}$, we can calculate the energy intensity of the BF/BOF and EAF production processes and from that obtain the total energy consumption of China's iron and steel industry. Table 2 lists the energy-efficient technologies that we considered for each process.

Table 2. Energy-efficient technologies and measures considered in this analysis

No.	Technology/measure	Typical energy saving (GJ/t-production)	Current adoption rate in China in 2010 (% of production)
Sintering			
1	Heat recovery	0.520	10%
2	Bed-depth increase	0.010	80%
3	Air-leakage reduction	0.050	70%
4	Low-temperature technology	0.020	60%
Coking			
5	Coke dry quenching	1.410	70%
6	Coal moisture control	0.170	5%
Iron making			
7	Top-pressure recovery turbine	0.166	83%
8	Pulverized coal injection	0.770	95%
9	Hot blast stove fuel and air preheating	0.002	5%
10	Coke oven gas injection in BF	0.427	0%
11	Slag heat recovery	0.350	1%
Steelmaking-BOF			
12	BOF sensible heat recovery	0.730	40%
13	Dry gas cleaning system	0.150	20%
Steelmaking-EAF			
14	Scrap preheating	0.220	0%
15	Flue gas waste-heat recovery	0.100	10%
Casting and hot rolling			
16	Integrated casting and rolling	0.300	20%
17	Recuperative or regenerative burner	0.700	30%
18	Hot strip mill process control	0.300	80%

No.	Technology/measure	Typical energy saving (GJ/t-production)	Current adoption rate in China in 2010 (% of production)
19	Cooling water waste heat recovery	0.039	20%
20	Casting billet hot delivery and hot charging	0.200	90%
Cold rolling and finishing			
21	Annealing line heat recovery	0.311	55%
22	Automated monitoring and targeting systems	0.216	55%
General technologies			
23	Integrated steel mill preventative maintenance	0.450	40%
24	EAF plant preventative maintenance	0.140	40%
25	Integrated steel mill energy monitoring and management systems	0.120	15%
26	EAF plant energy monitoring and management systems	0.030	15%
27	Variable speed drives for flue-gas control, pumps, fans in integrated steel mills	0.040	50%
28	Cogeneration using untapped coke oven gas, BF/BOF gas in integrated steel mills	0.380	15%

Source: Hasanbeigi et al. (2013b), Li and Zhu (2014).

The comprehensive energy intensity of the iron and steel industry is represented by (Hasanbeigi et al., 2014):

$$E_t = \sum_i EI_{\mathrm{PI},i,t} + \sum_i EI_{\mathrm{Oth},i,t} + \sum_i EI_{\mathrm{Aux},i,t} \tag{3}$$

Where:

i: process route (BF/BOF or EAF)

t: year

EI_t: energy intensity of iron and steel industry in year t

$EI_{PI,i,t}$: energy used to produce pig iron used in steel production in process route i in year t

$EI_{Oth,i,t}$: total energy use for steel production minus the energy consumed to produce pig iron used in steel production in process route m in year t

$EI_{Aux,i,t}$: total energy used by auxiliary processes such as oxygen production, steam generation, and some finishing, for route i in year t

We calculate the final energy intensity of the BF/BOF and EAF steel production processes separately. Because pig iron produced by a BF process is also used in EAF steel production in China (Wang et al., 2014; Hasanbeigi et al., 2014), we calculate the energy consumed to produce pig iron (or hot metal), as shown Equation 4:

$$EI_{PI} = EI_{\mathrm{coke}} \cdot F_{\mathrm{coke}} + EI_{\mathrm{sint}} \cdot F_{\mathrm{sint}} \cdot Sh_{\mathrm{sint}} + EI_{\mathrm{pell}} \cdot F_{\mathrm{pell}} \cdot Sh_{\mathrm{pell}} + EI_{\mathrm{BF}} \tag{4}$$

Where:

EI_{PI}: total energy intensity of pig iron production (GJ/t pig iron)

EI_{coke}: energy intensity of coking (GJ/t coke)

F_{coke}: amount of coke required per ton of pig iron, which was assumed to be 0.4t coke/t pig iron

EI_{sint}: energy intensity of sintering (GJ/t sinter)

F_{sint}: amount of sinter required per ton of pig iron; we assumed 1.5 t sinter/ pig iron

Sh_{sint}: share of sinter from total iron ore used in ironmaking; we assumed 85%

EI_{pell}: energy intensity of pelletization (GJ/t pellet)

F_{pell}: amount of pellet required per ton of pig iron; we assumed 1.5 t pellet/ pig iron

Sh_{pell}: pellet share of total iron ore used in ironmaking; we assumed 15%

EI_{BF}: energy intensity of ironmaking in BF (GJ/t pig iron)

Thus, the final energy intensity of BF/BOF and EAF steel production can be calculated, excluding auxiliary energy use, as shown in Equations 5 and 6.

BF-BOF route:

$$EI_{\mathrm{BF\_BOF\_X}} = EI_{\mathrm{PI}} \cdot F_{\mathrm{PI,BOF}} + EI_{\mathrm{BOF}} + EI_{\mathrm{rolling}} \cdot F_{\mathrm{rolling}} \tag{5}$$

EAF route:

$$EI_{\mathrm{EAF\_X}} = EI_{\mathrm{PI}} \cdot F_{\mathrm{PI,EAF}} + EI_{\mathrm{EAF}} + EI_{\mathrm{rolling}} \cdot F_{\mathrm{rolling}} \tag{6}$$

Where:

$EI_{\mathrm{BF-BOF-X}}$: final energy intensity of BF/BOF steel production (GJ/t crude steel)

$F_{\mathrm{PI,BOF}}$: ratio of pig iron used as feedstock per ton of crude steel produced by BOF

EI_{BOF}: energy intensity of BOF steelmaking (GJ/t crude steel)

EI_{rolling}: average energy intensity of rolling process (GJ/t)

F_{rolling}: ratio of rolled steel per crude steel; we assumed 0.95 t finished steel/t crude steel

$EI_{\mathrm{EAF-X}}$: energy intensity of EAF steel production (GJ/t crude steel)

$F_{\mathrm{PI,EAF}}$: ratio of pig iron used as feedstock per ton of crude steel produced by EAF process

EI_{EAF}: energy intensity of EAF steelmaking process (GJ/t crude steel)

The ratio of pig iron used as feedstock in EAF production per ton of crude steel produced and the share of total Chinese steel production represented by the EAF process are defined in scenarios in Section 3.3.

We have to account for the energy use of auxiliary processes to determine their final energy intensity, $EI_{Aux,i,t}$. We added $EI_{Aux,i,t}$ to $\mathrm{EI}_{BF-BOF-X}$ and EI_{EAF-X} to calculate EI_{BF-BOF} and EI_{EAF}, which are the final energy intensities of BF/BOF and EAF steel production processes, respectively, including auxiliary energy use.

Finally, we can calculate the combined final energy intensity of the China's iron and steel industry from the following equation:

$$EI = EI_{\mathrm{BF-BOF}} \cdot Sh_{\mathrm{BOF}} + EI_{\mathrm{EAF}} \cdot Sh_{\mathrm{EAF}} \tag{7}$$

Where:

Sh_{BOF} and Sh_{EAF} are the contributions of BF/BOF and EAF processes to total steel production in China in each year, respectively.

The total energy consumption of the Chinese iron and steel industry is represented by:

$$TU_t = EI_t \cdot P_t \tag{8}$$

Where:

TU_t: the total energy consumption in year t

P_t: the steel production in year t (see Section 3.2).

3.2 Future steel production forecast

Future steel production data are calculated based on Fridley et al. (2011) and divided into structural steel (for infrastructure and construction) and product steel (used in appliances, machinery, and other products for final consumption) as well as exports.

After calculating total steel production, we calculated the steel produced by EAF and BF/BOF processes under each scenario, based on the share of total Chinese steel production that is contributed by EAF production (see Section 4.1).

3.3 Scenario definitions

There are two main ways to reduce iron and steel industry energy use and CO_2 emissions: improving the penetration rate of energy-efficient technologies such as those listed in Table 2; and adjusting the structure of steel production, i.e., increasing the proportion of EAF production and decreasing the amount of pig iron used in EAF production. We designed the scenarios for our analysis based on two steel production cases (a reference production case and an industry structure adjustment production case) and two energy-efficiency improvement forecasts (a reference energy efficiency case and a high energy efficiency case) as described in Table 3.

Table 3. Scenario definitions

Scenarios	Production	Energy-efficiency improvement
Base case	EAF share will increase to 30%, and share of pig iron in EAF will decrease to 10% in 2050 (Reference Production-REP).	Penetration rate of energy-efficient technologies will increase 2.0% and 3.0% per year from 2010-2030 and 2030-2050, respectively (Reference Energy Efficiency-REE).
Moderate 1	EAF share will increase to 30%, and share of pig iron in EAF will decrease to 10% in 2050 (Reference Production-REP).	Penetration rate of energy-efficient technologies will increase 3.0% and 3.5% per year during 2010-2030 and 2030-2050, respectively (High Energy Efficiency-HEE).
Moderate 2	EAF share will increase to 45%, and no pig iron will be used in EAF in 2050 (Structure Adjustment Production-SAP).	Penetration rate of energy-efficient technologies will increase 2.0% and 3.0% per year during 2010-2030 and 2030-2050, respectively (Reference Energy Efficiency-REE).
Advanced	EAF share will increase to 45%, and no pig iron will be used in EAF in 2050 (Structure Adjustment Production-SAP).	Penetration rate of energy-efficient technologies will increase 3.0% and 3.5% per year during 2010-2030 and 2030-2050, respectively (High Energy Efficiency-HEE).

4. Results and Discussion

The discussion of results below is divided into a discussion of future trends in the structure of the Chinese steel industry followed by a discussion of future trends in the energy intensity and total energy consumption of the industry.

4.1 Future trends in Chinese steel production

With continued rapid urbanization and high domestic demand for steel, China’s steel production will continue increasing until 2020 and then decrease rapidly under both production forecasts.

Although the steel production is decreased in 2015 with the influence of economy addition, the China's steel production will increase slowly in next 5 years and then decrease rapidly. Under the reference production (REP) forecast, steel production will peak at 860 Mt in 2020 and then gradually decrease to 510 Mt in 2050. Under the structure adjustment production (SAP) forecast, steel production will continue increasing to 680 Mt in 2020 and then decrease to 400 Mt in 2050, which is 21.6% lower than under the REP forecast. See Figure 3.

Both steel stock and steel scrap will increase under both scenarios, and the production of EAF steel will also increase at a constant rate (Chen et al., 2014; Wang et al., 2014). The share of EAF in total steel production will increase from 10% in 2010 to 30% in 2050 under the REP scenario and to 45% under the SAP scenario.

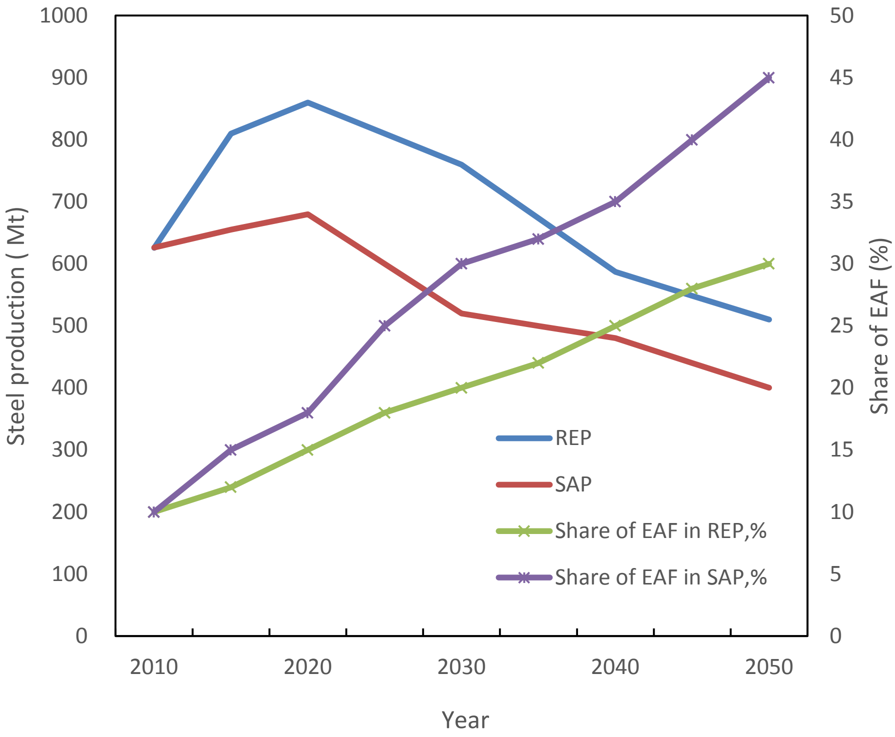
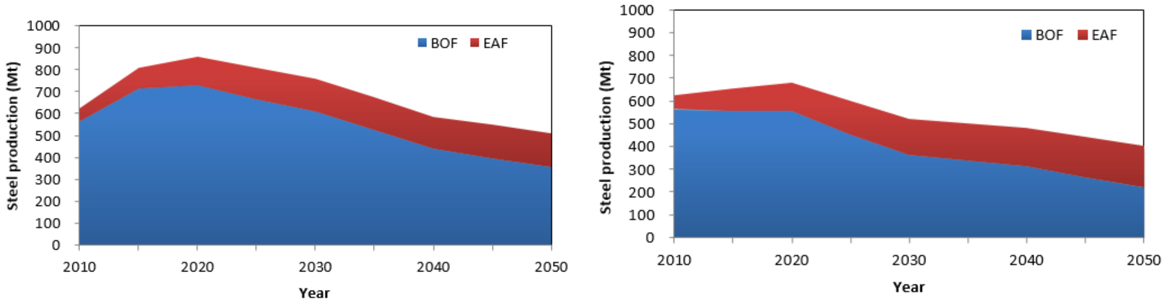


Figure 3. Forecast of steel production and EAF share

Because of the current configuration of the Chinese iron and steel industry, BF/BOF production will play an important role in the near future, and BOF production will represent the largest share of total steel production. However, as the availability of scrap increases, EAF steel production will increase, changing the production structure in China.

Under the REP forecast, BF/BOF production will peak at 731 Mt in 2020 and then gradually decrease to 357 Mt in 2050. BOF's share of total steel production will decrease at a constant rate from 90% in 2010 to 70% in 2050. EAF production will increase at a constant rate from 63 Mt in 2010 to 153 Mt in 2050, with EAF's share of total steel production increasing from 10% to 30% from 2010 to 2050 in the REP forecast. However, due to the shortage of steel scrap in China, the share of EAF steel production will not increase rapidly in the near future; the share represented by EAF production will remain at the 2010 world average, as shown in Figure 4 (a).



(a) REP (b) SAP

Figure 4. BOF and EAF steel production in the REP and SAP forecasts

In the SAP forecast, EAF production will increase rapidly and peak at 180 Mt in 2050, with EAF's share of total steel production increasing from 10% in 2010 to 45% in 2050. With decreasing use of pig iron in EAF production, BF/BOF production will decrease from 563 Mt in 2010 to 220 Mt in 2050, as shown in Figure 4 (b).

4.2 Energy intensity

Energy intensity is an important index of energy consumption in the iron and steel industry. To obtain the combined final energy intensity of the Chinese iron and steel industry, we assume the final energy intensity of the auxiliary process category based on Hasanbeigi et al. (2014) and add it to $\mathrm{EI}_{BF-BOF-X}$ and EI_{EAF-X} (Eq.(1)-Eq.(7)).

Because the energy intensity of each process is the value of key large and medium Chinese steel enterprises, which accounted for 87% of China's total crude steel production in 2010 (Hasanbeigi et al., 2014), we calculate the ratio of the energy intensity of the entire steel industry to that of large and medium enterprises based on Chen et al. (2014) and Hasanbeigi et al. (2014). Then we use the percentage share of EAF to obtain the combined final energy intensity representing China's total iron and steel industry, as shown in Table 4 and Table 5 under the REE and HEE forecasts. The "complete route" listed in the Tables refers to the combination of the EAF or BF/BOF route with relevant auxiliary processes.

Table 4. Final energy intensities (GJ/t crude steel) calculated for Chinese iron and steel industry in REE scenario

Year	Final energy intensity of EAF route excluding auxiliary energy use	Final energy intensity of BF-BOF route excluding auxiliary energy use	Combined final energy intensity excluding auxiliary energy use	Final energy intensity of auxiliary category	Final energy intensity of complete EAF route - L&M	Final energy intensity of complete BF/BOF route -L&M	Combined final energy intensity in the Chinese steel industry -L&M	Ratio of Entire steel EI to L&M EI (EAF)*	Ratio of Entire steel EI to L&M EI (BOF)*	Final energy intensity of complete EAF route -Entire steel	Final energy intensity of complete BF-BOF route - Entire steel	Combined final energy intensity in the Chinese steel industry - Entire steel
2010	11.19	16.89	16.48	1.0	12.19	17.89	17.50	1.23	1.21	15.0	21.7	**21.2**
2020	9.72	16.39	15.19	0.9	10.62	17.29	16.1	1.17	1.15	12.4	19.9	**18.5**
2030	7.99	15.89	14.31	0.9	8.89	16.79	15.2	1.17	1.15	10.4	19.3	**17.5**
2040	6.09	15.17	12.90	0.8	6.89	15.97	13.7	1.00	1.00	6.9	16.0	**13.7**
2050	4.42	14.43	11.43	0.8	5.22	15.23	12.2	1.00	1.00	5.2	15.2	**12.2**

*The ratio comes from the difference between Hasanbeigi et al., (2014) and Chen et al. (2014) in 2010. The future ratio is assumed by the authors of the current study.

Table 5. Final energy intensities (GJ/t crude steel) calculated for Chinese iron and steel industry in HEE scenario

Year	Final energy intensity of EAF route excluding auxiliary energy use	Final energy intensity of BF-BOF route excluding auxiliary energy use	Combined final energy intensity excluding auxiliary energy use	Final energy intensity of auxiliary category	Final energy intensity of complete EAF route -L&M	Final energy intensity of complete BF-BOF route - L&M	Combined final energy intensity in the Chinese steel industry -L&M	Ratio of Entire steel EI to L&M EI (EAF)*	Ratio of Entire steel EI to L&M EI (BOF)*	Final energy intensity of complete EAF route - Entire steel	Final energy intensity of complete BF-BOF route - Entire steel	Combined final energy intensity in the Chinese steel industry -Entire steel
2010	11.19	16.89	16.48	1.0	12.19	17.89	17.5	1.23	1.21	15.0	21.7	**21.2**
2020	7.91	15.64	14.25	0.9	8.81	16.54	15.1	1.17	1.15	10.3	19.0	**17.5**
2030	6.11	14.87	12.24	0.9	7.01	15.77	13.1	1.17	1.15	8.2	18.1	**15.7**
2040	4.35	14.26	10.79	0.8	5.15	15.06	11.6	1.00	1.00	5.1	15.1	**11.6**
2050	2.85	14.13	9.06	0.8	3.65	14.93	9.9	1.00	1.00	3.6	14.9	**9.9**

* The ratio comes from the difference between Hasanbeigi et al., (2014) and Chen et al. (2014) in 2010. The future ratio is assumed by the authors of the current study.

As energy-efficient technologies are deployed, the energy-saving potential will gradually increase in both the REE and HEE forecasts. As shown in Figure 5, under the REE forecast, the energy intensity will decrease by 42% from 21.2 GJ/t in 2010 to 12.2 GJ/t in 2050, and under the HEE forecast, the energy intensity will decrease from 21.2 GJ/t to 9.9 GJ/t from 2010 to 2050.

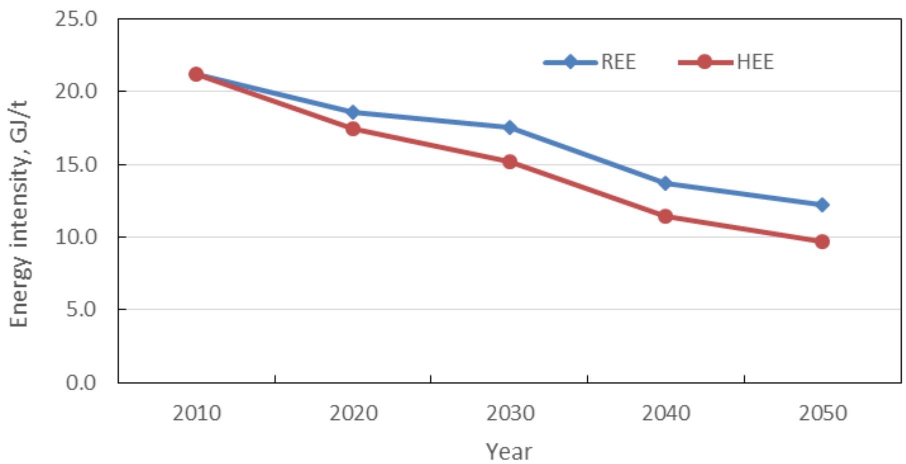


Figure 5. Energy intensity of REE and HEE forecasts

As shown in Table 6, under the REE forecast, the energy intensity of BF/BOF steel production will decrease by 29.9% from 21.7 GJ/t in 2010 to 15.2 GJ/t in 2050, and the energy intensity of EAF steel production will decrease much more quickly, from 15.0 GJ/t to 5.2 GJ/t, during the study period. Similarly, under the HEE forecast, the energy intensity of BF/BOF steel production will decrease from 21.7 GJ/t in 2010 to 14.9 GJ/t in 2050, and the energy intensity of EAF steel production will decrease much more quickly, from 15.0 GJ/t to 3.6 GJ/t during the study period, as a result of the decreasing use of pig iron in EAF production.

The difference in the energy intensity of BF/BOF steel production under REE and HEE forecasts is greater than the difference in energy intensity of EAF steel production under the two forecasts. However, decreasing use of pig iron use in EAF production means that the energy intensity of EAF production will decrease more quickly than the energy intensity of BF/BOF production under all scenarios.

Energy-efficiency improvements and industry structural adjustments both play important roles in reducing energy intensity but on different time scales. In the near future, reductions in iron and steel production energy intensity will come primarily from energy-efficiency improvements. However, in the long term, changes in the industry structure toward a greater proportion of EAF production will contribute more to reducing energy intensity.

Table 6. Energy intensity in China's steel industry (GJ/t-steel)

	Average energy intensity		BF/BOF		EAF	
	REE	HEE	REE	HEE	REE	HEE
2010	21.2	21.2	21.7	21.7	15.0	15.0
2020	18.5	17.5	19.9	19.0	12.4	10.3
2030	17.5	15.7	19.3	18.1	10.4	8.2
2040	13.7	11.6	16.0	15.1	6.9	5.1
2050	12.2	9.9	15.2	14.9	5.2	3.6

4.3 Total energy consumption

Increased steel production is the main force driving energy consumption before 2020 under the base-case and moderate 1 scenarios. From 2020 on, the adoption of advanced energy-efficient technologies along with adjustments in the industry's production structure result in a gradual decrease in energy consumption. Under the moderate 2 scenario, energy consumption decreases from 13,262 petajoules (PJ) in 2010 to 12608 PJ in 2020 and then decreases steadily to 4,890 PJ in 2050 (see Figure 6). Under the advanced scenario, energy consumption decreases steadily from 13,271 PJ in 2010 to 3,942 PJ in 2050. The advanced scenario energy consumption in 2050 is 37% lower than the base-case scenario value in 2050.

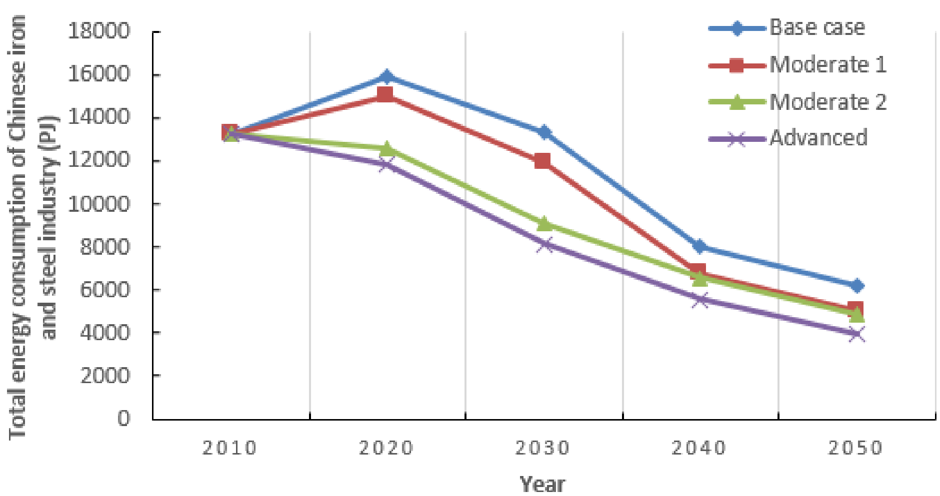


Figure 6. Total iron and steel industry energy consumption under different scenarios

5. Policy roadmap

The results of our simulations of steel production and energy intensity suggest the need for a policy roadmap to ensure that the energy-saving and emissions reduction potential of both energy-efficient technologies and steel industry structural adjustments are realized. Such a roadmap needs to take into account the barriers to improving the steel industry's energy efficiency and adjusting its structure. To assist in the development of appropriate and effective policies, this section summarizes the barriers to saving energy and our recommendations for short-term (2010-2030) and long-term (2030-2050) policies.

5.1 Barriers to saving energy in China's iron and steel industry

Table 7 shows the behavioral, economic, and technical barriers to saving energy through adoption of energy-efficient technologies and changes in production structure in China's iron and steel industry. We divide these barriers into four categories: structural, information/knowledge, management & regulations, and cost & finance (UNEP,2006; Hasanbeigi et al., 2010).

An unavoidable structural barrier results from increasing domestic demand for steel to meet the needs of continued, rapid urbanization, combined with a lack of available scrap, which limits the share of demand that can be met by EAF production. Among the reasons for the growing demand for steel are short building (product) lifetime, short-sighted urban planning, and low-quality products.

The second category of barriers to increasing the efficiency of steel production includes both lack of information and knowledge and limited application of information and knowledge. Manufacturers first need to obtain information and knowledge about energy conservation strategies. However, even after an enterprise is informed about energy-saving options, management may be reluctant to act on this knowledge out of a desire to avoid uncertainty and to adopt only technologies for which there are demonstrated results.

China's iron and steel industry includes many small and medium enterprises whose equipment and technologies are outdated and thus use more energy than modernized equipment at larger and more prosperous facilities. In general, these small and medium enterprises lack awareness of energy savings and advanced energy management and are less likely to have the financial means to update their equipment. Thus, small and medium enterprises may face more barriers to adopting energy-saving measures than larger enterprises.

Table 7. Barriers to saving energy in China's iron and steel industry

Category	Barriers
Structural	• High domestic demand for steel products • Low availability of scrap • Weak implementation /enforcement of phasing out outdated capacity
Information / knowledge	• Uncertainty about performance and future cost of technologies • Lack of expertise and personnel knowledgeable about energy efficiency • Lack of practical studies demonstrating effectiveness • Lack of information and knowledge among companies, especially small and medium enterprises
Management & regulations	• Management concerns More About Production => Efficiency investment not directly tied to production • Management concerns about time required to improve energy efficiency • Lack of enforcement of government regulations • Inadequate maintenance and updating of technologies • Lack of enforcement of minimum energy performance standards
Cost & finance	• Enterprise concerns about the investment costs for energy-efficiency measures • Fluctuations in energy prices • Lack of financial resources, especially at small and medium enterprises

5.2 Policy recommendations

Our analysis and findings demonstrate that adoption of energy-efficient technologies will be the main driver of near-term energy savings in China's iron and steel industry. The Chinese government has already promoted some energy-efficient technologies in the 12th Five-year plan for the iron and steel industry (Li and Zhu, 2013); however, to achieve the full potential of efficient technologies, subsequent five-year plans should increase the penetration rate of these technologies and add new technologies (Wen et al., 2014), such as low-temperature waste heat power generation and cascade use of energy. Our recommended policy roadmap is shown in Figure 7.

In addition, the structure of iron and steel industry should be adjusted by adoption of policies to increase the share of EAF steel production and decrease the amount of pig iron used in EAF production. To date, no government policies are focused on transforming the structure of the industry or reducing the use of pig or molten iron in EAF production (Wang et al., 2014). We recommend that the government guide investment to increase the share of EAF production and resolve technological barriers to this shift. From a technological perspective, effective policies would include: increasing research, development, and demonstration of new technologies; increasing waste management capacity for scrap; and improving product quality/eco-design.

We also recommend adding polices and measures to enhance promotion of energy-efficient technology, including: 1) Setting strict standards for industry updates, 2) Eliminating outdated technologies, and 3) Improving scrap management and reducing scrap prices to facilitate an increased share of EAF production.

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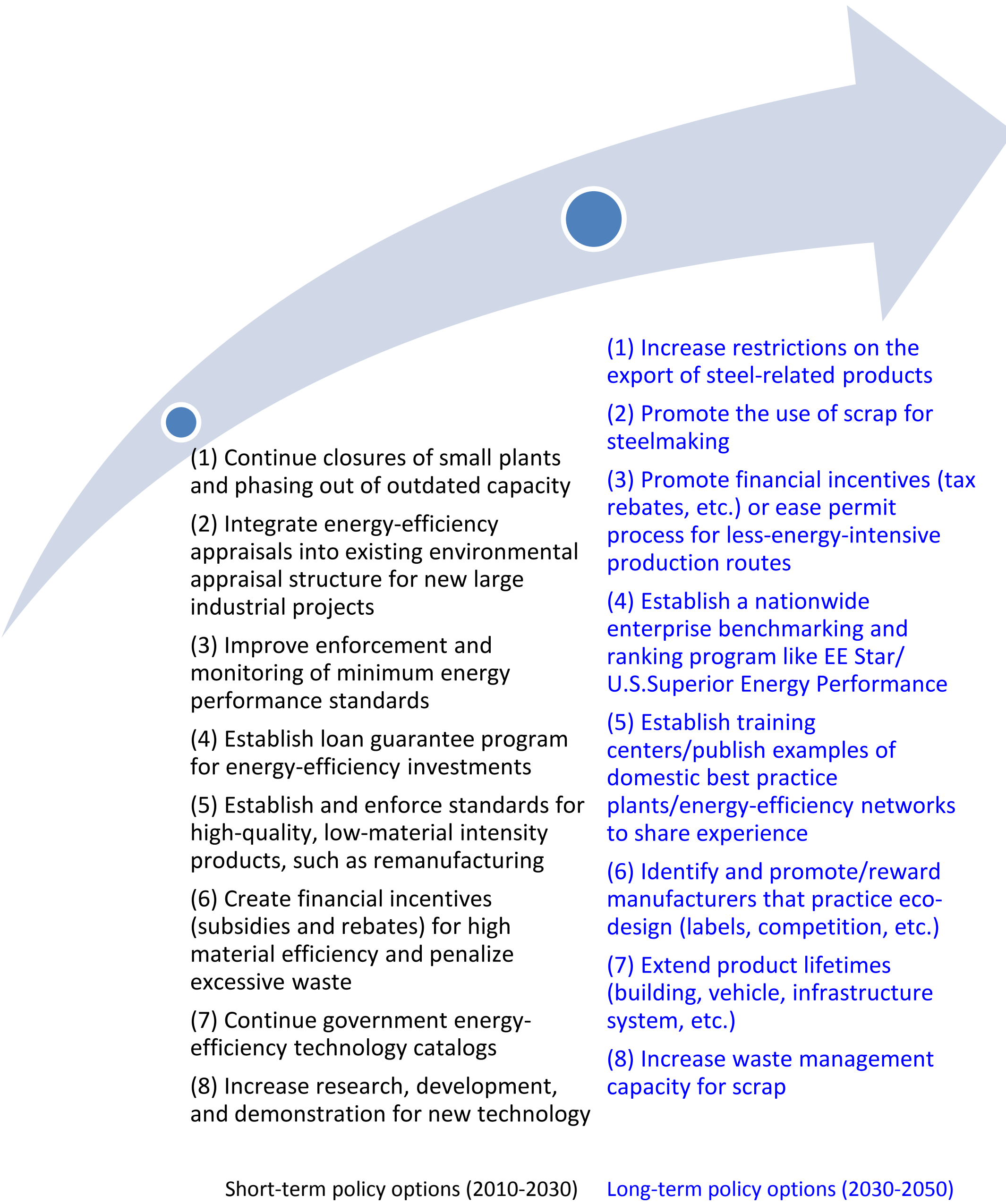

Figure 7. Policy roadmap for reducing energy use in Chinese steel industry

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