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Article

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Assessment on the energy flow and carbon emissions of integrated steelmaking plants

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ABSTRACT

China's iron and steel industry has developed rapidly over the past two decades. The annual crude steel production is nearly half of the global production, and approximately 90% of the steel is produced via BF–BOF route that is energy-intensive. Based on the practice of integrated steelmaking plants, a material flow analysis model that includes three layers, i.e., material, ferrum, and energy, was constructed on process levels to analyze the energy consumption and carbon emissions according to the principle of mass conservation and the First Law of Thermodynamics. The result shows that the primary energy intensity and carbon emissions are 20.3 GJ/t and 0.46 tC/t crude steel, respectively, including coke and ancillary material's preparation. These values are above the world's average level of the BF–BOF route and could be regarded as a high-performance benchmark of steelmaking efficiency. However, the total energy consumption and carbon emission from steelmaking industry were approximately 13 095 PJ and 300 MtC, respectively, on the best practice estimation in 2011, and are still large numbers for achieving the goal of reducing global warming. The potential carbon reduction will be limited if no significant changes are undertaken in the steel industry.

1. Introduction

The climate change has been a hot issue around the globe since the agreed framework for all international climate change deliberations, the United Nations Framework Convention on Climate Change (UNFCCC), ratified in 1994 and implemented in the Kyoto Protocol in 1997. Currently, China has become the world's second-largest economy and the biggest energy consumer. The iron and steel industry is one of the most important industrial sectors in term of CO_2 emissions which is a major factor in global warming. China alone responsible for over 50% of CO_2 emissions from global steel production, and the climate change objectives – keeping global warming to below 2 °C by 2050 – will not be achieved without the full participation of Chinese steel industry (European Steel Association, 2009).

In the current steel industry, there are two main process routes for crude steel production: the blast furnace and basic oxygen furnace (BF–BOF) steelmaking and the electric arc furnace (EAF) steelmaking. The former is based on the use of coal and iron ore, which is a traditional way of steel production; the latter is based on the use of scraps and electricity. The BF–BOF route consumes significantly more energy and produces more carbon emissions than the EAF route. Besides, the BF–BOF steelmaking also produces significant amounts of energy byproducts, such as coke oven gas, BF-gas, BOF-gas, and steam. If these gaseous energy carriers are recycled, the energy efficiency will be improved significantly. As the world's largest steel producer, China produced 683 Mt crude steel in 2011, and about 92% of the steel were produced via the BF–BOF route (World Steel Association, 2011).

After the Circular Economy Promotion Law of China had been ratified in 2008, the concept of circular economy in the iron and steel industry was adopted broadly. This law encourages energy saving, emission reduction, material and energy recycling as necessary foundations. Current steelmaking industry has widely deployed various energy saving technologies such as Coke Dry Quenching (CDQ), Top-pressure Recovery Turbine (TRT), Coal Moisture Control (CMC), continuous casting, slab hot charging and delivery, and recovering energy from coke oven gas, BF gas, con-

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vert gas and steams, all of which have improved energy conservation and emission reduction impressively (Zhang and Wang, 2008; Chen et al., 2014). Many studies have been conducted to analyze the reduction options of carbon emission within the iron and steel industry from the engineering or economic perspectives (Worrell et al., 1997, 2001; Price et al., 2002; Wu et al., 2006). Different methods have been adopted to evaluate the energy efficiency and reduction potential for carbon emissions and the driving forces for emission changes at present and in the future, which range from empirical analyses and decomposition analyses to scenario analyses, using various data models such as Malmquist Productivity Index (MPI) model, Data Envelopment Analysis (DEA) model, Conservation Supply Curve (CSC) model, logarithmic mean Divisia index (LMDI) model, and the China TIMES model developed within the Energy Technology System Analysis Program (ETSAP) of the International Energy Agency (Liu et al., 2007; Wang et al., 2007; Wei et al., 2007; Guo et al., 2011; Choi et al., 2012; Bian et al., 2013; Tian et al., 2013; Lin and Wang, 2015; Ouyang and Lin, 2015; Zhang and Da, 2015). This paper provides an approach carried by the process of life cycle inventory to estimate the energy intensity and carbon emissions in China's integrated steelmaking plants, which offers some essential benefits that cannot be obtained from other ways when the inventory is considered (Iosif et al., 2010). This approach is based on the principle of mass conservation and the First Law of Thermodynamics, which deal with the amounts of materials and energy of various forms transferred between a system and its surroundings and also deal with the changes in the mass and energy stored in the system. This approach is convenient for studying changes in energy consumption and carbon emissions; however, it is insufficient for forecasting future emissions. This inadequacy can be remedied by empirical and scenario analyses.

2. Data and methodology

2.1. Boundaries

To analyze the potential for energy conservation and carbon reductions, we disaggregated the integrated steel plants by major steelmaking processes. Materials, energy, and ferrum flows were identified and analyzed in each process under a unified framework. The system boundary includes four processes, coking, sintering, iron making, and steel making, based on available data. Fig. 1 shows the interconnection of these processes. The processes of steel casting, hot rolling, cold rolling, galvanizing and coating were excluded because of their relatively less energy consumption and carbon emission. For example, the average primary energy intensity for casting and rolling that use thin slab is merely 0.6–0.9 GJ/t steel (Worrell and Moore, 1997).

Products imported to these processes such as oxygen, fresh water and electricity were counted by adding the energy used for producing these products to the total energy input. The electricity required to operate the processes was considered within the system, which included an internal power station using the steelwork gas (e.g. BF gas, Coke gas, and BOF gas). For the first stage of this study, the system does not count the embodied energy of scraps used in the BOF process and the energy demands for mining and beneficiation of raw materials, their transportation, and the waste storage.

2.2. Data description

The heating value of a fuel source represents the amount of heat released during combustion. This study uses the lower heating value (LHV) to convert the physical quantities of fuels to a common energy unit by the convention of China's energy statistics. The conversion rates are provided in the General Principles for Calculation of the Comprehensive Energy Consumption, GB2589-2008 (Standardization Administration of China, 2008a). Table 1 provides the conversion factors of fuels and energy carriers used in this analysis. CO_2 emissions are expressed in metric tons of carbon. The carbon conversion factors for calculating carbon emissions from energy consumption are derived from the National Development and Reform Commission of China (NDRCC). We define the energy intensity in terms of physical output rather than others, e.g. economic output.

The carbon emissions caused by the decarbonization of limestone ($CaCO_3$) and dolomite ($MgCO_3$), which act as fluxes in ironmaking, were not counted, and these emissions amount to 0.44 t CO_2/t limestone and dolomite (Gielen, 1997). The carbon content in the crude steel, usually less than 1.7%, were not subtracted from the primary steel production.

In the sintering model, we assume the iron contents in ores are between 62% and 65% Fe, because the Australian iron ores (62% Fe) are the benchmark throughout the industry, and the grade of Brazilian iron ores is usually between 63.5% and 65% Fe. Both Australia and Brazil are the major sources of iron ores for China. Meanwhile, low-quality ores ($\leq$60% Fe) were restricted to be imported by the official China Chamber of Commerce of Metals, Minerals and Chemicals Importers and Exporters, known as CCCMC, from 2010.

As an illustration, Table 2 shows the major materials in the MFA model. When data on specific processes were not available, substitute values were adopted from the recent relevant literature based on process energy intensity or just left it blank.

2.3. Material flow analysis

Material flow analysis (MFA) is a procedure to quantify and evaluate the flows and stocks of goods and substances in the perspective of sustainable use of materials. It is used in the field of industrial ecology on various spatial and temporal scales (Brunner and Ma, 2009). Over the past decades, MFA has become a reliable instrument to describe material flows and stocks within varied systems.

MFA is based on the principle of mass conservation, which assumes that mass cannot vanish and could be expressed in the simple form of balance equation (1) below. Meanwhile, the energy consumption obeys the First Law of Thermodynamics, which could also be used to establish the energy balance for process investigation.

$$\sum Inputs = \sum Outputs + Changes\ in\ stock. \quad (1)$$

These principles serve as means of control in the case where all flows are known, and they can be used to determine one unknown flow per process. Therefore, we constructed an MFA model that includes three layers (material, ferrum, and energy) to count both the material and energy consumption in integrated steelmaking plants.

In this paper, the aim of MFA is to describe and analyze the steelmaking system as simple as possible, where only the primary inputs and outputs are of interest, but it is in enough detail to make right results to evaluate the energy efficiency and carbon emissions. This MFA model can also effectively avoid the double counting of material and energy consumption by considering the interactions between processes.

In this model, we assume that all the materials and energy in the system boundary are used to preheat material handling equipment, and the transfer efficiency of substance and energy between processes is not examined.

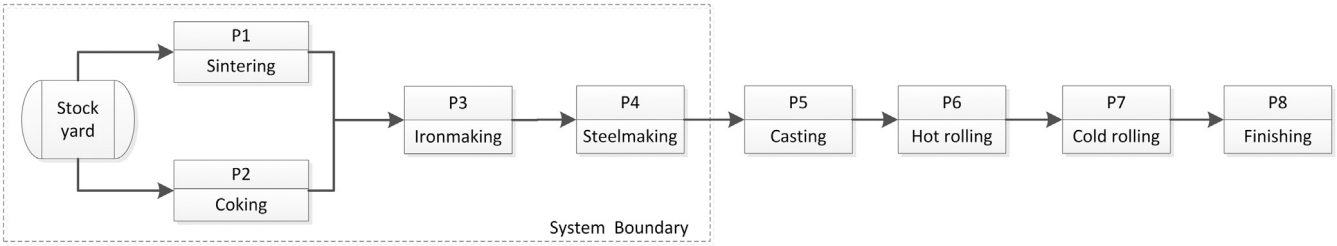

Fig. 1. The key iron and steelmaking processes and the system boundary.

Table 1
Energy content of fuels and energy carriers.[a].

Fuel	Unit	LHV (MJ/unit)	Energy carrier	Unit	Energy intensity (MJ/unit)
Coke	kg	28.435	Fresh water	t	2.51
Cleaned coal	kg	26.344	Oxygen	m^3	11.72
Steam (low pressure)	t	3.763	Nitrogen	m^3	11.72
BF gas	m^3	3.763	Argon	m^3	–
Coke gas	m^3	16.726–17.981	Blow	m^3	0.88
			Electricity	kWh	3.6[b]

[a] Energy intensity in China is measured in units of kilograms of coal equivalent per metric tonne (kgce/tonne). To convert kgce to MJ, multiply by 29.307.
[b] Energy equivalent value.

Table 2
Materials consumed in the main processes of China's integrated iron and steel industry (Standardization Administration of China, 2008a,b, 2007; Ministry of Environmental Protection of China, 2008a,b,c; Yin, 2008).

Catalog	Input material	Unit	Quantity	Output material	Unit	Quantity
Coking	Coking coal	kg	1326	Coal coke	kg	1000
	BF gas	m^3	970	Coke gas	m^3	420
	Electricity	kWh	35	Recovered steam	kg	574.24
	Fresh water	m^3	0.72	Waste gas	m^3	2000
				Electricity	kWh	1000
Sintering	Concentrate fines	kg	895.50	Sinter	kg	1000
	Hearth	kg	97.85	others	kg	–
	Flux	kg	140.70	Waste gas	m^3	–
	Others	kg	98.10	Dust	kg	3 ± 1
	Coke gas	m^3	3.12	Recovered steam	kg	75
	Fine coke	kg	51.04			
	Fresh water	kg	87			
	Steam	kg	1.1			
	Electricity	kWh	4.93			
Iron making	Sinter	kg	1314.17	Hot iron	kg	1000
	Raw ore	kg	269.17	Slag	kg	298
	Coke	kg	288	Dust	kg	20 ± 5
	Injected coal	kg	205	BF gas	m^3	1391.96
	Electricity	kWh	110	TRT electricity	kWh	36.44
	Hot blast	GJ	1.89			
Steel making	Hot iron	kg	950	Hot steel	kg	1000
	Scrap	kg	140	Slag	kg	85
	Fresh water	kg	310	Dust	kg	10
	Steam	kg	5.5	BOF gas	m^3	105
	Oxygen	m^3	51.08	Recovered steam	kg	41.3
	Nitrogen	m^3	23.11	Others		–
	Argon	m^3	0.98			
	Coke gas	m^3	1.25			
	Electricity	kWh	35.5			

3. Results

After understanding the material and energy flows in the main processes, we estimate that the primary energy intensity and carbon emission of the integrated steelmaking plants are 20.3 GJ/t and 0.46 tC/t crude steel, respectively, including coke and ancillary material's preparation. The material consumption is 2.69 t/t crude steel, excluding water and air. Table 3 shows the detail of the mass and energy consumption and the carbon emissions. Fig. 2 ranks the top 5 materials and byproducts by the mass quantity of producing one metric ton of crude steel. The proportions of mass consumption are iron ores 55.7%, coal 23.8%, flux 6.5%, scrap 5.2%, and oxygen 2.7%, respectively, to the total input mass.

The MFA model shows that the direct energy consumption is 18.7 GJ/t, which is mainly from coal (16.9 GJ) and hot blast (1.8 GJ) and represents 92% of the comprehensive energy intensity (Fig. 3). This model also examined the recovered energy and recycled energy, which are mainly in the forms of gas, steam, and electricity (Fig. 4).

Table 3 also reveals the change in ferrum at each process. The total ferrum consumption was about 1.1 tons to produce a ton of crude steel that contains about 0.99 tons of ferrum. Therefore, the

Table 3
Materials and energy consumption per metric ton of crude steel.

Process	Material	Mass (kg)	Ferrum (kg)	Energy (MJ)	CO_2 emission (kg C)
Coke making					
Input	Coking coal	447.3		11783.3	269.4
	Heating gas (BF gas)	163.6 ± 16.4		1368.2	
	Electricity			42.5	1.0
Output	Coal coke	337.3		10320.6	
	Coke gas	70.8 ± 7.1		2458.6 ± 88.9	
	Recovered steam	193.7		728.9	
	Waste gas & etc.	202.7 ± 17.8		414.9 ± 88.9	
	Recovered electricity			1214.4	
Sintering					
Input	Concentrate fines	1118.0	715.5 ± 11.2		
	Hearth	122.2	78.2 ± 1.2		
	Flux	175.6			
	Others (OG slurry, etc.)	122.5			
	Coke gas	2.0 ± 0.2		67.6 ± 2.4	
	Fine coke	63.7		1811.8	
	Fresh water	108.6		0.3	0.01
	Steam	1.4		5.2	0.1
	Electricity			180.4	4.1
Output	Sinter	1248.5	786.5 ± 8.8		
	Others	–			
	Waster gas	–			
	Dust	3.8 ± 1.3	7.2 ± 14.3		
	Recovered steam	93.6		352.4	
Iron-making (BF)					
Input	Sinter	1248.5	786.5 ± 8.8		
	Raw ore	255.7	163.7 ± 2.6		
	Coke	273.6		7779.8	
	Injected coal	194.8		5130.5	117.3
	Electricity			376.2	8.6
	Hot blast			1795.5	41.1
Output	Hot iron	950.0	916.8 ± 6.7	9195.7 ± 24.5[a]	
	Slag & etc.	283.1	33.4 ± 11.4	523.7 ± 24.5	
	Dust	19.0 ± 4.8			
	BF gas	720.4 ± 4.8		5238.0	
	TRT electricity			124.6	
Steel-making (BOF)					
Input	Hot iron	950.0	916.8 ± 6.7	9195.7 ± 24.5[a]	
	Scrap	140.0	138.6 ± 1.4		
	Fresh water	310.0			
	Steam	5.5		20.7	0.5
	Oxygen	73.0		598.7	13.7
	Nitrogen	28.9		270.9	6.2
	Argon	1.8			
	Coke gas	0.6 ± 0.1		21.7 ± 0.8	
	Electricity			127.8	2.9
Output	Hot steel	1000.0	990.0 ± 10.0	9140.5 ± 103.5[a]	
	Slag	85.0	65.4 ± 12.1	157.3 ± 12.8	
	Dust	10.0			
	BOF gas	52.5 ± 5.3		782.3 ± 99.8	
	Recovered steam	41.3		155.4	
	Others	321.0 ± 5.3			

[a] The enthalpy of pig iron is 1221 kJ/kg at 1350 °C.

conversion efficiency of ferrum is about 90.3% for the integrated steelmaking plants.

We use the Sankey diagrams, in which the width of arrows is shown proportionally to the flow quantity, to visualize the material and energy transformation between processes (Fig. 5). These diagrams provide a clear framework to summarize the complex information of the material and energy efficiency and flows in each process. Fig. 5(a) and (b) compare the material and energy flows of producing one metric ton of crude steel. Leaving aside of the minor portion of mass and energy supply and reproduction, it is clear that the material and energy flows track the ways obviously different before the BF process and couple together similarly after the BF. It reveals that the reduction of coal consumption is the primary issue for the reduction of carbon emissions, and the recycle of byproducts could improve the energy efficiency.

4. Discussion

4.1. Energy consumption and carbon emissions

Studying the material and energy flows in each process, we found that the primary energy intensity and carbon emission were 20.3 GJ/t and 0.46 tC/t crude steel, respectively, including coke and ancillary material's preparation, which represented the performance of advanced integrated steelmaking plants in China by 2011. However, this energy intensity was 14.7% higher than the official average value of 605 kgce/t (17.7 GJ/t) of China's steel industry in 2010 (State Council of China, 2012), and that is quite contrary to the performance as we expected. A most possible reason is that the Chinese official energy-use statistics for the iron and steel industry are based on enterprise information, as

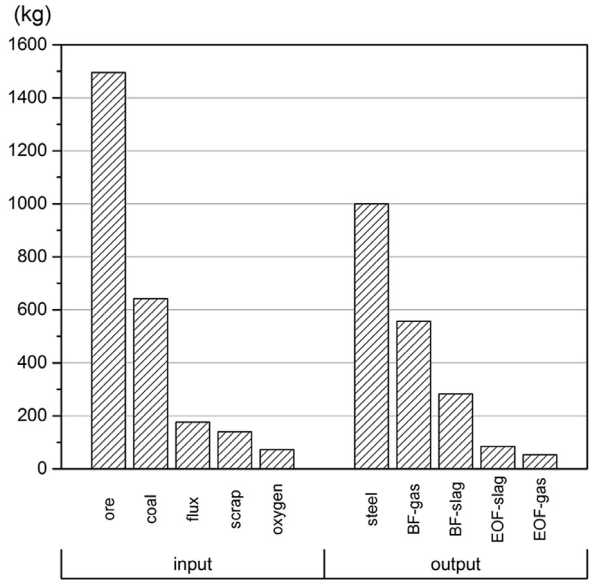

Fig. 2. Ranks of material consumption and byproducts per metric ton of crude steel.

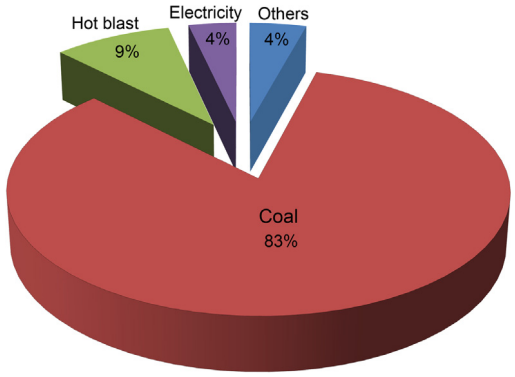

Fig. 3. The shares of comprehensive energy consumption for one metric ton of crude steel.

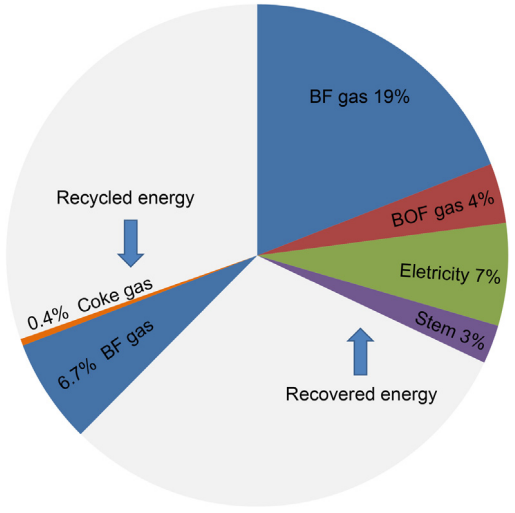

Fig. 4. The shares of recovered and recycled energy for one metric ton of crude steel.

stipulated in the corporate law rather than product laws, in which the enterprise energy use does not always correspond to products. In China, about two-thirds of consumed coke in the steel industry are produced separately by independent coking plants, and the steelmaking plants themselves produce the other one-third. In this study, the net energy consumption in the coking process was 3.6 GJ/t crude steel. Therefore, if the coking process had been excluded, the energy intensity would drop to 16.7 GJ/t crude steel, that may correctly represent the actual performance. Worldsteel (World Steel Association, n.d.a) provided 20.9 GJ/t and 0.51 tC/t pig iron as world's average energy intensity and carbon emission. This study shows that the energy intensity and carbon emissions were 15.9 GJ/t and 0.44 tC/t pig iron, respectively, including the coal combustion in coke-making and BF processes, which are much better than the average.

Price et al. (2002) pointed out that the primary energy intensity and carbon emission were 36.7 GJ/t and 0.87 tC/t crude steel respectively in China in 1995, after adjusting the statistical data not directly associated with steel production and double-count energy consumption. They also indicated that the best practice energy intensity and carbon emission were 20.2 GJ/t and 0.43 tC/t crude steel, if best practice technology had been used to produce the same amount and types of steel. This study shows the goal has been almost achieved by the integrated steelmaking plants in China. It may also mean that a further improvement of energy efficiency and carbon reduction will be difficult in the future. Reviewing the development of China's steel industry (Fig. 6), we found that the steel production increased 555 Mt from 2000 to 2011. In other words, 81% of the steel production was produced from the newly established steelmaking capacity compare to 2000. The newly constructed or upgraded steel plants usually have similar technology and energy efficiency as we analyzed in this paper. Especially, there were about 80% of steel production are produced from the key medium and large-size steel enterprises in China.

However, published studies (International Energy Agency, 2010; Xu, 2010) indicate there is still 10%–20% potential reduction of energy and carbon emission in China's steel industry, compare to its counterparts such as the Europe Union, US, and Japan. Based on the analysis above, the explanatory variables are primarily due to the structural difference in steelmaking. For example, China produced a significantly greater share of the high energy-intensive BF–BOF steel, accounting for 92% of the total crude steel in 2011. The final energy intensity of the US iron and steel industry in 2003 showed that the energy intensity of BF–BOF route (22.7 GJ/t) was about 3.7 times higher than the EAF route (6.1 GJ/t) (American Iron and Steel Institute, 2005). Sakamoto and Tonooka (2000) pointed out the emission factor of CO_2 from integrated steel plants was approximately 3.8 times higher than that from EAF route mills in Japan. Based on this assumption and the discussion above, we could estimate the total energy consumption and carbon emission caused by the crude steel production of China were 13 095 PJ and 300 MtC, respectively, in 2011.

It should be pointed out that China's economic development is unbalanced in eastern, central, and western regions. For the iron and steel industry, there are obvious regional gaps in energy-saving technologies and equipment, productive efficiency, and investment. The eastern region is ahead of the central and western regions (Yao et al., 2015) and plays a dominant role. The difference of firm-level efficiency for the enterprises in the eastern region and coastal areas is not obvious (Zhang and Wang, 2008). Since the referenced plants in this study are located in the eastern region, these estimations should be regarded as the best practice benchmark for the steel industry. Therefore, based on this estimation, the potential reduction of energy and carbon emission would be limited if no significant changes were undertaken.

4.2. Comparison of the energy consumption and carbon emissions

Although China's iron and steel industry is one of the major sources of energy consumption and carbon emissions, studies on

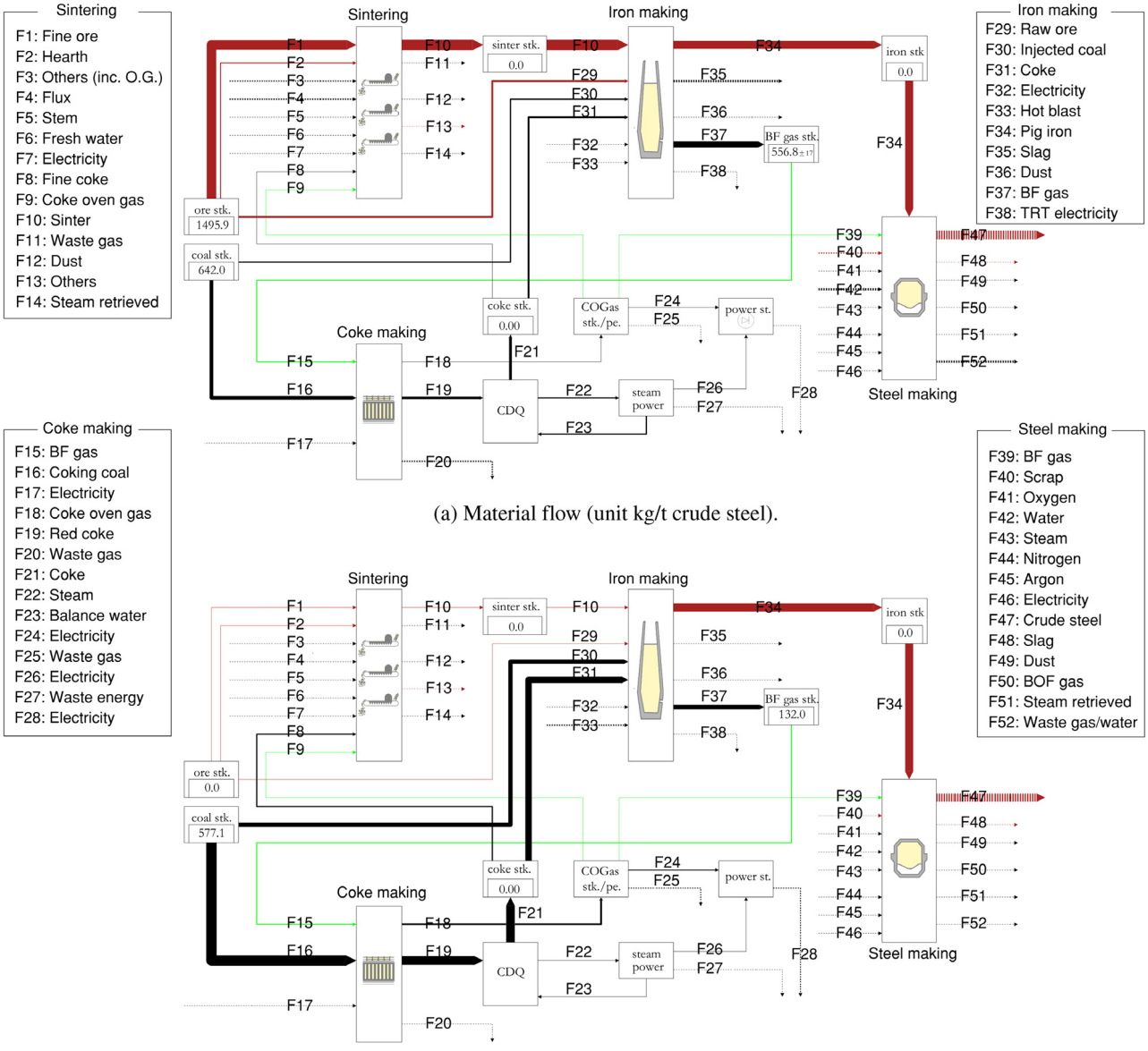

Fig. 5. Material and energy flow model for one metric ton of crude steel.

the energy conservation and carbon reduction in this industry are still limited in the scientific literature. In addition, it is relatively difficult to compare the results of carbon emissions from different research groups because of the rapid changes in boundary conditions, such as the development of technology and update of equipment in the steel industry, the steady growth of steel production, and the complicity of steelmaking.

According to the CEInet Industry Database (China Economic Information Network, 2012), the total energy consumption of China's steel industry in 2011 is 588.96 Mtce (17 261 PJ), which include the consumption of coal (299.7 Mt), coke (329.1 Mt), crude oil (1.8 kt), gasoline (111.3 kt), kerosene (3.1 kt), diesel (841.4 kt), fuel oil (91.3 kt), natural gas (2.9 billion m^3), and electricity (524.8 billion kWh). This energy consumption is 32% higher than what we estimate of 13 095 PJ in this study. Two major reasons may cause the discrepancy. First, the system boundary of steelmaking in CEInet is broader than that in this study, which extends to the process of casting, rolling, and alloy smelting. Second, the statistics of CEInet are for the whole country, which includes local middle and small enterprises where outdated and inefficient technologies are still in use. Therefore, the results calculated in this study should be considered as the best practice benchmark that reflects the energy conservation for China's integrated steel industry.

Tian et al. (2013) pointed out that the greenhouse gas (GHG) emissions from coke, sinter and steel production in BOF were approximately 1.088 billion tons CO_2e, which is about 297 MtC, and contributed to 99% of the total energy-related emission from iron and steel industry in 2010. The total production of crude steel of China is 637 Mt and 683 Mt in 2010 and 2011, respectively. If we assume the energy efficiency had not improved and the steel industrial structures had not changed in the two adjacent years, the GHG emissions would be 318 MtC, which are very close to the estimation of 300 MtC in this study. Applying more detailed data and making the system framework correspond more closely to the reality, the MFA model will yield more accurate results for the carbon emission evaluation.

The comparisons indicate that the result of energy consumption and carbon emissions is more comparable on a process level than on a country level. In most of China's key state-owned steel plants,

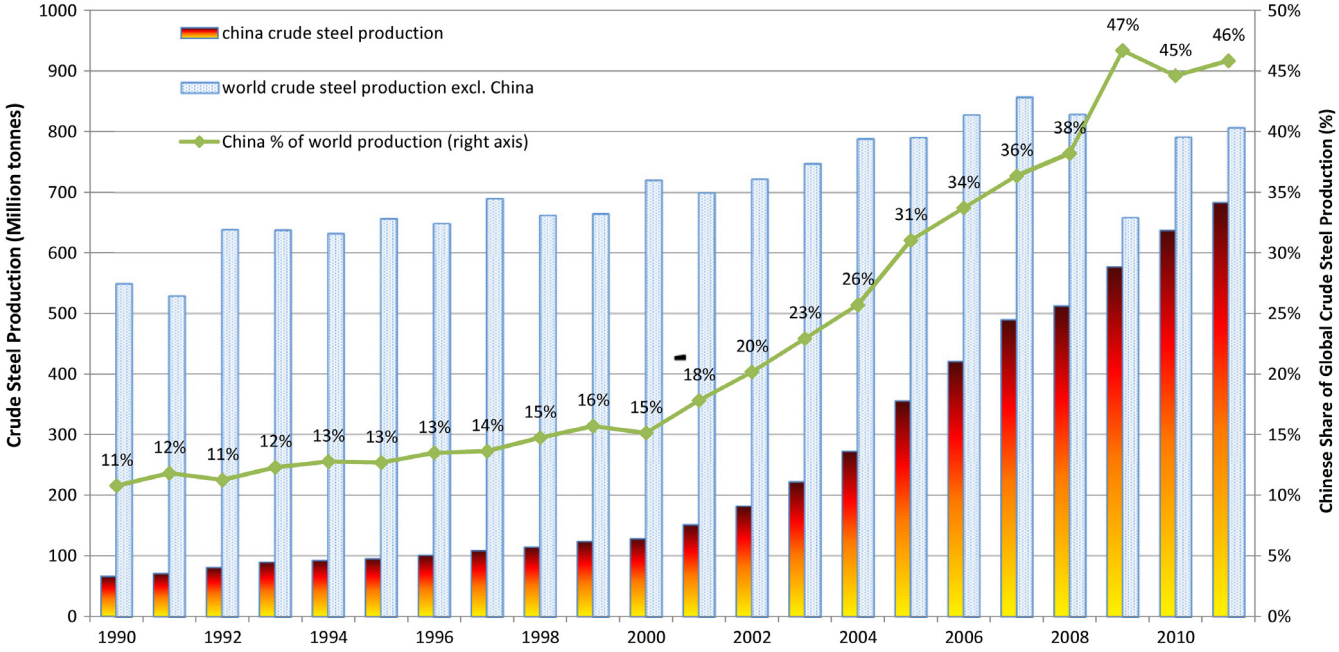

Fig. 6. Comparison of China and world crude steel production (1990–2011).
Source: World Steel Association (n.d.b).

an entire community was devoted to the production of steel, therefore, the statistics of energy and materials consumption usually include those used for various other function departments, both directly and indirectly related to the production of steel. Double counting is another problem to overestimate the inefficiency of steel industry (Worrell et al., 2001; Ouyang and Lin, 2015).

4.3. Policy implications

The rapid industrialization and urbanization in China are accompanied by large-scale infrastructure construction and enormous office and residential buildings to accommodate the huge population. Therefore, a significant amount of steel consumption is inevitable. The steel industry plays an important role in the processes, and it also needs to take responsibility for global carbon emissions.

The results show that the coal-related fuels account for 90% of the direct energy consumption, or 83% of the total comprehensive energy consumption which includes coke and ancillary material's preparation. Therefore, coal is the major driving force for carbon emission in the steel industry, and a substitution of coal by other environment-friendly energy sources such as renewable energy or nuclear power will considerably reduce carbon emissions. That means the structure of current steel industry has to be changed from the BF–BOF dominated steel production to the EAF dominated steel production. The EAF route is essentially a steel recycling process; therefore, the recovery and recycling of steel industry should be encouraged by government policies.

However, the ongoing urbanization progress needs an enormous amount of steels, which are too large to be depended on scraps or to be imported from other countries. Besides, there is no contribution to the global environment if all of the BF–BOF steel production capacity are migrated to other developing regions because the enterprises producing only pig iron have the lowest technical efficiency compare to those producing only finished steel products (Ma et al., 2002). Integrated steelmaking plants possess a substantial efficiency advantage over small and medium-scale enterprises (Zhang and Wang, 2008). The result comparison also implies that a small portion of steel products may come from the inefficient plants which consume too much energy and should be eliminated or phased out from the market. At present stage, this study shows that what is particularly required for reducing energy consumption and carbon emissions is integration more than technique innovation or plant migration.

The Paris Agreement of UNFCCC in 2015 has been favorable to new initiatives for the goal of reducing global warming. Government and the public society need more accurate and reliable results to evaluate their actions. In this study, we perform the MFA model to identify and quantify the changes and flows after the materials and energy are put into the steelmaking system, through their usage, recovery, and reuse in processes. However, these results are still insufficient. In developing the MFA model, a major obstacle has been the data absence. Many data are initially used for other works than estimating material or energy flows, and some data are considered commercial secrets. In fact, the iron and steel making processes are more complex than this simplified model. However, by applying adequate monitoring methods and providing necessary data, this model could be improved substantially and express detailed and accurate results on a firm-level to improve energy efficiency or on regional and national levels for policy recommendation.

5. Conclusions

This study adopts the MFA model to estimate the energy consumption and carbon emission in China's integrated steelmaking plants. This method, which includes three layers (material, ferrum, and energy), reveals the material and energy flows in the primary production processes and tackles the data uncertainty problems to make the assessment successful and accurate. According to this analysis, the primary energy intensity of 20.3 GJ/t and carbon emission of 0.46 tC/t crude steel, including coke and ancillary material's preparation, could be regarded as a high-performance benchmark of integrated steelmaking plants currently in China. Further estimation of the total energy consumption and carbon emission of the steel making were roughly about 13 095 PJ and 300 MtC, respectively, in 2011. We believe this estimation is relatively conservative since we have not included all possible efficiency measures

of steelmaking. Given the fact that the steel industry continues to evolve, additional updates of the analysis would be necessary to reflect the changing industry. Furthermore, many integrated steelmaking plants are located in the economic zones of coastal areas usually with other energy-intensive industries, such as chemical, petroleum, power, and cement. The material and energy interconnection and flows between different industries are worthwhile to be evaluated in the next study.

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