Energy Policy 56 (2013) 352–361

Contents lists available at SciVerse ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

An analysis of energy-related greenhouse gas emissions in the Chinese iron and steel industry

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HIGHLIGHTS

- ▶ Energy related GHG emission trajectories, features, and driving forces for Chinese ISI were explored.
- ▶ LMDI decomposition analysis was conducted for uncovering the drivers of Chinese ISI GHG emissions.
- ▶ Chinese ISI experienced a rapid growth of GHG emission.
- ▶ Construction sector is the largest embodied energy emission sector for Chinese ISI.
- ▶ Mitigation policies for Chinese ISI should consider both ISI and its supply chain related sectors.

ARTICLE INFO

Article history:
Received 9 July 2012
Accepted 24 December 2012
Available online 4 February 2013

Keywords:
Greenhouse gas emission
Iron and steel industry
LMDI

ABSTRACT

With China's increasing pressures on reducing greenhouse gas (GHG) emission, Chinese iron and steel industry (ISI) is facing a great challenge. In this paper, we address the energy-related GHG emission trajectories, features, and driving forces in Chinese ISI for 2001–2010. First, energy related GHG inventory for ISI is made for both scope 1 (direct emissions) and scope 2 (including imported electricity emission). Then, the driving forces for such emission changes are explored by utilizing the method of logarithmic mean Divisa index (LMDI) decomposition analysis. Results indicate that Chinese ISI experienced a rapid growth of energy related GHG emission at average annual growth rate of 70 million tons CO_2e. Production scale effect is the main driving factor for energy related GHG emission increase in Chinese ISI, while energy intensity effect and emission factor change effect offset the total increase and energy structure has marginal effect. Construction, manufacture of general purpose and special purpose machinery and manufacture of transport equipment sectors are main sectors for embodied emissions, amounting for more than 75% of the total embodied emissions from Chinese ISI. Such research findings propose that a detailed consideration can help make appropriate polices for mitigating ISI's energy-related GHG emission.

1. Introduction

As the largest manufacturing energy user (Watson et al., 2003) and the second largest industrial energy user (International Energy Agency-Energy Technology Systems Analysis Programme (IEA-ETSAP), 2010), accounting for approximately 4–5% of the world's total GHG emissions, iron and steel industry (ISI) has become one of the major contributors to the rapid growth of total GHG emission in the world. Therefore, ISI is playing a significant role on GHG emission reduction. Currently, China is the biggest country on iron and steel production and consumption, contributing around 50% of iron and steel products in the world (World Steel Association (WSA), 2012). Total production of crude steel in China increased from 152 million tons in 2001 to 627 million tons in 2010 (World Steel Association (WSA), 2001–2011) (shown in Fig. 1). Besides, China is also the biggest country for iron ore import, accounting for about 60% of the global total import (World Steel Association (WSA), 2001–2011) (shown in Fig. 2). Rapid industrialization and urbanization are the two main reasons for the huge demand of iron and steel products, especially from construction sector and industrial manufacturing sectors. Such an increase also results in the rapid growth of related energy consumption, increased from 107 million tons of standard coal in 2001 to 464 million tons of standard coal in 2010 (shown

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http://dx.doi.org/10.1016/j.enpol.2012.12.068

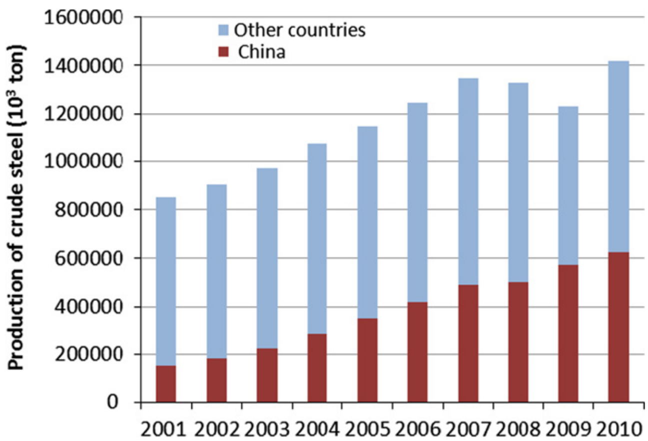

Fig. 1. Comparison of crude steel production between China and other countries.

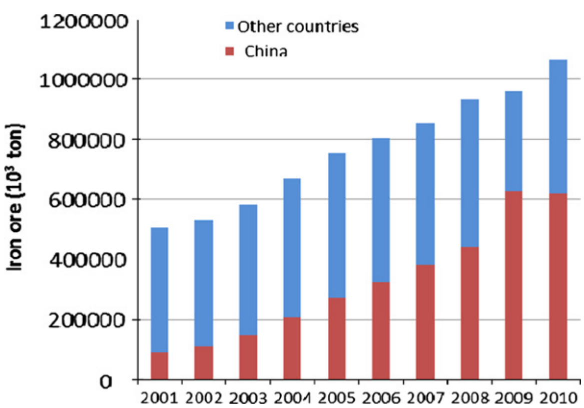

Fig. 2. Comparison of iron ore import between China and other countries.

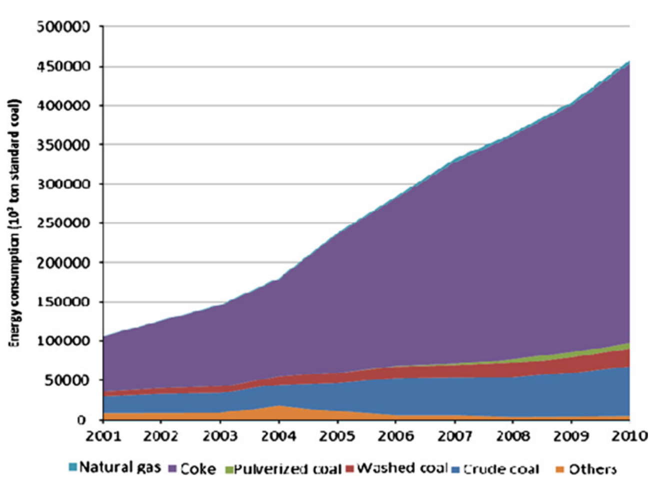

Fig. 3. Primary energy consumptions in Chinese iron and steel industry.

in Fig. 3). Moreover, ISI is the third largest GHG emission sector in China, following power generation sector and construction material sector and accounting for 10% of total GHG emission in China (Zeng et al., 2009). Therefore, to make appropriate policies for GHG emission reduction in Chinese ISI is imperative.

Currently, in order to respond national policies on energy conservation and emission reduction (Geng and Sarkis 2012), several measures have been promoted in Chinese ISI, including "National Industrial Structure Adjustment Directory (for steel)", "Outline of China Resources Comprehensive Utilization", "Cleaner Production Standard for Steel Industry", "Construction and Implementation Programme of Energy Management Center in Iron and Steel Enterprises" (China Iron and Steel Association (CISA) 2001–2011). The main feature of these measures is to encourage the application of energy efficient technologies and management in ISI companies. Generally, the implementation of these measures has brought positive effects. For instance, till the end of October 2010, the Baosteel in Shanghai (the fourth largest steel company in the world) had saved a large amount of energy source with a figure of 1.26 million tons standard coal through applying innovative technologies and promoting integrated energy management measures. Similar cases can also be found in the Anshan Iron and Steel company (the third largest steel company in the world) and the Wuhan Iron and Steel company (the fifth largest steel company in the world) (China Iron and Steel Association CISA, (2001–2011)). From the whole country point of view, energy demand per unit output from ISI process (such as coke production, sinter production, iron production and steel production from basic oxygen furnace (BOF) and electric arc furnace (EAF)) has decreased since 2005 and energy cascading efforts (such as the use of by-product gas from coke oven, blast furnace and converter) have increased (China Iron and Steel Association CISA, 2001–2011). Academically, several studies on this sector have been conducted. For instance, Guo and Fu (2010) and Hidalgo et al. (2005) found that the application of emission reduction technologies was one efficient measure. Through scenarios analysis, Hu et al. (2006) proposed that reducing production, increasing the use of scrap steel and promoting carbon capture and storage (CCS) were main measures to reduce GHG emission of ISI. Zeng et al. (2009) found that the promotion of clean development mechanism (CDM), corporate social responsibility (CSR), energy auditing and emission reduction-oriented investment can efficiently reduce ISI's carbon emission. In addition, emission trading mechanism (ETM) is also considered as one efficient method to reduce GHG emission in Chinese ISI (Demailly and Quirion, 2008). These studies provide a solid foundation for further studying the effectiveness of various measures and policies within the Chinese ISI, but a consideration between Chinese ISI and related industrial sectors is still missing, especially the effects of the related downstream sectors.

Hence, this study fills such a gap by assessing ISI related downstream activities. The main objective of this paper is to identify major influencing factors of the energy related GHG emission growth in Chinese ISI so that more efficient policies and measures for mitigating the energy-related GHG emission within Chinese ISI can be raised. Although a very limited carbon released from non-energy related process will become a small part of the final steel products, such carbon is mainly generated from the use of auxiliary materials for steel making, such as $CaCO_3$ (with a 12% carbon concentration), $CaMg(CO_3)_2$ (with a 13% carbon concentration). Comparing with main fuels for steel making, such as charcoal (with over 80% carbon content), both the total consumption of such auxiliary materials and the carbon concentration in such auxiliary materials are very minimal. For instance, Chinese ISI consumed 355.01 million tons of charcoal in 2009, but only consumed 22.0968 million tons of $CaCO_3$ and $CaMg(CO_3)_2$ (China Steel and Iron Industry Yearbook 2010). Thus, the total carbon released from such auxiliary materials is relatively marginal. Under such a circumstance, we focus on energy-related GHG emissions from Chinese ISI in this study. In order to achieve it, we first introduce our methodology, including research scope, data collection, and the detailed calculation process of total and sectoral emission in Chinese ISI. We then present our research results. Our main focus is to have a detailed discussion through scenario analysis so that appropriate and efficient policies can be raised by considering the Chinese realities. We finally draw our conclusions.

2. Methodology

2.1. Energy related emissions from Chinese iron and steel industry

As one of the fundamental industries, Chinese ISI exchanges a huge amount of materials, products, and energy with numerous industries through its supply chain. Hence, it is critical to first set up a defined boundary for inventorying energy-related GHG emission of ISI. In this study boundary definition refers to "The Greenhouse Gas Protocol—A Corporate Accounting and Reporting Standard" (Bhatia and Ranganathan, 2004), which is shown in Table 1. Owing to statistics data limitations, the energy related GHG emissions from Scope 1 and Scope 2 (electricity) are considered in this study, while process related GHG emissions are not covered.

2.1.1. Direct energy-related emission calculation

2.1.1.1. Total direct energy-related emission calculation. The total direct energy-related GHG emissions (Scope 1) of ISI, including emissions from onsite burning of fossil fuels and iron and steel manufacturing process, can be estimated by using IPCC national GHG inventory guidelines (Intergovernmental Panel on Climate Change (IPCC), 2006) and GHG protocol tool for energy consumption in China (Song and Yang, 2011). Although energy related GHG emissions of ISI are generated in various chemical processes, the carbon contents of different fuels and materials are quite different. This study utilizes the principle of carbon conservation to avoid the repetitive computation. Three kinds of GHG emissions, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), are investigated by transferring to carbon dioxide equivalents (CO_2e). The global warming potentials (GWP) of CH_4 and N_2O are 21 and 310, respectively (Intergovernmental Panel on Climate Change (IPCC), 2006). The total direct energy-related CO_2 emissions within ISI's boundary are estimated based upon energy consumption, emission factors (EF), the fraction of oxidized carbon by fuels and the carbon sequestration of steel products. The following equation presents the calculation method.

$$C_{total-direct} = \sum_i E_i EF_i O_i - P_{CS} C_{CS} M \quad (1)$$

where $C_{total-direct}$ represents the total direct energy-related CO_2 emission (in tons, t), subscript i represents energy fuel type i;E_i represents the energy consumption (in tons, t) of fuel type i;EF_i represents the EF of the fuel type i (t CO_2/t fuel);O_i represents the oxidation rate of fuel type i;P_{CS}represents the quantity of crude steel (in tons, t); C_{CS} represents the carbon content of crude steel (0.01 t C/ton crude steel) and M represents the molecular weight

Table 1
Energy related GHG emission boundary definitions and examples.

Emission type	Scope	Definition	Examples
Direct emission	Scope 1	Direct GHG emissions which occur from sources that are owned or controlled by the companies in ISI	Emissions from combustion in owned or controlled boilers, furnaces, vehicles, etc; emissions from chemical production in owned or controlled process equipment
Indirect emission	Scope 2	GHG emissions from the generation of purchased electricity heat, steam, etc., consumed by the companies in ISI	Emissions occur at the facility where purchased electricity, heat and steam are generated
	Scope 3	Emissions from a consequence of the activities of ISI, but occur from sources not owned or controlled by the companies in ISI	Emissions from extraction and production of purchased materials; transportation of purchased fuels; and use of sold products and services

Table 2
GHG emission factors for various energy types.
sources: Song and Yang, 2011.

	Oxidation rate (%)	CO_2EF (ton CO_2/ton)	CH_4EF (g CH_4/ton)	NO_2EF (g NO_2/ton)	GHG EF (ton CO_2e/ton)
Crude coal	100	2.01	209.08	31.36	2.02
Washed coal	100	2.53	263.44	39.52	2.55
Other washed coal	100	1.00	104.54	15.68	1.01
Molded coal	100	1.69	175.84	26.38	1.70
Coal water slurry	100	1.91	198.54	29.78	1.92
Pulverized coal	100	2.01	209.33	31.40	2.03
Coke	100	3.04	284.35	42.65	3.06
Other coking products	100	4.08	380.99	57.15	4.10
Natural gas	100	21.8[a]	389.3[b]	38.9[c]	21.86[a]
Crude oil	100	3.07	125.45	25.09	3.08
Gasoline	100	2.99	129.21	25.84	3.00
Kerosene	100	3.10	129.21	25.84	3.11
Diesel oil	100	3.16	127.96	25.59	3.17
Fuel oil	100	3.24	125.45	25.09	3.25
Liquefied petroleum gas	100	3.17	50.18	5.02	3.17
Other petroleum products	100	2.58	105.50	21.10	2.59
Other fuels	100	2.493[d]	–	–	2.493[d]

[a] The unit is ton $CO_2/10^4$ m^3.
[b] The unit is g $CH_4/10^4$ m^3.
[c] The unit is g $CH_4/10^4$ m^3.
[d] The unit is ton CO_2/ton ce.

ratio of carbon dioxide to carbon (44/12). The emission factors of CO_2, CH_4, N_2O and GHG are shown in Table 2.

Data on total direct fuel consumption come from China Steel Yearbook (China Iron and Steel Association CISA, 2001–2011) and China Energy Statistics Yearbook (National Development and Reform Commission (NDRC), 2010), in which 20 fuel types are shown, covering crude coal, washed coal, other washed coal, molded coal, coal water slurry, pulverized coal, coke, other coking products, coke oven gas, blast-furnace gas, other gas, natural gas, crude oil, gasoline, kerosene, diesel oil, fuel oil, liquefied petroleum gas (LPG), other petroleum products, and industrial waste. In order to avoid repetitive computation, consumption of coke oven gas, blast-furnace gas and other gas, are not considered in this computation because these fuels are generated in one industrial process and combusted in other industrial processes. Meanwhile, 30% of Crude Coal, 92% of washed coal and 30% of other washed coal are utilized to produce secondary energy sources (such as coke), thus these fuels are also excluded from our calculation.

2.1.1.2. Direct energy-related emission from industrial processes. In general, the direct emissions from industrial processes are calculated based upon the IPCC method (Intergovernmental Panel on Climate Change (IPCC), 2006). Such emissions include two main parts, namely those generated from coke production and from iron and steel production. In particular, energy-related emissions from industrial process include CO_2 emissions from production of pig iron, CO_2/CH_4 emissions from production of direct reduced iron (DRI), CO_2/CH_4 emissions from sinter production, CO_2 emissions from pellet production and CH_4 emissions from blast furnace production of pig iron. The detailed calculation process and emission factors are referred to the Tier 1 method of the iron and steel industry of IPCC (Intergovernmental Panel on Climate Change (IPCC), 2006). Data of the production of coke, pig iron not processed into steel, DRI, sinter, pellet, and steel from basic oxygen furnace (BOF), electric arc furnace (EAF), and open hearth furnace (OHF), come from China Steel Yearbook (2001–2010) (China Iron and Steel Association CISA, 2001–2011).

2.1.2. Indirect energy-related GHG emission

Indirect energy-related GHG emissions in Chinese ISI come from electricity consumption related with ISI production. In China, energy related GHG emission from electricity generation is determined by the energy mix in the process of electricity generation. Due to different technology level and energy mix in different periods and regions, emission factors of electricity generation change significantly over time and across different regions. There are seven state grids in China, namely, North China Grid, Northeast China Grid, East China Grid, Central China Grid, Northwest China Grid, South China Grid and Hainan Grid (Lindner et al., 2013). In this study, total energy related GHG emissions from each state grid are calculated according to the yield of steel products in different years and regions. Energy related GHG emissions of electricity generation in the Chinese ISI are calculated by applying the following equation:

$$C_{Electricity} = \sum_k EF_e^k \times Pe \times Ps_k / Ps_{total} \tag{2}$$

where $C_{Electricity}$ represents the energy related GHG emission of electricity generation, k represents the region that receives power supply from the state grid. EF_e^k represents the emission factor of GHG emission of electricity generation. Pe denotes electricity power consumption in the steel and iron manufacturing industry. Ps_k denotes the yield of iron and steel products in region k and Ps_{total} denotes the total yield of iron and steel products in China. The emission factors of state grid electricity are referred to GHG protocol tool for energy consumption in China, and listed in Table 3.

2.1.3. GHG emission flows to downstream sectors (embodied emissions)

In order to further study the driving forces of Chinese ISI industry, a further analysis of ISI energy consumption is required, including not only the direct energy consumption activities but also the indirect activities that induce energy consumption throughout the whole supply chain, namely, the embodied energy consumption perspective (energy consumption reallocated through this sector's supply chain). According to National Statistics Bureau of China (NSBC), main consuming sectors on iron and steel products include Construction, Manufacture of General Purpose and Special Purpose Machinery, Manufacture of Transport Equipment (Manufacture of Railroad Transport Equipment, Manufacture of Automobiles and Manufacture of Boats, Ships and Floating and Manufacture of Other Transport Equipment), Manufacture of Electrical Machinery and Equipment, Manufacture of Metal Products, other sectors and export. The consumption volume of iron and steel products by these different sectors in 2004 and 2009 are shown in Fig. 4 (World Steel Association (WSA), 2012; Li, 2006). Construction sector is the largest sector which accounts for more than 50% of the total demand, followed by Manufacture of General Purpose and Special Purpose Machinery, Manufacture of Transport Equipment and Export. The proportions of consumption volume of iron and steel products by these sectors for the year of 2004 and 2009 remain unchanged except for the other sectors and export. The GHG emission flows

Table 3
GHG emission factors on electricity generation from 2006 to 2008.
Sources: Song and Yang, 2011.

Region	Provinces included	CO_2 EF (ton CO_2/10^3 kwh)			CH_4EF (g/10^3 kwh)			N_2O EF (g/10^3 kwh)			GHG EF (ton CO_2/10^3 kwh)		
		2006	2007	2008	2006	2007	2008	2006	2007	2008	2006	2007	2008
North China	**Beijing, Tianjin, Hebei, Shanxi, Shandong, Inner Mongolia**	1.1083	1.0842	1.1232	11.8555	11.7144	12.2043	16.9690	16.4563	16.9560	1.114	1.090	1.129
Northeast	**Liaoning, Jilin, Heilongjiang**	1.2082	1.1554	1.1716	13.0127	12.5337	12.6657	18.4177	17.5052	17.8076	1.214	1.161	1.177
East China	**Shanghai, Jiangsu, Zhejiang, Anhui, Fujian**	0.8686	0.8462	0.8238	9.6495	9.2655	9.0349	13.0024	12.7372	12.3726	0.873	0.850	0.828
Central China	**Henan, Hubei, Hunan, Jiangxi, Sichuan, Chongqing**	0.7846	0.7744	0.6887	8.3140	8.2933	7.3811	12.0615	11.8499	10.5120	0.789	0.778	0.692
North west	**Sha'anxi, Gansu, Qinghai, Ningxia, Xinjiang**	0.8464	0.8731	0.8533	8.9166	9.2796	9.0594	13.0478	13.3660	13.0827	0.851	0.877	0.858
South China	**Guangdong, Guangxi, Yunnan, Guizhou**	0.7549	0.7451	0.6590	9.3380	8.8327	7.6938	11.2867	11.0810	9.7769	0.759	0.749	0.662
Hainan	**Hainan**	0.7185	0.7680	0.7753	9.7406	8.9051	8.9969	9.5467	10.3972	10.3958	0.722	0.771	0.779

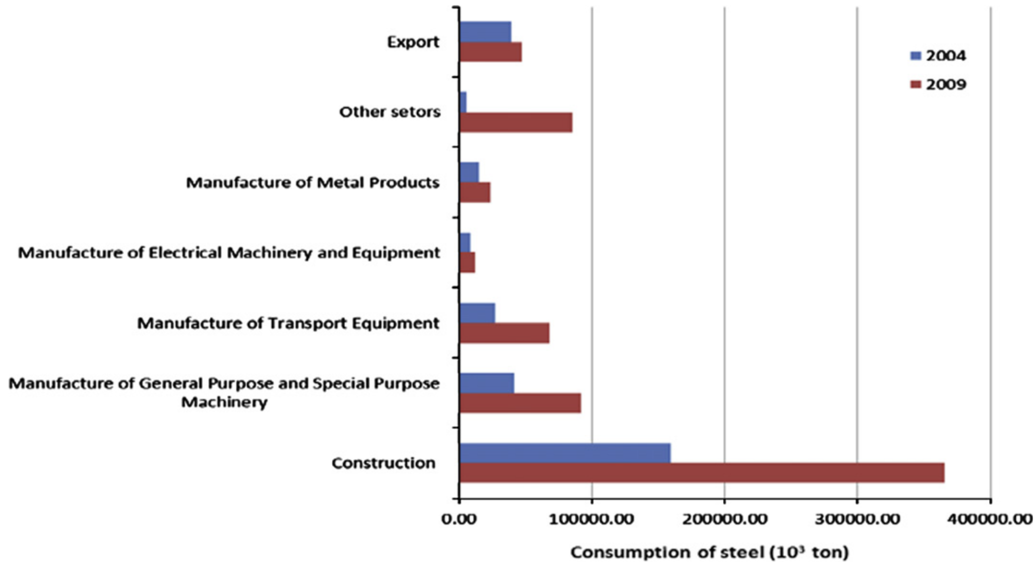

Fig. 4. Consumption volumes of iron and steel products by various sectors for the year of 2004 and 2009.

to the downstream sectors are allocated based on proportions of consumption volumes of iron and steel products by these downstream sectors.

2.2. Index decomposition analysis

In order to further identify the key factors that influence the growth of energy consumption and related GHG emission in Chinese ISI and quantify the effects of such factors, a decomposition analysis method is employed. There are two widely adopted decomposition analysis methods, namely structural decomposition analysis (SDA) and index decomposition analysis (IDA). The Logarithmic Mean Divisa Index (LMDI) method with time-series (chaining method) manners was adopted due to its sound theoretical foundation, adaptability and convenience (Ang, 2004; Ang and Liu, 2001; Ang and Zhang, 2000; Hoekstra and Bergh, 2003; Liu and Ang, 2003). This method has been used to analyze the driving forces of GHG emissions and energy consumption at the industrial level (Akbostancı et al., 2011; Sun et al., 2011,2012) and at the national level (Liu et al., 2007,2012; Sorrell et al., 2009; Tan et al., 2011; Wang 2007; Zhao et al., 2010). With regard to Chinese ISI, driving factors of influencing energy related GHG emissions through temporal analysis include the following four factors: emission factor change effect (over time the emission factors of fuels and electricity can vary), energy structure effect (different fuels have different emission factors (the carbon emitted for a given amount of delivered energy)); as such, power grids in different regions have different fuel mixes, energy intensity effect (less (or more) energy is used to produce the same output, reflecting the impact of technology improvement), and production scale effect (total production scale has direct impact on energy use) (Ang, 2005; Hammond and Norman, 2012; Sun et al., 2011,2012). Theoretically it will be more appropriate to add one more factor, namely the effect of structural changes within the iron and steel sector (for example shifts from a BOF production route to the EAF route) (Long, 2005; Hammond and Norman 2012; Kim and Worrell 2002). However, due to time and data availability, such a factor was not investigated in this study. The index decomposition analysis of energy related GHG emissions for ISI is conducted by the following equation:

$$C=\sum_i C_i=\sum_i \frac{C_i}{E_i}\frac{E_i}{E}\frac{E}{P}P=\sum_i F_iS_iBP \tag{3}$$

where C represents total energy related carbon emission; C_i represents carbon emission from fuel i, $i=1, 2, \ldots 18$, denoting crude coal, washed coal, other washed coal, molded coal, coal water slurry, pulverized coal, coke, other coking products, coke oven gas, blast-furnace gas, other gas, natural gas, crude oil, gasoline, kerosene, diesel oil, fuel oil, liquefied petroleum gas (LPG), Other petroleum products, industrial waste and electricity, respectively; E represents the total energy consumption, E_i represents the consumption of energy source, i and P represent the consumption volume of iron and steel products. F_i, S_i, and B represent GHG emission intensity of energy source i, energy consumption share of source i, and energy consumption per unit steel products, respectively.

Aggregated effects of driving factors from baseline year to final year can be investigated by Eq. (3).

$$\Delta C^T=C^T-C^0=\Delta C_T^F+\Delta C_T^S+\Delta C_T^B+\Delta C_T^P \tag{4}$$

And annual effects of driving factors can be investigated by Eq. (4).

$$\Delta C=C^{t+1}-C^t=\Delta C_F+\Delta C_S+\Delta C_B+\Delta C_P \tag{5}$$

The subscripts F, S, B, P in these two equations denote emission factor change effect, energy structure effect, energy intensity effect, and production scale effect. The superscripts of 0 and T denote the baseline year (2001) and the final year (2010), and the t and $t+1$ denote the current year t and the next year $t+1$. The detail of the calculation process refers to the following literature (Sun et al., 2011).

3. Results

3.1. Energy-related GHG emission trajectory and features for Chinese ISI

3.1.1. Total energy-related GHG emission from different energy sources

Chinese ISI experienced a rapid growth of energy-related GHG emission, increasing from 416.8 million tons of CO_2e in 2001 to 1.82 billion tons of CO_2e in 2010. Fig. 5 shows the proportion of energy-related GHG emissions from different energy sources, including 17 different types of fuels and electricity in Chinese ISI for the years of 2001, 2005 and 2010. The proportion of GHG emissions from different energy sources comparatively remains

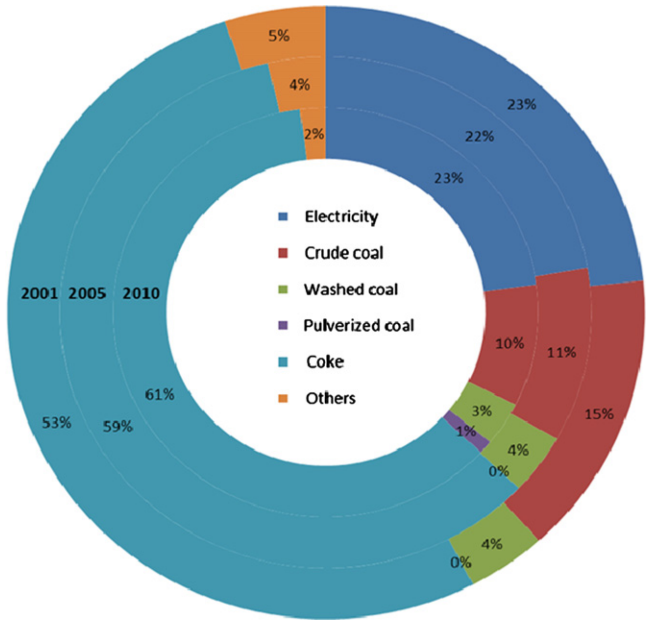

Fig. 5. Energy-related GHG emissions for Chinese ISI from different energy sources (inner: year 2010; interim: year 2005; external: year 2001).

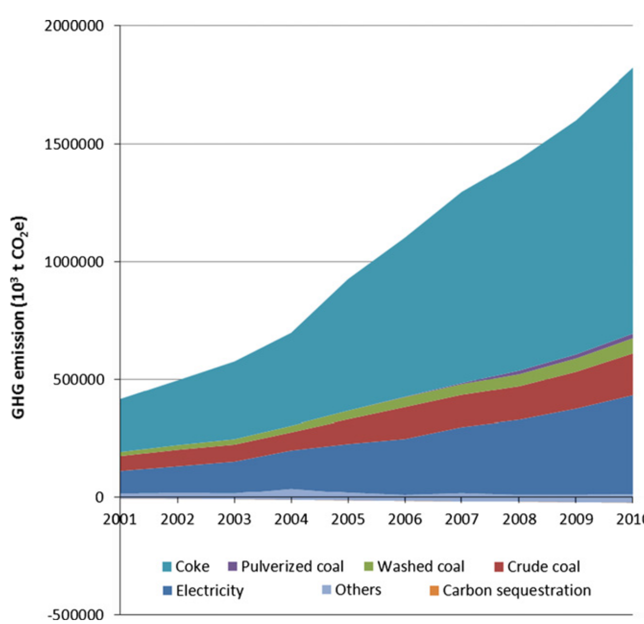

Fig. 6. Trajectory of energy-related GHG emissions from different energy sources in Chinese ISI.

unchanged. Coke is the one which emitted the largest amount of GHG emission, followed by electricity, crude coal and washed coal. These four energy sources generate over 90% of total energy-related GHG emission, accounting for 1.79 billion tons of CO_2e in 2010. In particular, emission from coke combustion shows a significant increase, contributing to 53%, 59% and 61% of total energy-related GHG emission in year 2001, 2005 and 2010, respectively, while the proportions of electricity (23%, 22% and 23%), crude coal (15%, 11% and 10%) and washed coal (4%, 4% and 3%) remain relatively stable. Moreover, the proportions of GHG emissions from fuel oil and other fuels slightly declined from 2001 to 2010. Fig. 6 shows the trajectories of GHG emissions from different energy sources in Chinese ISI. The trajectory of total energy-related GHG emission is divided into three stages. First, the total energy-related GHG emission presented a relatively steady growth trend during 2001–2004; then, it experienced a sharp increase during 2005–2007; finally, the increasing trend slowed down during the period of 2008–2010. From the whole study period perspective (2001–2010), GHG emission from coke and electricity played a leading role on the total GHG emission trajectory as the GHG emissions from coke increased from 222 million tons of CO_2e in 2001 to 1.126 billion tons of CO_2e in 2010 and the GHG emissions from electricity increased from 99 million tons of CO_2e in 2001 to 421 million tons of CO_2e in 2010.

3.1.2. Energy-related GHG emissions from industrial processes in Chinese ISI

Energy-related GHG emissions from various industrial processes of iron and steel manufacturing, including sinter production, coke production, iron production, pellet production, steel production in BOF, steel production in EAF, and steel production in OHF, as well as related energy consumption for delivery and office activities, are presented in Fig. 7. It shows that energy-related GHG emissions from industrial processes contributed to more than 60% of the total energy-related GHG emissions as such an emission increased from 298 million tons in 2001 to 1.096 billion tons of CO_2e in 2010. The GHG emission from iron production is the largest contributor to the energy-related GHG emission from industrial processes in Chinese ISI, which increased from 195 million tons of CO_2e in 2001 to 812 million tons of CO_2e in 2010. The GHG emissions from coke production, sinter production and steel production in basic oxygen furnace (BOF) increased from 46 million tons, 39 million tons and 14 million tons in 2001 to 76 million tons, 138 million tons and 62 million tons in 2010, respectively. These four main sources emitted approximately 1.088 billion tons CO_2e and contributed to 99% of total energy-related emission from industrial processes in 2010. The proportions of the GHG emissions from these four processes are 65%, 16%, 13% and 5% in 2001 and 74%, 7%, 13% and 6% in 2010, respectively. Besides, energy-related GHG emission from other related activities (e.g. delivery of iron and steel products and office activities) is also one contributor to the total energy-related

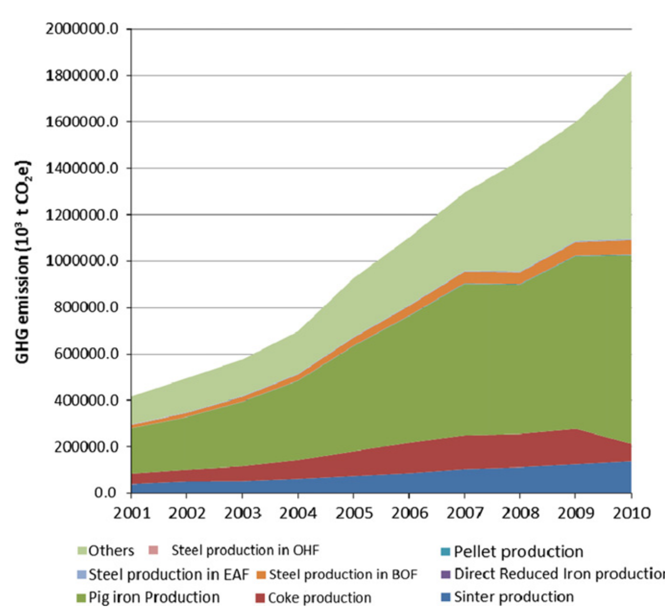

Fig. 7. Trajectory of energy-related GHG emissions from industrial processes for Chinese ISI (2001–2010).

emission, which increased from 110 million tons of CO_2e in 2001 to 683 million tons of CO_2e in 2010.

3.1.3. Energy-related GHG emission flows of Chinese ISI

Fig. 8 presents a holistic picture of energy-related GHG emission flows in Chinese ISI for the year of 2009 (similar to a Sankey diagram), including the emissions allocated along its supply chain (from upstream to downstream). The width of each line represents the amount of the related GHG emissions. Among all energy-related GHG emission sources for ISI, the emission from iron and steel production (743.9 million tons) is the largest, followed by electricity used in iron and steel manufacturing (341.1 million tons of CO_2e), coke production (153.2 million tons of CO_2e) and sinter production (124.5 million tons of CO_2e). In 2009, the construction sector was the largest embodied energy consumption sector with a figure of 842.6 million tons of CO_2e and accounted for 52.7% of total embodied emission. Manufacture of general purpose and special purpose machinery (13.3%), manufacture of transport equipment (9.8%), Export (6.9%), manufacture of metal products (3.4%) and manufacture of electrical machinery and equipment (1.7%) were other main sectors for embodied emissions. The embodied emissions for these sectors were 212.3 million tons of CO_2e, 156.4 million tons of CO_2e, 110.0 million tons of CO_2e, 54.2 million tons of CO_2e and 27.6 million tons of CO_2e, respectively.

3.2. Driving forces of energy-related GHG emission changes in Chinese ISI

Driving forces of energy-related GHG emission changes in Chinese ISI are uncovered by using the LMDI decomposition analysis method. Annual effects of driving forces and aggregated effect of driving forces are expressed in Figs. 9 and 10, respectively. Results show that the production scale effect (ΔC_P) is the main driving force, followed by energy intensity effect (ΔC_B), emission factor change effect (ΔC_F) and energy structure effect (ΔC_S). Fig. 9 shows that the production scale effect keeps positive and pushes the growth of emission in Chinese ISI from 2001 to 2010 and the other three driving forces present different effects in different years. From the perspective of aggregated effects, the production scale effect is the most important factor for the increment of emission, increased from 83 million tons of CO_2e in 2002 to 1.535 billion tons of CO_2e in 2010. However, energy intensity effect and emission factor change effect offset the growth during the period of 2002–2010, and energy structure effect is marginal. The offset effects of energy intensity and emission factor change increased from 3.4 million tons of CO_2e and 3.6 million tons of CO_2e in 2002 to 138.3 million tons of CO_2e and 38.3 million tons of CO_2e in 2010, respectively. Besides, energy structure effect has very little influence on the total emission.

4. Discussion and policy implications

Total amount of energy-related GHG emission from Chinese ISI reached 1.82 billion tons of CO_2e in 2010, increased with an average annual growth of 70 million tons of CO_2e during 2001–2010. With the technology improvement, energy-related GHG emission per steel production had declined from 2.59 ton of CO_2e to 2.27 ton of CO_2e during 2001–2010, but still lagged behind the international advanced level (1.9 ton) (World Steel Association (WSA), 2012), indicating a great potential for GHG emission reduction through further technology improvement. The soaring

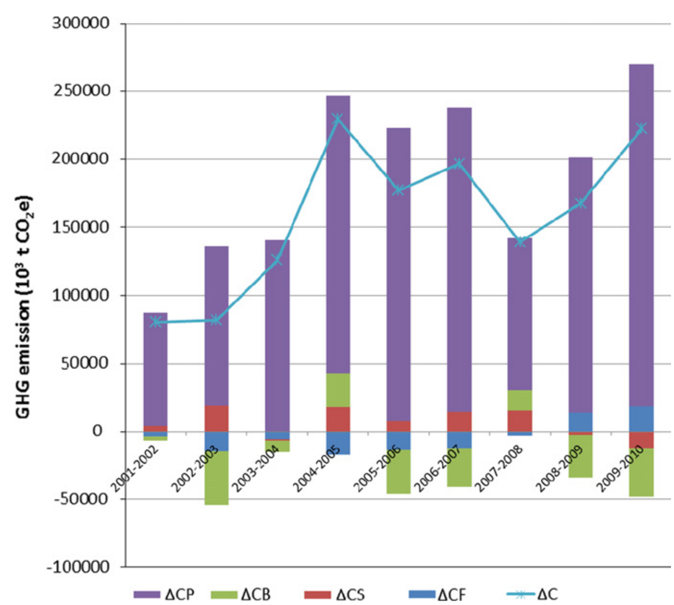

Fig. 9. Annual effects of driving forces for energy-related GHG emissions increment in Chinese ISI (2001–2010).

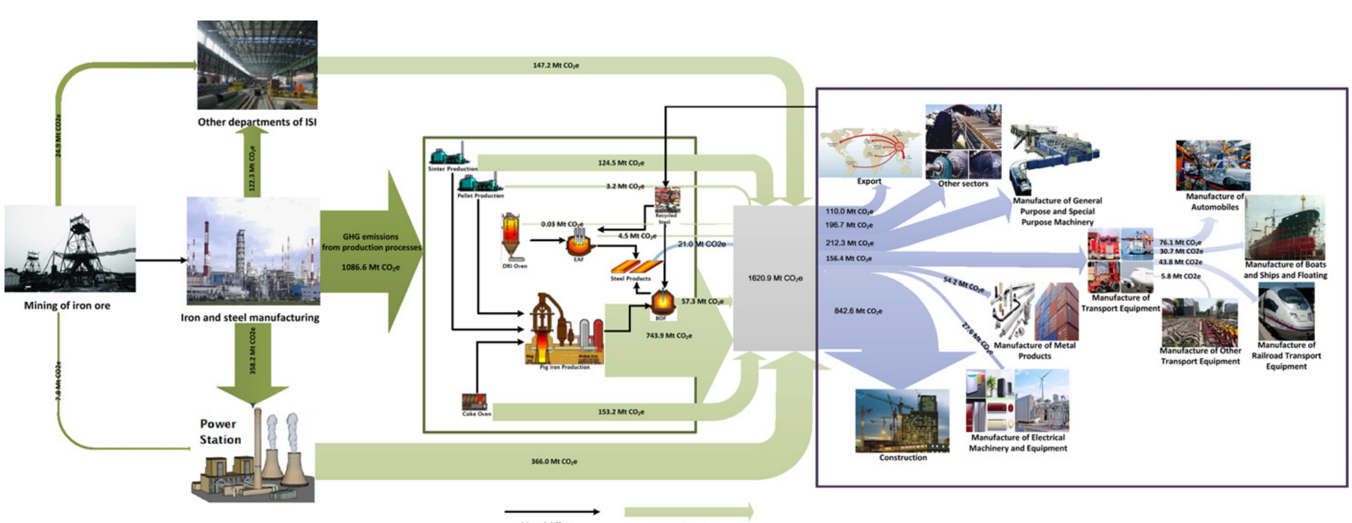

Fig. 8. Energy related GHG emission flows of Chinese ISI in 2009.

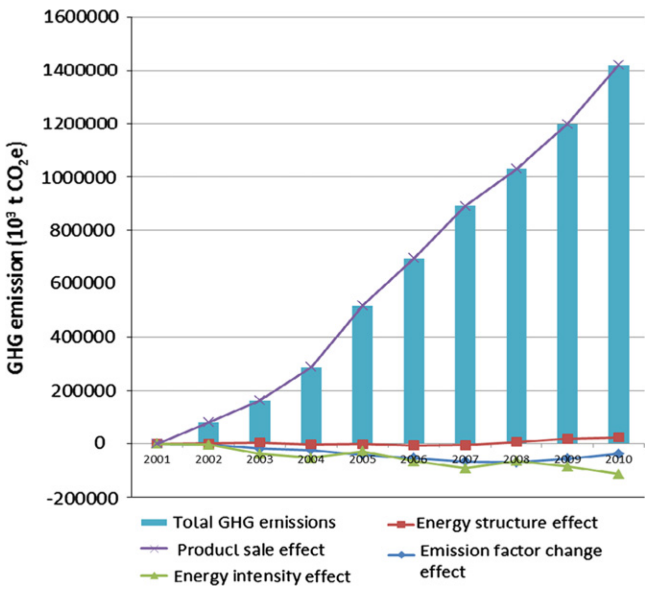

Fig. 10. Aggregated effects of driving forces for energy-related GHG emissions increment in Chinese ISI (2001–2010).

demand on iron and steel products is the dominant driving force of energy-related GHG emission growth in Chinese ISI. Both rapid industrialization and urbanization drove such a demand, resulting in that the consumption of iron and steel products increased from 160 million tons of CO_2e in 2001 to 800 million tons of CO_2e in 2010. Particularly, urbanization is the main influencing factor on the huge demand as construction sector consumed 52.7% of the total iron and steel products. Under such a circumstance, GHG emission mitigation measures and policies should focus on both ISI per se and the related downstream sectors.

4.1. Actions in Chinese ISI

The mitigation actions and policies for Chinese ISI should be prepared by considering 3R (reduce, reuse and recycling) principles, especially focusing on the process of steel production in iron production, coke production and sinter production. First, the advanced technologies of improving energy efficiency (such as top-pressure recovery turbine (TRT), coke dry quenching (CDQ), high temperature air combustion (HTAC), etc.) should be promoted. Second, gas reuse programs (reuse of coke oven gas, converter gas, blast furnace gas) and energy cascading program (such as industrial waste heat and steam) need to be implemented. Third, waste iron and steel collection and recycling programs should be widely applied so that the total consumption of virgin materials can be reduced, especially due to the fact that the extraction and processing of pig iron are very energy intensive. Finally, to improve the quality of iron and steel products through quality control programs can extend the life cycle of these products, leading to less GHG emissions from ISI sector.

4.2. Actions in related downstream sectors

4.2.1. Construction sector

Construction sector is the largest consumption sector of iron and steel products. Residential buildings, infrastructural facilities and industrial buildings amount for 60%, 20% and 15% of total iron and steel consumption in the construction sector, respectively. The main problem for construction sector is that buildings in China have relatively shorter life expectancy that is just about 30 years, while such a figure in European countries is around 80 years, and 44 years in the United States (Geng et al., 2012). Such a situation results in repeated construction and huge consumption on iron and steel products. Consequently, it is critical to initiate green building efforts so as to alleviate the potential impacts from building sector. But the development of green buildings in China is still at its initial stage, such as higher costs for both construction and receiving certification, lack of convincible indicators, and lack of applying innovative green technologies (Geng et al., 2012). This requires that significant improvements should be made so that the revised green building criteria can better facilitate those developers for their efforts on constructing green buildings (serving the need to extend the life cycle of new buildings). Another problem is that many newly built buildings are not physically operated, resulting in that 16% of newly built residential buildings were idle in 2009 (Lu and Yue, 2010). Many real estate investors simply want to seek value-adding, while the real consumers cannot afford the higher price of such properties. Therefore, governmental involvement on real estate market is necessary so that rational price can be made and real demand can be met with.

4.2.2. Manufacture of general purpose and special purpose machinery

Manufacture of general purpose and special purpose machinery is the second largest consumption sector on iron and steel products, with a fact that more than 80% of machinery material is made of iron and steel. Particularly, China is facing a peak period of machinery retirement. According to a national statistics, total amount of in-use machineries was more than 7 million units, among which over 2 million has been used for more than ten years (80% of such machineries are already without quality guarantee (Xu, 2010)). This reality requires that a comprehensive consideration on this sector should be paid. First of all, remanufacturing is one effective approach to extend the life of such machineries and can significantly reduce iron and steel consumption, thus contributing to mitigate the emissions from Chinese ISI. Compared with the manufacture of new machinery products, remanufacturing can save 70% of materials (National Development and Reform Commission (NDRC), 2010). However, remanufacturing is still in its early stage in China and the total amount of such machineries is still very less. Also, due to conservative awareness and quality concerns, remanufactured products are not widely recognized by the Chinese consumers. Therefore, policies for promoting remanufacturing should be prepared and research efforts on remanufacturing should be strengthened so that quality of such products can be guaranteed. Second, design for environment or eco-design should be promoted in this sector so that the total consumption of iron and steel can be reduced (Allwood and Cullen, 2011). Third, a collection network on retired machines should be established so that the iron and steel parts from such machines can be reused or recycled.

4.2.3. Manufacture of transport equipment

Manufacture of transport equipment includes four sub-sectors, namely, manufacture of railroad transport equipment, manufacture of automobiles and manufacture of boats, ships and floating, and manufacture of other transport equipment. In current legal framework, all the transport equipments should be recycled and the iron and steel parts should be shredded into scrap steel after the end of their life cycles. In 2010 Chinese ISI consumed 86.7 million tons of scrap steel. Comparing with pig iron steelmaking for the same amount, such a use of scrap steel reduced to 167.5 million tons GHG emission (1.93 ton of CO_2e can be reduced through the use of one ton scrap steel) (China Iron and

Steel Association CISA, 2001–2011). Automotive industry is one main resource for providing scrap steel. Especially, with the rapid development of automobile industry during the last decade, China has to face the "End-of-Life Vehicles (ELVs)" problem as millions of vehicles will reach the ends of their life cycles. The total amount of ELVs in 2009 was 2.7 million, indicating a great potential for providing scrap steel to Chinese ISI (Yu 2011). However, the actual number of recycling and dismantling ELVs is only about half million due to several factors, such as immature ELVs collection system, backward technologies on dismantling ELVs, lack of economic drivers (Yu, 2011). Therefore, more efforts should be made so that more ELVs can be collected, dismantled and more scrap steel can be obtained (Allwood and Cullen, 2011).

4.3. Scenario analysis

Scenario analysis is one effective measure to reasonably estimate the potential energy savings and CO_2 emissions reduction from Chinese ISI. Such scenarios may reflect consequences of the implementation of different economic and technological policies. Due to data availability, the year of 2012 was chosen as the baseline year, while the year of 2030 was chosen as the end year for scenario analysis since China's economic development will reach a relatively steady phase by then (Jiang and Hu, 2007).

Four scenarios are designed; including business as usual (BAU) scenario, high-efficiency scenario (HE), medium-efficiency scenario (ME), and low-efficiency scenario (LE). Several assumptions are made in order to keep four scenarios analysis consistent. First, the iron and steel products emission intensity is assumed to decrease from 2.27 ton of CO_2e per ton in 2010 to the current international level (1.9 ton) in 2030 (World Steel Association (WSA), 2012). Second, the average annual growth rate of total vehicles in use is set up to be 13.3% during 2011–2020 and to be 5.4% during 2021–2030 (Hao et al., 2011), while the proportion of ELVs is set up to be 4% of the total vehicles in use and the average weight of scrap steel per vehicle is set up to be 1.5 ton (Yu 2011). As such, the GHG emission reduction per ton scrap steel is assumed as 1.93 ton CO_2e (China Iron and Steel Association CISA, 2001–2011). Third, the four scenarios are designed according to the idle proportion of newly built residential buildings (IPR), demolition proportion of old residential and non-residential buildings (DPR and DPN) in construction sector, remanufacturing proportion in Manufacture of General Purpose and Special Purpose Machinery sector (RPM), and recycling proportion of ELVs (RPE).

BAU scenario means that nothing will be changed and the values of IPR, DPR, DPN, RPM and RPE are 16%, 11%, 9%, 5% and 56%, respectively. HE scenario is the best practice scenario in which mitigation actions and policies obtain maximum reduction on the demand of iron and steel products. Particularly, IPR value is reduced to 4%, indicating that 12% of iron and steel products used in residential buildings construction are saved; DPR value and DPN value are decreased from 11% and 9% to 5% and 4.5%, indicating a reduction of 6% and 4.5% of iron and steel products used in oldresidential and non-residential buildings respectively; RPM is increased to 25%, indicating that 25% of iron and steel products used in manufacturing new machineries are reduced; RPE value is increased from 56% to 90%, indicating that 34% of scrap from ELVs will be used in iron and steel remanufacturing. Both ME scenario and LE scenario are moderate scenarios, in which ME scenario is better than LE scenario. Detailed values for four scenarios are listed in Table 4.

Fig. 11 is made to present the comparisons among four different scenarios. The results show that energy-related GHG emission reduction potentials in Chinese ISI are 2.8%, 5.5% and 8.2% of total GHG emission under LE, ME and HE scenarios, respectively. Specially, in each scenario, value changes of IPR, DPR, DPN, RPM and RPE contribute to 46%, 23% 12% 17% and 2% of total energy related GHG emission reduction. This indicates that construction sector has the largest potential to reduce its embodied emissions, accounting for 81% of total emission reduction, followed by Manufacture of General Purpose and Special Purpose Machinery (17%) and Manufacture of Transport Equipment (Manufacture of Automobiles) (2%). Consequently, mitigation policies and actions for construction sector are extremely significant.

Table 4
Different values for four scenarios.

	BAU (%)	HE (%)	ME (%)	LE (%)
IPR	16	4	8	12
DPR	11	5	7	9
DPN	9	4.5	6	7.5
RPM	5	20	15	10
RPE	56	90	80	70

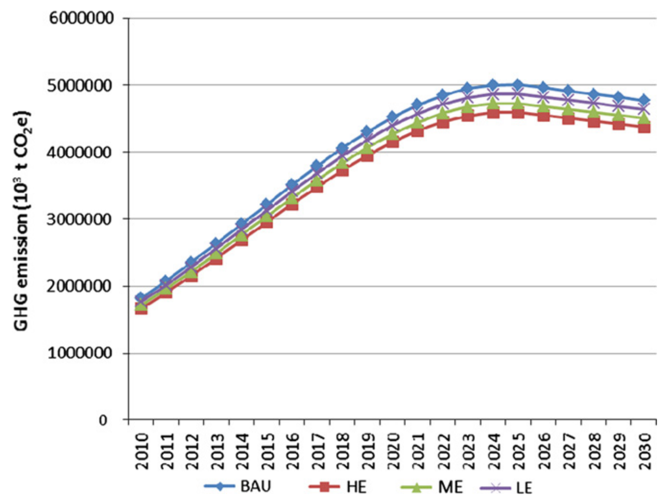

Fig. 11. Comparisons on emission reduction between four scenarios.

5. Conclusions

With the rapid urbanization and industrialization in China, iron and steel consumption by various sectors have significantly increased and will continue to grow. Consequently, a detailed analysis on Chinese ISI is necessary so that the energy related GHG emission trajectories, features and driving forces can be uncovered. This paper deals with these issues and presents various research outcomes for providing decision support. First of all, Chinese ISI had experienced a rapid growth of energy-related GHG emission during 2001–2010, with a quadruple increase. Such a production scale effect is the main contributor to the rapid increase of energy-related GHG emission in Chinese ISI. Coke, electricity, crude coal and washed coal were four main energy sources for Chinese ISI and generated over 90% of total energy related GHG emission. Second, energy emission factor change and energy intensity are two main factors contributing to energy related GHG emission reduction in Chinese ISI. Although energy-related GHG emission per steel production had decreased during 2001–2010, it is still far away from the international best practices. From industrial process perspectives, the GHG emission from steel production in iron production is the largest contributor among all emission flows, followed by coke production and sinter production. Hence mitigation actions and measures such as cleaner production and energy efficiency programs should be promoted within the Chinese ISI. Third, energy-related GHG emission growth in Chinese ISI during 2001–2010 was mainly due to the production scale effect, namely, the increasing demand from various sectors. Construction, manufacture of general purpose and special purpose machinery and manufacture of transport equipment sectors are main sectors responsible for embodied emissions, amounting for more than 75% of the total embodied emissions from Chinese ISI, thus, polices for reducing iron and steel products demand and collecting and recycling scrap steel need to be prepared by considering the Chinese realities.

Acknowledgment

This study was supported by a grant from National Science Fund for Distinguished Young Scholars (71025002), Natural Science Foundation of China (71033004), Chinese Academy of Sciences (2008-318), and Ministry of Science and Technology (2011BAJ06B01).

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