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# Analysis of the Past and Future Trends of Energy Use in Key Medium- and Large-Sized Chinese Steel Enterprises, 2000-2030

**Ali Hasanbeigi, Zeyi Jiang, Lynn Price**

China Energy Group
Energy Analysis and Environmental Impacts Department
Environmental Energy Technologies Division
Lawrence Berkeley National Laboratory

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# Analysis of the Past and Future Trends of Energy Use in Key Medium- and Large-Sized Chinese Steel Enterprises, 2000-2030

**Ali Hasanbeigi [a], Zeyi Jiang [a,b], Lynn Price [a]**

[a] China Energy Group, Energy Analysis and Environmental Impacts Department, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, Berkeley, CA, U.S.A

[b] School of Mechanical Engineering, University of Science and Technology Beijing, China

## Abstract

The iron and steel industry is one of the most energy-intensive and polluting industries in China. This industry accounted for approximately 27% of China's primary energy use for the manufacturing industry in 2010. Also, China's steel production represented around 47% of the world steel production that year. Hence, reducing energy use and air pollutant emissions from the Chinese steel industry not only has significant implications for China but also for the entire world. For this reason, it is crucial and it is the aim of this study to analyze influential factors that affected the energy use of the steel industry in the past in order to try to quantify the likely effect of those factors in the future.

This study first analyzes energy use trends since 2000 of China's key medium- and large-sized steel enterprises and also makes projections for energy use and production up to 2030 for the key medium- and large enterprises. The study then uses a refined Logarithmic Mean Divisia Index (LMDI) decomposition analysis to quantify the effects of various factors in shaping energy consumption trends in the past and in the near future. Throughout this report all of the data presented are for the key medium- and large-sized steel enterprises unless noted otherwise.

The result of our forecast shows that although under all scenarios the total annual crude steel production of key Chinese steel enterprises (and most likely entire Chinese steel industry) is assumed to peak in 2030, the total final energy use of the key Chinese steel enterprises peaks earlier, i.e. in year 2020 under scenario 1 and scenario 2 and in 2015 under scenario 3.

The retrospective decomposition analysis shows that energy intensity reduction was almost the only reason for reduced final energy use in key Chinese steel enterprises between 2000 and 2010. The structural (activity share of each process route [BF-BOF or EAF route]) effect and the pig iron ratio (the ratio of pig iron used as feedstock in each process route) effect played a minor role and even increased the energy demand during this period.

The three scenarios produced for the forward-looking (prospective) decomposition analysis for 2010-2030 show that contrary to the experience during the 10th and 11th Five Year Plan (FYP) periods, the structural effect is expected to be negative (i.e. reducing final energy use) and play an important role during 2010-2030 because of increases in the electric arc furnace (EAF) share of steel production in this period. Similarly, the pig iron ratio effect will play an

influential role and reduces the final energy use of key steel enterprises because of the reduction in the share of pig iron used as a feedstock in EAF steel production during this period. The magnitude of the structural effect and pig iron ratio effect varies across the scenarios, with scenario 3 having the largest structural effect and pig iron ratio effect because of the assumption of higher EAF steel production and lower pig iron use in EAFs in this scenario.

The intensity effect plays the most significant role in reducing final energy use of steel manufacturing during 2010-2030. This is primarily because of the assumption for energy intensities for production processes in 2020 and 2030. While the realization of such energy intensity reduction is uncertain and remains to be seen in the future, the aggressive policies of the Chinese government to reduce the energy use per unit of product of the energy intensive sectors, especially the steel sector, are a promising sign that the Chinese steel industry is moving towards those energy intensity targets.

## Contents

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## 1. Introduction

### 1.1. Overview of China's iron and steel industry

Production of iron and steel is an energy-intensive manufacturing process. In 2010, the iron and steel industry accounted for around 27 percent of primary energy consumption of Chinese manufacturing[1] (NBS 2011). The energy efficiency of steel production has a direct impact on overall energy consumption and related emissions of carbon dioxide ($CO_2$) and other air pollutants.

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

The Chinese iron and steel industry has made much progress in reducing energy use, starting from energy saving of individual equipment and process energy conservation in the 1980s to systematic energy conservation via process optimization in the 1990s and 2000s. China's energy consumption per tonne of steel has declined significantly, especially since the 1990s, largely due to process restructuring and optimization and phasing out of inefficient backward technologies.

The promotion and application of energy-saving technologies has become an important step for increasing energy efficiency and reducing energy consumption of steel enterprises, especially during the 11th Five Year Plan (FYP) (2006-2010) and 12th FYP (2011-2015). During this time, energy-efficiency technologies adopted in China's steel industry included:

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[1] Manufacturing sector does not include mining, oil and gas extraction, power generation, and construction.

Coke Dry Quenching (CDQ), Top-pressure Recovery Turbine (TRT), recycling converter gas, continuous casting, slab hot charging and hot delivery, Coal Moisture Control (CMC), and recycling waste heat from sintering. The penetration level of energy-efficiency technologies in the steel industry has improved greatly in China, improving its energy efficiency and emission reductions (Hasanbeigi et al. 2011).

**Key medium- and large-sized Chinese steel enterprises**

Table 1 shows the criteria that an steel enterprise should meet to be categorized as a key medium- and large-sized steel enterprise. A list of these companies can be found in the *Editorial Board of China Steel Yearbook* (EBCSY 2001-2011).

Table 1. Criteria for medium- and large-sized steel enterprises in China (SETC/SPC/MoF/NBS, 2003)

| Criteria | Unit | Medium-sized | Large-sized |
|---|---|---|---|
| Number of employees | Person | 300 - 2000 | ≥2000 |
| Product sales revenue | Million Yuan | 30 - 300 | ≥300 |
| Total assets | Million Yuan | 40 - 400 | ≥400 |

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

Throughout this report all the data presented are for the key medium- and large-sized steel enterprises unless it is noted otherwise. The reason why we chose to do the analysis for the key medium- and large-sized steel enterprises is that the energy intensity data by process for various years, which are used in our analysis as explained in section 3, are only reported for the key medium- and large-sized steel enterprises and such data are not reported for the entire Chinese steel industry.

## 1.2. Previous literature on Chinese steel industry energy use

A number of analyses of historical energy use of China's iron and steel industry have been conducted. He et al. (2012) used data from 50 enterprises in China's iron and steel industry to evaluate their energy efficiency and productivity change using data envelopment analysis. Their results indicated inefficiency in many of the plants. Wei et al. (2007) used the Malmquist Index Decomposition to investigate the energy efficiency of China's iron and steel sector during the period 1994–2003.Their results indicate that the energy efficiency in China's iron and steel sector increased by 60% between 1994 and 2003, mainly attributable to technical progress rather than technical efficiency improvement. In order to assess the $CO_2$ abatement potential of China's steel industry, Wang et al. (2007) developed a model using LEAP software to generate 3 different $CO_2$ emission scenarios for the industry from 2000 to 2030. They concluded that there is great potential for $CO_2$ abatement in China's steel industry and adjusting the structure of the industry and technological advancement will play an important role in emissions reduction. Zeng et al. (2009) analyzed the major issues currently faced by the Chinese iron and steel industry, and proposed four approaches through which the industry might reduce its GHG emissions. A survey of key issues associated with the development in the Chinese iron and steel industry and the current situation relate to energy consumption are described in a paper by Guo and Fu (2010). Zhang and Wang (2008) used the Cobb–Douglas (C–D) type production function to estimate the impact of energy saving technologies and innovation investments on the productive efficiency of Chinese iron and steel enterprises for the period 1990–2000.

However, comprehensive analyses of important factors influencing the Chinese iron and steel industry's historical energy use trends are scarce. More importantly, in the context of this study, careful projections of key factors affecting China's iron and steel sector energy use over the next decade are also rare. This study conducts both such analyses.

### 1.3. Introduction to decomposition analysis

Energy-to-GDP ratios have been widely used internationally to measure the energy efficiency performance of national economies, until a body of research exposed the limits of using this indicator (Schipper et al. 1992; Patterson 1993; Ang and Lee 1994; IEA 2004). Energy analysts demonstrated that factors other than energy intensity were also affecting changes in energy use, especially the overall level of aggregate activity (the activity effect) and the composition of various activities within the economy (the structure effect). Techniques for factorization or decomposition analysis were developed to isolate the energy intensity effect in order to give a better estimate of energy efficiency improvements. Ang (2004) provides a complete review of the different aspects and evolution of these techniques. Ultimately, the more the effects affecting energy use are isolated, the better is the estimate of the energy intensity effect. However, available data to allow factorizing additional components of the decomposition analyses can be limited.

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

Decomposition analysis can be conducted for the entire industrial sector (e.g. Hasanbeigi et al. 2013; Hasanbeigi et al. 2012; Reddy and Ray 2010; Salta et al. 2009; Bhattacharyya and

Ussanarassamee 2005) or for a sub-sector of industry (e.g. Sheinbaum et al. 2010; Xu et al. 2012). Reviews of decomposition analysis used at the national and international level include de la Rue du Can et al. (2010) and Liu and Ang (2003).

Decomposition of past trends helps modelers to accurately project future changes in energy use. For example, decomposition allows separate modeling of structural and intensity trends and combining of their effects to improve the accuracy of estimates of future energy demand. Projection and decomposition of future trends will help analysts and policy makers to estimate how the energy use will change over years in the future and how much of the changes are likely the result of energy efficiency policies and how much are from structural change or other policies. This can help them to adjust their policies if needed to meet a certain target (e.g. 12th FYP energy intensity reduction target in China).

## 2. Description of Iron and Steel Production

Iron ore is chemically reduced to produce steel by one of these three process routes: blast furnace (BF)/basic oxygen furnace (BOF), direct reduction/electric arc furnace (EAF), or smelting reduction/BOF (EIPPCB 2010). Steel is also produced by direct melting of scrap in an EAF. Each of these processes is briefly explained in the section below. Figure 1 is a simplified flow diagram of the steel production processes.

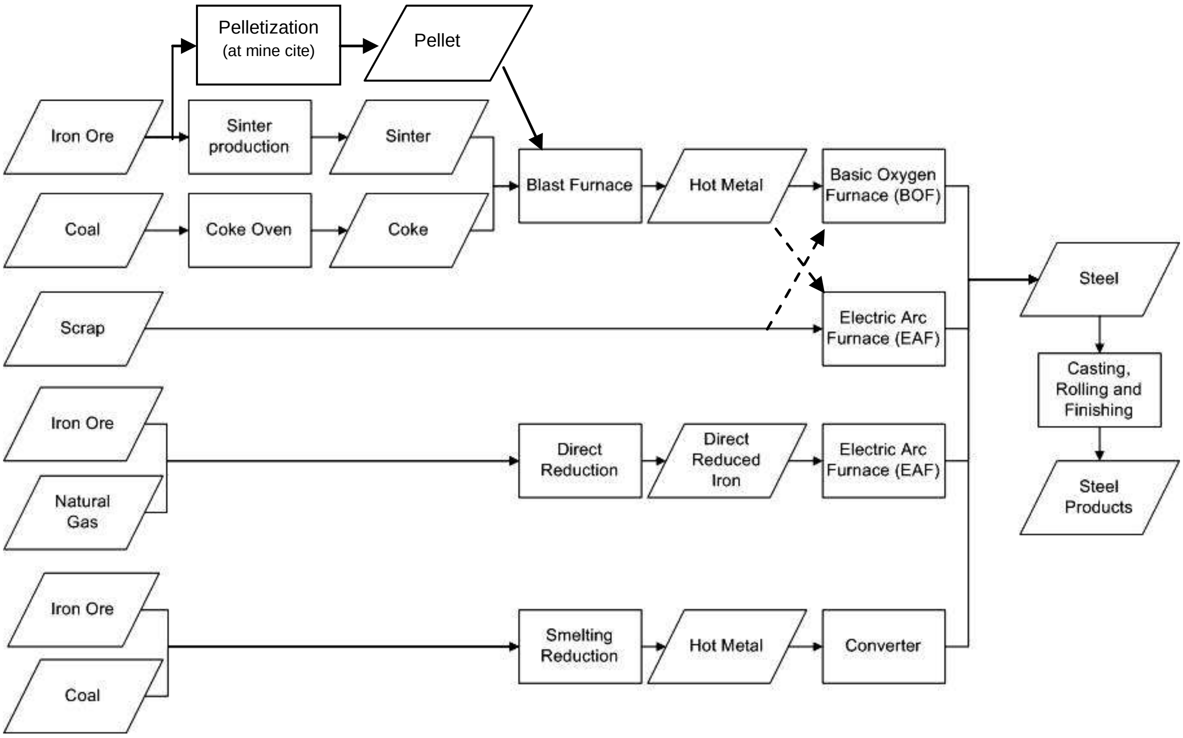

Figure 1. Flow diagram of steel production

BF-BOF and EAF production are the most common steel production processes worldwide. In 2010, BF-BOF production accounted for approximately 65 percent of the steel manufactured worldwide, and EAF production accounted for approximately 30 percent (worldsteel 2011). In

China, the BF-BOF production process accounted for 89.6 percent of total steel production in China and 92.8 percent of the steel produced by key medium- and large-sized steel enterprises in China in 2010. Almost all the remaining steel is produced by the EAF in China. [2]

## 2.1. Raw materials

### *Sintering*

In sintering, iron ore fines, other iron-bearing wastes, and coke dust are blended and combusted; the heat induces incipient fusion to convert the fines into coarse lumps (sinter) that can be used as raw material (charge) in a BF. Sintering enables manufacturers to use iron ore fines and other iron bearing wastes but requires a large capital investment and air pollution controls (APP 2010).

### *Pelletizing*

In pelletizing, iron ore is crushed and ground to remove impurities. The resulting beneficiated (iron-rich) ore is mixed with a binding agent and then heated to create durable, marble-sized pellets. These pellets can be used in both BF and direct reduction steel manufacturing (APP 2010). Pellet plants are mostly located at mining sites.

### *Coke Making*

Coke is a carbon product formed by thermal distillation of metallurgical coal at high temperatures in the absence of air. Coke is produced in batteries of coke ovens. Coke is used to provide a reducing atmosphere in a BF and is also a source of fuel. One of the key characteristics of coke is its porosity which enables the gas exchange throughout the BF from the bottom to the top. Approximately one-third of the cleaned coke oven gas (COG) is used to fuel the coke ovens, and the remainder is used in other steel plant combustion units. Some newer coke plants use non-recovery coke ovens that burn rather than recover the byproducts. The new non-recovery coke plants capture combustion waste heat to generate steam and electricity. The primary $CO_2$ emissions point at coke plants is the combustion stack from the ovens (U.S. EPA 2010).

## 2.2. Ironmaking

The subsections below describe three ironmaking processes: the BF/BOF, direct reduction, and smelting reduction processes.

### *Blast Furnace*

A BF is a huge shaft furnace that is top fed with iron ore, coke, and limestone. These materials form alternating layers in the furnace and are supported on a bed of incandescent coke. Hot air is blown through an opening into the bottom of the furnace and passes through the porous bed. The coke combusts, producing heat and carbon monoxide (CO) gas. The heat melts the charge,

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[2] The description of process is partially excerpted from (APP 2010, AISI 2010, US EPA 2010, and IEA 2010). More detailed descriptions can be found in these sources.

and the CO removes the oxygen from the iron ore, producing hot metal.[3] Hot metal is a solution of molten iron at approximately 1,480ºC, which contains 4 percent carbon and some Silicon. This hot metal flows to the bottom of the furnace, through the coke bed and is periodically "tapped" from the furnace into transfer cars and transported to the BOF where it is refined into steel. The BF is the most energy-intensive step in the BF-BOF steelmaking process, generating large quantities of $CO_2$ (AISI 2010).

### *Direct Reduction*

Direct reduction is the removal (reduction) of oxygen from iron ore in its solid state. This technology encompasses a broad group of processes based on different feedstocks, furnaces, reducing agents, etc. Natural gas (and in some cases coal) is used as a reducing agent to enable this process. In 2000, 92.6 percent of direct reduction worldwide was based on natural gas and took place in shaft furnaces, retorts, and fluidized bed reactors. The metallization rate of the end product, called Direct Reduced Iron (DRI) or "sponge iron", ranges from 85 percent to 95 percent (often even higher). In 2008, 68.5 Mt of DRI was produced worldwide, using primarily MIDREX technology (58.2 percent). The MIDREX process typically consists of four stages: 1) reduction, 2) reforming, 3) heat recovery, and 4) briquette making. A mixture of pellets or lump ore, possibly including up to 10 percent fine ore, enters the furnace shaft. As the ore descends, oxygen is removed by counter-flowing reduction gas, which is enriched with hydrogen and CO (IEA 2010). The iron is then formed into briquettes, and heat from the process is recovered. The amount of DRI produced in China is minimal.

### *Smelting Reduction*

Smelting reduction iron (SRI) is an alternative to the BF/BOF process, as it also produces liquid iron. Smelting reduction was developed to overcome the need for the energy-intensive products coke and sinter (if sinter is used in BF). Instead smelting reduction uses coal and iron fines. Several smelting reduction processes are under development; some have been commercially proven (COREX, FINEX, ITmk3) while others are under demonstration (e.g. Hismelt). Iron ore first undergoes a solid-state reduction in a pre-reduction unit. The resulting product at this stage - similar to DRI - is then smelted and further reduced in the smelting reduction vessel where coal is gasified, producing heat and CO-rich hot gas that can be further oxidized to generate additional heat to smelt the iron. Coal gasification is the result of a reaction with oxygen and iron ore in a liquid state. The heat is used to smelt iron and the hot gas is transported to the pre-reduction unit to reduce the iron oxides that enter the process. This process is called post-combustion and leads to a tradeoff in the utilization of the gas between increased pre-reduction potential or increased heat delivery for smelting (IEA 2010). Commercial smelting reduction is still dominated by first-generation processes, notably the COREX process developed in Germany and Austria (IEA 2010). The amount of steel produced by smelting reduction processes in China is minimal.

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[3] When hot metal is allowed to solidify in a pig iron casting machine, the resultant solid iron is called pig iron.

## 2.3. Steelmaking

The subsections below describe the steelmaking processes.

### *Basic Oxygen Furnace (BOF)*

The BOF converts liquid hot metal from the BF into steel. The main operation is the addition of oxygen to remove carbon from the hot metal. In recent years, extensive ladle metallurgy processes have been developed to improve steel quality. A BOF uses virtually no energy and does not produce net energy (IEA 2007).

### *Electric Arc Furnace (EAF)*

EAFs are mainly used to produce steel by recycling ferrous scrap. DRI and pig iron can also be fed to the EAF as a scrap substitute. EAFs are equipped with carbon electrodes that can be raised or lowered through the furnace roof to provide the necessary energy by an electric arc. Energy consumption in EAF-steelmaking is much lower, as the energy-intense reduction of iron ore has already been carried out in the BF (or in the DRI or SR plant). EAF steelmaking can use a wide range of scrap types, direct reduced iron (DRI), pig iron, and molten iron (up to 30 percent) as the feed charge. The liquid steel from an EAF is generally sent to a Ladle Metallurgy Station (LMS) to improve the steel quality. Recycling of scrap into steel saves virgin raw materials as well as the energy required for converting them (APP 2010).

## 2.4. Casting, rolling, and finishing

The molten steel produced by both BOFs and EAFs follows similar routes after leaving the furnace: it is transferred from the LMS to the continuous caster, which forms the steel into semi-finished shapes (e.g., slabs, blooms, billets, rounds, and other special sections). Steel from the continuous caster is mainly processed in rolling mills to produce the final shapes that are sold by the steel mill. These shapes include coiled strips, rails, sheets, many structural shapes, rods and bars. Because rolling mills consume electricity, they contribute to indirect greenhouse gas emissions. Fossil fuels (e.g. natural gas) are consumed in furnaces to reheat the steel before rolling. The products from the hot rolling mill may be further processed in various ways, such as annealing, hot forming, cold rolling, heat treating (tempering), pickling, galvanizing, coating, or painting. The furnaces are custom designed for the type of steel, the dimensions of the semi-finished steel pieces, and the desired temperature (U.S. EPA 2010).

## 3. Methodology

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

### 3.1. Decomposition analysis method

A decomposition analysis separates the effects of key components on energy end-use trends over time. Three main components that are usually considered in a decomposition analysis are: 1) aggregate activity, 2) sectoral structure, and 3) energy intensity. The IEA defines these three components as (Unander et al., 2004):

1. *Aggregate activity*: This is a measure of the total amount of output of the industry sector being analyzed. Depending on the economic sector, this component is measured in different ways. For manufacturing, it is often measured as value added of the sector.
2. *Sectoral structure*: This component represents the mix of activities within a sector and further divides activity into subsectors.
3. *Energy intensity*: This component refers to energy use per unit of activity (i.e. value added).

Different studies have used different mathematical techniques for decomposition analysis. Liu and Ang (2003) explain eight different methods for decomposing the aggregate energy intensity of industry into the impacts associated with aggregate activity, sectoral structure, and energy intensity. They argue that the choice of method can be influenced by limitations such as the data set (e.g., whether or not there are negative values) and the number of factors in the decomposition.

Ang et al. (2010) propose the use of the Logarithmic Mean Divisia Index (LMDI) method, which is recognized as superior in comparative studies such as Liu and Ang (2003). One of the LMDI method's main advantages compared to other widely used decomposition methods such as the Laspeyres method is that LMDI leaves no residual term, which in other methods can be large and affect the results and their interpretation. Two types of decomposition can be performed with LMDI: additive and multiplicative (Ang, 2005). The additive LMDI approach is easier to use and interpret, and its graphical results show effects in a clearer way than is the case for multiplicative analysis. The LMDI method can also be used for both changing and non-changing analysis. Changing analysis is based on yearly evaluations, and non-changing analysis is based on evaluation for a base-year period and an end-year period. For this study, we used additive LMDI decomposition analysis with non-changing analysis. Non-changing decomposition is used because for future projections changing analysis (which requires annual data) is less relevant and non-changing analysis with a 5-year or 10-year period is more appropriate since the energy intensity and production forecasts are assumed in 5-year (2010-2015 and 2015-2020) or 10-year (2020-2030) terms.

Ang (2005) provides practical guidelines for using the LMDI method that describes the formulas used in the additive LMDI method for decomposing energy use into activity, structural, and energy intensity effects.

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

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

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

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

*Where :*

i: process route (BF-BOF or EAF route)

t: year

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

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

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

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

*Where :*

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

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

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

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

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

*Where:*

T: last year of the period

T= 0: base year of the period

E: total final energy consumption of the key medium- and large-sized steel enterprises

$\Delta E_{tot}$: aggregate change in total final energy consumption of the key medium- and large-sized steel enterprises

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

$$\mathbf{\Delta E_{tot} = \Delta E_{act} + \Delta E_{str} + \Delta E_{ratio} + \Delta E_{int}} \tag{4}$$
$$\Delta E_{act} = \Delta E_{act.PI} + \Delta E_{act.Oth} \tag{5}$$
$$\Delta E_{Str} = \Delta E_{Str.PI} + \Delta E_{Str.Oth} \tag{6}$$
$$\Delta E_{shar} = \Delta E_{ratio.PI} \tag{7}$$
$$\Delta E_{int} = \Delta E_{int.PI} + \Delta E_{int.Oth} \tag{8}$$

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

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

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

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

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

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

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

Where:

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

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

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

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

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

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

$Q_{crude,t}$: total crude steel production in year t
$Q_{crude,i,t}$: crude steel production by process route i in year t
$Q_{PI,i,t}$: pig iron used by process route i in year t

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

### 3.2. Historical final energy intensity of the key medium- and large-sized steel enterprises

In this study the final energy[4] intensity of the BF-BOF and EAF steel production routes are calculated separately. Further, the energy use for the production of pig iron used in each steel making route is calculated separately in order to be used in the decomposition analysis (see Eq. 1). The final energy intensities are calculated by a bottom-up approach using the sub-processes energy intensities mostly provided in *China Steel Yearbooks* (EBCSY 2001-2011). Table 2 shows the final energy intensity of major iron and steel production sub-processes. It should be noted that this table only includes the major sub-processes and does not include all sub-processes in the steel plants. For example, several sub-processes such as steam generation, oxygen production, and some finishing processes, etc. are missing. We categorized all these sub-processes that are missing as “Auxiliary” and we calculate the energy intensity for this category below.

Table 2: Final energy intensity of the main steel-making processes in key medium- and large-sized Chinese steel enterprises (2000-2010) (EBCSY 2001-2011; Zhang and Wang 2006).

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

Notes: 1) The original data for energy intensities in years 2000-2005 was in primary energy. We converted those intensities from primary to final energy using assumptions of the share of electricity intensity from primary energy intensity in each process in China (13% for coking, 18% for sintering, 10% pelletization, 2% for BF, 85% for BOF, 85% for EAF, 40% for rolling and finishing). 2) The data for years 2000-2004 are from Zhang and Wang (2006) and for years 2005-2010 are from Steel Yearbooks (EBCSY 2001-2011).

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[4] In final energy, electricity is converted from kWh to GJ or PJ using a simple unit conversion without taking into account the power generation and transmission and distribution losses.

Final energy intensity for the production of one tonne of pig iron (or hot metal) can be calculated from the following equation:

$$EI_{PI} = EI_{coke} * F_{coke} + EI_{sint} * F_{sint} * Sh_{sint} + EI_{pell} * F_{pell} * Sh_{pell} + EI_{BF} \qquad (21)$$

*Where:*

$EI_{PI}$ : total energy intensity of pig iron production (GJ/t pig iron)
$EI_{coke}$ : energy intensity of coke making (GJ/t coke)
$F_{coke}$ : amount of coke required per tonne of pig iron: we assumed 0.4 t coke/t pig iron
$EI_{sint}$ : energy intensity of sintering (GJ/t sinter)
$F_{sint}$ : amount of sinter required per tonne of pig iron: we assumed 1.5 t sinter/t pig iron
$Sh_{sint}$: share of sinter from total iron ore used in the Chinese steel industry (see table 3)
$EI_{pell}$ : energy intensity of pelletization (GJ/t pellet)
$F_{pell}$ : amount of pellet required per tonne of pig iron: we assumed 1.5 t pellet/t pig iron
$Sh_{pell}$: share of pellet from total iron ore used in the Chinese steel industry (see table 3)
$EI_{BF}$ : energy intensity of ironmaking in BF (GJ/t pig iron)

Next the final energy intensity of BF-BOF and EAF steel production excluding auxiliary energy use can be calculated as follows. Auxiliary energy use refers to the uses of energy in the steel industry that are not presented explicitly in Eq. 21. These are utilities and other additional processes in the steel industry. Results are presented in Table 4.

$$EI_{BF\text{-}BOF\text{-}X} = EI_{PI} * F_{PI,BOF} + EI_{BOF} + EI_{roll} * F_{roll} \qquad (22)$$

$$EI_{EAF\text{-}X} = EI_{PI} * F_{PI,EAF} + EI_{EAF} + EI_{roll} * F_{roll} \qquad (23)$$

*Where:*

$EI_{BF\text{-}BOF\text{-}X}$ : final energy intensity of BF-BOF steel production route excluding “Auxiliary” energy use (GJ/t crude steel)
$EI_{PI}$ : total energy intensity of pig iron production (calculated using Eq. 21)
$F_{PI,BOF}$ : ratio of pig iron used as feedstock per tonne of crude steel produced by BOF: we assumed 1 t pig iron/t crude steel
$EI_{BOF}$ : energy intensity of BOF vessel (see Table 2)
$EI_{roll}$ : average energy intensity of rolling process (see Table 2)
$F_{roll}$: the ratio of rolled (finished) steel per crude steel: we assumed 0.95 t finished steel/t crude steel
$EI_{EAF\text{-}X}$ : energy intensity of EAF steel production route excluding “Auxiliary” energy use (GJ/t crude steel)
$F_{PI,EAF}$ : ratio of pig iron used as feedstock per tonne of crude steel produced by EAF (see Table 3)
$EI_{EAF}$: energy intensity of EAF vessel (see Table 2)

Table 3. Ratio of pig iron used as feedstock in EAF per tonne of crude steel produced and share of sinter and pellet from total iron ore used in the Chinese steel industry (EBCSY 2001-2011)

| Year | Pig iron ratio in EAF (t pig iron/t crude steel) | Share of sinter from total iron ore used | Share of pellet from total iron ore used | Share of EAF steel production from total steel production |
|---|---|---|---|---|
| **2000** | 0.25 | 90% | 10% | 12.1% |
| **2001** | 0.25 | 90% | 10% | 14.3% |
| **2002** | 0.30 | 89% | 11% | 15.0% |
| **2003** | 0.30 | 88% | 12% | 15.7% |
| **2004** | 0.36 | 87% | 13% | 14.3% |
| **2005** | 0.45 | 86% | 14% | 11.7% |
| **2006** | 0.50 | 85% | 15% | 9.7% |
| **2007** | 0.48 | 84% | 16% | 9.6% |
| **2008** | 0.46 | 85% | 15% | 8.8% |
| **2009** | 0.54 | 85% | 15% | 7.1% |
| **2010** | 0.47 | 85% | 15% | 7.2% |

The pig iron ratio in the EAF process in China, which was 47 percent in 2010, is higher than most other countries. For example, this ratio is between 10 and 15 percent in the U.S. steel industry. Since production of pig iron is highly energy-intensive, the higher the ratio of pig iron used as feedstock in the EAF process, the higher the energy intensity of the steel produced by the EAF route. The main reason why China uses a high ratio of pig iron as feedstock in the EAF process is lack of scrap availability and the high price of imported scrap. Hence, the Chinese EAF steel makers often prefer to use pig iron instead of higher priced imported scrap. We can calculate the combined final energy intensity of steel production excluding auxiliary energy use in key medium- and large-sized Chinese steel enterprises using the following equation. The results are presented in Table 4.

$$EI_{X} = EI_{BF\text{-}BOF\text{-}X} * Sh_{BOF} + EI_{EAF\text{-}X} * Sh_{EAF} \qquad (24)$$

*Where:*

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

Next, we have to calculate and take into account the energy use of the auxiliary category. To do this, first we calculate the combined energy intensity of key medium- and large-sized Chinese steel enterprises excluding the auxiliary energy use. Then, we subtract this combined energy use from the "comprehensive final energy intensity" of key medium- and large-sized Chinese steel enterprises reported in China Steel Yearbook (EBCSY 2001-2011), which accounts for the total energy use in key medium- and large-sized Chinese steel enterprises. The difference will be the auxiliary energy use related to processes such as steam generation, oxygen production, onsite power generation energy use, waste water treatment, etc.

Comprehensive energy intensity values for years 2000-2005 given in EBCSY (2001-2011) are in primary energy[5] instead of final energy. Since the share of end-use electricity use from the total energy use in the key medium- and large-sized Chinese steel enterprises in various years is unknown, we could not convert the primary energy intensities into final energy intensity. Hence, for years 2000-2005, the final energy intensity of auxiliary category is assumed equal to average final energy intensity of auxiliary category in 2006-2010.

Once we calculated the final energy intensity of auxiliary category, we add it to $EI_{BF\text{-}BOF\text{-}X}$ and $EI_{EAF\text{-}X}$ in order to calculate $EI_{BF\text{-}BOF}$ and $EI_{EAF}$ which are the final energy intensity of BF- and EAF steel production route including auxiliary energy use, respectively (Table 4). Finally, we can calculate the combined final energy intensity of key medium- and large-sized Chinese steel enterprises including the auxiliary energy use (EI) from the following equation:

$$EI = EI_{BF\text{-}BOF} * Sh_{BOF} + EI_{EAF} * Sh_{EAF} \qquad (25)$$

*Where:*

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

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[5] In primary energy, electricity use is converted from final to primary energy using the average power generation efficiency in China in various years.

Table 4. Final energy intensities (GJ/t crude steel) calculated for key medium- and large-sized Chinese steel enterprises (2000-2010)

| Year | Final energy intensity of EAF route excluding auxiliary energy use ($EI_{EAF-X}$) | Final energy intensity of BF-BOF route excluding auxiliary energy use ($EI_{BF-BOF-X}$) | Combined Final energy intensity of key enterprises excluding auxiliary energy use | Comprehensive final energy intensity [a] | Final energy intensity of auxiliary category [c] | Final energy intensity of complete EAF route | Final energy intensity of complete BF-BOF route | Combined Final energy intensity of key enterprises |
|---|---|---|---|---|---|---|---|---|
| **2000** | 10.2 | 20.6 | 19.3 | N.A. [b] | 0.9 | 11.1 | 21.5 | 20.3 |
| **2001** | 9.4 | 19.9 | 18.4 | N.A. [b] | 0.9 | 10.3 | 20.8 | 19.3 |
| **2002** | 10.1 | 19.7 | 18.2 | N.A. [b] | 0.9 | 11.0 | 20.6 | 19.2 |
| **2003** | 9.9 | 19.8 | 18.3 | N.A. [b] | 0.9 | 10.8 | 20.8 | 19.2 |
| **2004** | 10.8 | 19.7 | 18.5 | N.A. [b] | 0.9 | 11.7 | 20.7 | 19.4 |
| **2005** | 11.9 | 19.3 | 18.4 | N.A. [b] | 0.9 | 12.8 | 20.2 | 19.4 |
| **2006** | 12.6 | 18.6 | 18.0 | 18.9 | 0.9 | 13.4 | 19.5 | 18.9 |
| **2007** | 12.0 | 18.2 | 17.6 | 18.4 | 0.8 | 12.8 | 19.0 | 18.4 |
| **2008** | 11.5 | 18.1 | 17.5 | 18.5 | 0.9 | 12.4 | 19.0 | 18.5 |
| **2009** | 12.3 | 17.4 | 17.0 | 18.1 | 1.1 | 13.4 | 18.5 | 18.1 |
| **2010** | 11.3 | 17.2 | 16.7 | 17.7 | 1.0 | 12.2 | 18.1 | 17.7 |

N.A.: Not Available

[a] Source: EBCSY (2001-2011)

[b] Comprehensive energy intensity for this year given in EBCSY (2001-2011) is in primary energy instead of final energy. Since the share of end-use electricity use from the total energy use in the key medium- and large-sized Chinese steel enterprises in various years is unknown, we could not convert the primary energy intensities into final energy intensity.

[c] For years 2000-2005, the final energy intensity of auxiliary category is assumed equal to average final energy intensity of the auxiliary category in 2006-2010.

To calculate $E_{PI,i}$ (final energy use for production of pig iron used for steel production in process route i) and $E_{Oth,i}$ (total final energy use for steel production by process route i minus the energy use for production of pig iron used for steel production in process route i) which are used in the decomposition analysis (Eq. 1 – Eq. 20), we made the followings calculations:

- We assumed that 50% of the auxiliary energy use is used before the production of pig iron and the rest after the production of pig iron in the steel industry in China.
- We used the following equations to calculate the $E_{PI,i}$ for EAF and BF-BOF routes:

$$E_{PI,EAF} = (EI_{PI} * F_{PI,EAF} + EI_{Aux} * 0.5 * F_{PI,EAF})* P_{EAF} \quad (26)$$

*Where:*

$E_{PI,EAF}$ : Energy use for production of pig iron used for EAF steel production
$EI_{PI}$ : total energy intensity of pig iron production (calculated using Eq. 21)
$EI_{Aux}$ : energy intensity of the auxiliary category (see Table 4)
$F_{PI,EAF}$ : ratio of pig iron used as feedstock per tonne of crude steel produced by EAF (see Table 3)
$P_{EAF}$: Production of crude steel by EAF

$$E_{PI,BOF} = (EI_{PI} * F_{PI,BOF} + EI_{Aux} * 0.5 * F_{PI,BOF})* P_{BOF} \quad (27)$$

Where:

$E_{PI,BOF}$: Energy use for production of pig iron used for BF-BOF steel production
$EI_{PI}$ : total energy intensity of pig iron production (calculated using Eq. 21)
$EI_{Aux}$ : energy intensity of the auxiliary category (see Table 4)
$F_{PI,BOF}$ : ratio of pig iron used as feedstock per tonne of crude steel produced by BOF (see Table 3)
$P_{BOF}$: Production of crude steel by BOF

- We subtracted $E_{PI,BOF}$ from total final energy use by BF-BOF production route in key enterprises ($EI_{BF\text{-}BOF}$ * total BOF crude steel production) and $E_{PI,EAF}$ from total final energy use by EAF production route in key enterprises ($EI_{EAF}$ * total EAF crude steel production) to calculate the $E_{Oth}$ for EAF and BF-BOF routes, respectively. These calculations were done for each year separately. The results are presented in Table 5.

Table 5. Final energy use data used in the decomposition analysis (Petajoule [PJ])

| | $E_{PI,EAF}$ | $E_{PI,BOF}$ | $E_{Oth,EAF}$ | $E_{Oth,BOF}$ | **Total** |
|---|---|---|---|---|---|
| **2000** | 67 | 1,927 | 95 | 351 | 2,440 |
| **2001** | 87 | 2,078 | 115 | 363 | 2,643 |
| **2002** | 132 | 2,467 | 139 | 402 | 3,140 |
| **2003** | 157 | 2,811 | 158 | 439 | 3,564 |
| **2004** | 216 | 3,586 | 175 | 549 | 4,525 |
| **2005** | 260 | 4,405 | 167 | 664 | 5,496 |
| **2006** | 287 | 5,326 | 168 | 825 | 6,606 |
| **2007** | 308 | 6,057 | 188 | 884 | 7,438 |
| **2008** | 278 | 6,303 | 177 | 898 | 7,656 |
| **2009** | 301 | 7,241 | 160 | 1,041 | 8,742 |
| **2010** | 299 | 8,167 | 186 | 1,170 | 9,822 |

### 3.3. Forecasting energy intensity of the key medium- and large-sized steel enterprises

Similar steps as described in section 3.2 were taken to forecast the final energy intensity of key medium- and large-sized Chinese steel enterprises in 2015, 2020, and 2030. However, instead of using the process energy intensities given in Table 2, we used the "advanced value of energy intensity from national standard"[6] given by China's Ministry of Industry and Information Technology (MIIT) and also in "GB 21256-2007: The norm of energy consumption per unit product of major processes of crude steel manufacturing" as the basis for our assumptions for energy intensity of each of the main steel-making processes (MIIT 2010; Standards Press of China, 2007). Table 6 shows the assumed energy intensities for each process in 2030. We assume that the energy intensity of steel-making processes in key medium- and large-sized Chinese steel enterprises in 2030 will be equal to the "advanced value of energy intensity from national standard." Then, we assumed that the reduction in energy intensity of processes between 2010 and 2030 will be linear and based on the calculated the energy intensity for each process in 2015 and 2020.

Table 6. Energy intensity of main steel-making processes assumed for 2030 (MIIT 2010: Standards Press of China 2007)

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

[a] The energy intensity of rolling was given for 12 different product categories in MIIT (2010) which varies based on the type of products. We calculated the weighted average energy intensity of rolling based on energy intensity of each product category and the production of that product in 2010 given in China Steel Yearbook 2011 (EBCSY 2001-2011).

Once we have the final energy intensities of steel-making processes, the calculations to determine the energy intensities of BF-BOF and EAF steel-making in 2015, 2020, and 2030 are similar to those described in section 3.2. Several other assumptions were made before calculating the future energy intensities. The most important assumptions were the pig iron feed ratio in EAF production and the share of EAF steel production within total steel production in the future. Several drivers can influence these two factors such as the steel scrap availability, the retirement rate of the BF-BOF plants and the construction rate of the new EAF plants, the future steel demand and production in China, etc. There are varying forecasts for all of the aforementioned drivers in different studies (McKinsey & Co. 2009; Hatch. 2012; Valle 2013; Wang et al. 2013; Zhu et al. 2012), which make it difficult to determine one absolute number for the pig iron ratio in EAF and the EAF share. Therefore, we decided to develop three different scenarios to address this issue and to capture the effect of different assumption of the final results. Total steel production is kept constant across the three scenarios. The three scenarios are as follows:

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

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

Table 7 presents the values for pig iron feed ratio in EAF and the EAF steel production share in the future under different scenarios. It also presents the assumptions on the share of sinter and pellet from total iron ore used in the future.

Table 7. Several assumptions used in calculating the future energy intensities

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

Using the values in Table 6 and Table 7 and the method explained in section 3.2., we calculated the final energy intensities for the BF-BOF and EAF steel production routes in 2015, 2020, and 2030. The results are presented in section 4.1.

### 3.4. Historical and future production for key medium- and large-sized steel enterprises

In the decomposition analysis equations (section 3.1), the production of crude steel by BF-BOF and EAF production routes as well as the amount of pig iron used in EAF and BOF is needed. The pig iron ratio for EAF in different years is given in Table 3. We also assumed that the pig iron ratio for BOF is equal to 1 in all years. These ratios can be multiplied by the crude steel production in EAF and BOF production to determine the pig iron used in EAF and BOF steel production, respectively. The historical production data for key enterprises are obtained from various years of the China Steel Yearbook (EBCSY 2001-2011).

Future production data are calculated based on Fridley et al. (2011) which forecasts 804 million tonne (Mt) and 831 Mt steel production in China in 2020 and 2030, respectively, using several assumptions on drivers such as infrastructural and construction demand as well as demand for product steel used in appliances, machinery, and other products for final consumption. The details of their assumptions can be found in Fridley et al. (2011). However, the steel production forecast data in Fridley et al. (2011) is for the entire Chinese steel industry and not for key enterprises. Hence, we could not use those forecast data directly. First, we calculated the average annual growth rate (AAGR) of the steel production in the periods of 2010-2015 (2.1%), 2015-2020 (1.4%), 2020-2025 (0.4%) and 2025-2030 (0.2%) from Fridley et al. (2011). Then, we used these AAGRs, as shown in Table 8, to calculate the total steel production of key enterprises in 2015, 2020, 2025, and 2030. Following equation is used to calculate the future productions using the AAGRs:

$$P_{(t)} = P_{(t0)} * (1+AAGR_{t0\text{-}t})^{(t-t0)} \qquad (28)$$

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

After calculating the total steel production of key enterprises, we used the share of EAF steel production from total steel production in key enterprises (Table 7) to calculate the steel production by EAF and BF-BOF production routes under each scenario.

Table 8. Assumptions on AAGR used to forecast total steel production in key enterprises (Fridley et al. 2011)

| | 2010-2015 based on 2010 production | 2015-2020 based on 2015 production | 2020-2025 based on 2020 production | 2025-2030 based on 2025 production |
|---|---|---|---|---|
| **AAGR** | 2.1% | 1.4% | 0.4% | 0.2% |

The pig iron ratio for EAF in 2015, 2020, and 2030 (Table 7) is multiplied by the crude steel production by EAF to achieve the pig iron used in EAF. The pig iron ratio for BOF is assumed to be equal to 1.0 in all years. The results for the production of key steel enterprises are presented in section 4.1.

## 4. Results and Discussion

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

### 4.1. Final energy intensity, energy use, and crude steel production in key medium- and large-sized steel enterprises

Figure 2 shows the calculated final energy intensities for BF-BOF and EAF steel production routes in key steel enterprises from 2000 to 2030. It shows that energy intensity of both the BF-BOF route and the combined energy intensity have a declining trend, while the energy intensity of the EAF route has an increasing trend between 2001 and 2009 and then decreasing up to 2030. The increasing trend of the EAF route energy intensity is primarily because of upwards trend of pig iron ratio in EAF production as a feedstock (Table 3) in this period. Overall, compared to 2010 level, the combined final energy intensity of key medium- and large-sized Chinese steel enterprises in 2015, 2020, and 2030 declines by 4 percent, 8 percent, and 17 percent, respectively (around 4 percent reduction every five years), under scenario 1 (low scrap usage) and by 4 percent, 11 percent, and 29 percent, respectively, under scenario 3 (high scrap usage). A 4 to 6 percent reduction in combined energy intensity every 5 years observed under scenario 1 and 2 is also consistent with the observed reductions in the past few years. On the other hand, the 7 to 10 percent reduction in combined energy intensity every 5 years observed under scenario 3 will be an accelerated energy intensity reduction which is only possible with a high rate of scrap use which means high share of EAF steel production and lower use of pig iron in EAFs in China during the 2010 – 2030 period.

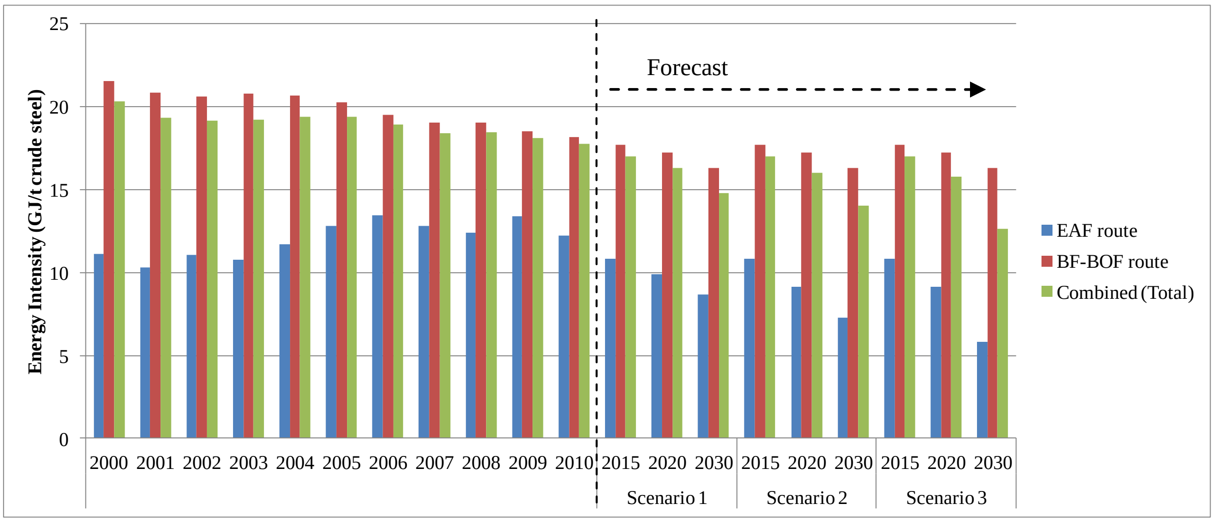
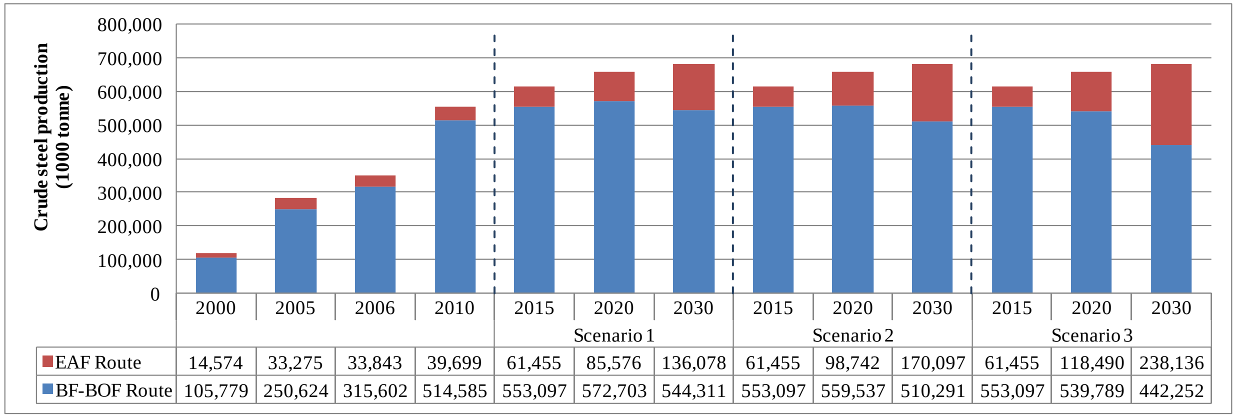


Figure 2. Final energy intensities calculated for key medium- and large-sized Chinese steel enterprises (2000-2030)

Table 9 shows the calculated steel production and pig iron used in EAF and BF-BOF routes in key medium- and large-sized Chinese steel enterprises between 2000 and 2030. Figure 3 illustrates the total crude steel production by the EAF and BF-BOF production routes in key enterprises under different scenarios. Since the retrospective decomposition analysis is conducted for the periods of 2000-2005 and 2006-2010, we only present the historical production data for these years. Figure 3 shows clearly that scenario 1 and scenario 3 have the lowest and highest overall EAF steel production between 2010 and 2030, respectively. The total steel produced by the key steel enterprises are the same across the scenarios and only the share of EAF steel production varies among the scenarios. One important point is that under all scenarios, the total annual crude steel production of key Chinese steel enterprises (and most likely the entire Chinese steel industry) is assumed to peak in 2030. Also, the AAGR of crude steel production in key steel enterprises in the periods of 2000-2005 and 2006-2010 were 19 percent and 12 percent, respectively, which are far higher than the future AAGR of crude steel production between 2010 and 2030 given in Table 8. The decomposition analysis results presented in the next section show how the lower AAGR of steel production in the future contributes to the changes in the total energy use trend of the steel industry.

Table 9. Annual crude steel production and pig iron used in EAF and BF-BOF steel production routes in key medium- and large-sized Chinese steel enterprises under each scenario

| | | | | | | **Scenario** 1 | | | **Scenario** 2 | | | **Scenario** 3 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **2000** | **2005** | **2006** | **2010** | **2015** | **2020** | **2030** | **2015** | **2020** | **2030** | **2015** | **2020** | **2030** |
| **Annual crude steel production (1000 t crude steel)** | BF-BOF Route | 105,779 | 250,624 | 315,602 | 514,585 | 553,097 | 572,703 | 544,311 | 553,097 | 559,537 | 510,291 | 553,097 | 539,789 | 442,252 |
| | EAF Route | 14,574 | 33,275 | 33,843 | 39,699 | 61,455 | 85,576 | 136,078 | 61,455 | 98,742 | 170,097 | 61,455 | 118,490 | 238,136 |
| | **Total Key Steel Enterprises** | **120,353** | **283,899** | **349,444** | **554,284** | **614,552** | **658,279** | **680,388** | **614,552** | **658,279** | **680,388** | **614,552** | **658,279** | **680,388** |
| **Annual pig iron use (1000 t pig iron)** | BF-BOF Route | 105,779 | 250,624 | 315,602 | 514,585 | 553,097 | 572,703 | 544,311 | 553,097 | 559,537 | 510,291 | 553,097 | 539,789 | 442,252 |
| | EAF Route | 3,702 | 14,807 | 17,023 | 18,817 | 24,582 | 29,952 | 40,823 | 24,582 | 29,623 | 34,019 | 24,582 | 35,547 | 23,814 |
| | **Total Key Steel Enterprises** | **109,481** | **265,431** | **332,625** | **533,403** | **577,679** | **602,655** | **585,134** | **577,679** | **589,160** | **544,311** | **577,679** | **575,336** | **466,066** |



| | 2000 | 2005 | 2006 | 2010 | 2015 | 2020 | 2030 | 2015 | 2020 | 2030 | 2015 | 2020 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Scenario 1 | | | Scenario 2 | | | Scenario 3 | | |
| 🟥 EAF Route | 14,574 | 33,275 | 33,843 | 39,699 | 61,455 | 85,576 | 136,078 | 61,455 | 98,742 | 170,097 | 61,455 | 118,490 | 238,136 |
| 🟦 BF-BOF Route | 105,779 | 250,624 | 315,602 | 514,585 | 553,097 | 572,703 | 544,311 | 553,097 | 559,537 | 510,291 | 553,097 | 539,789 | 442,252 |

Figure 3. Total crude steel production by EAF and BF-BOF steel production routes in key enterprises under different scenarios (2000-2030)

From the energy intensity and production data given in Figure 2 and Table 9 and by using Eq. 26 and Eq. 27 (section 3.2), we can calculate the future final energy use data used in the decomposition analysis for each scenario (Table 10).

Table 10. Forecasted final energy use data used in the decomposition analysis for each scenario (in PJ)

| | | $E_{PI.EAF}$ | $E_{PI.BOF}$ | $E_{Oth.EAF}$ | $E_{Oth.BOF}$ | **Total** |
|---|---|---|---|---|---|---|
| **Scenario 1** | 2015 | 383 | 8,615 | 284 | 1,168 | 10,449 |
| | 2020 | 458 | 8,752 | 387 | 1,117 | 10,713 |
| | 2030 | 599 | 7,988 | 584 | 876 | 10,046 |
| **Scenario 2** (High | 2015 | 383 | 8,615 | 284 | 1,168 | 10,449 |
| | 2020 | 453 | 8,551 | 449 | 1,091 | 10,543 |
| | 2030 | 499 | 7,488 | 736 | 821 | 9,545 |
| **Scenario 3** (Low | 2015 | 383 | 8,615 | 284 | 1,168 | 10,449 |
| | 2020 | 543 | 8,249 | 539 | 1,052 | 10,383 |
| | 2030 | 349 | 6,490 | 1,040 | 711 | 8,591 |

Figure 4 shows the total final energy use in key medium- and large-sized Chinese steel enterprises under each scenario during 2000-2030. The interesting result shown in Figure 4 is that the total final energy use of the key Chinese steel enterprises (and most likely the entire Chinese steel industry) peaks in 2020 under scenario 1 and scenario 2 and in 2015 under scenario 3. In addition, the percentage change in final energy use between 2010 and 2030 is equal to +2 percent, -3 percent, and -13 percent under scenario 1, 2, and 3, respectively (Figure 4). This is a very important finding that deserves further investigation. The decomposition analysis results presented in the next section will show what contributed (changes in steel production, EAF share of total production, pig iron ratio in EAF production, and energy intensity of steel production) to the reduction in the final energy use and its peak under each scenario.

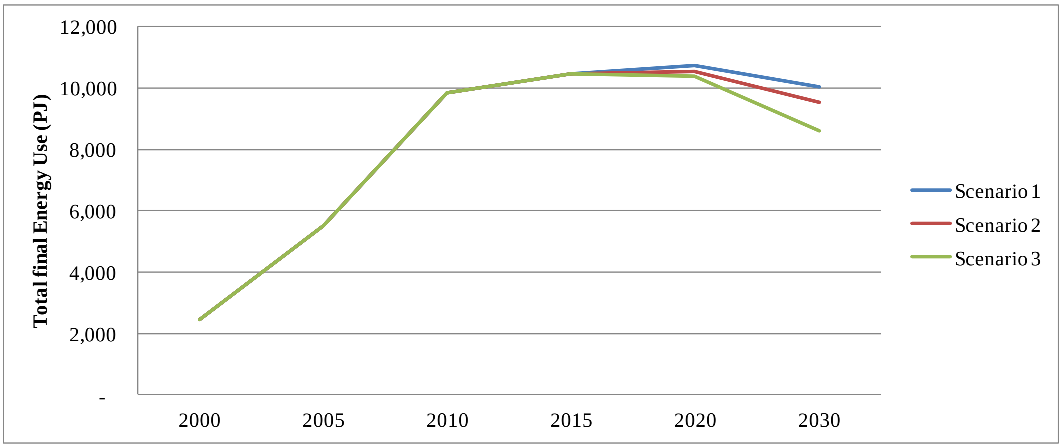


Figure 4. Total final energy use in key medium- and large-sized Chinese steel enterprises under each scenario (2000-2030)

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

### 4.2. Decomposition of key medium- and large-sized steel enterprises' energy use

We conducted separate decomposition analysis for each of the three scenarios explained in section 3 in order to show how different assumptions regarding the crude steel production forecast will affect the prospective decomposition results.

A LMDI decomposition analysis was performed for the Chinese key medium- and large-sized steel enterprises for five time periods: 2000-2005, 2006-2010, 2010-2015, 2015-2020, and 2020-2030. These five periods were chosen based on the Chinese government Five Year Plan periods. Each FYP period is associated with a set of Government policies that affect manufacturing energy intensity. Starting in the 11th FYP, specific policies, programs, incentives, and targets were established with the stated intent of reducing China's overall energy intensity and a substantial share of these were focused on reducing manufacturing energy intensity, especially in the energy-intensive sectors like iron and steel industry.

It should be noted that the initial year in each period in this decomposition analysis is used as the base year for steel production and energy use data. Thus, the decomposition for each period shows the subsequent change compared to the initial year for that period. For example, the decomposition analysis for 2000-2005 shows the changes in final energy use and influential factors in 2001-2005 (10th FYP) compared to the final energy use in 2000. Similarly, the decomposition analysis for 2010-2015, 2015-2020, and 2020-2030 show the changes in final energy use and influential factors during 12th, 13th, and 14th plus 15th FYP, respectively. The only exception is the period of 2006-2010. Because the original energy intensity data for major steel production processes given in China Steel Yearbooks were in primary energy for years 2000-2005 and in final energy for years 2006-2010, we had to convert the primary energy intensities to final energy intensities for each process for years 2000-2005 by assuming a certain share for electricity intensity from total primary energy intensity given for these years as well as power generation efficiency. While we believe that the calculated final energy intensities for years 2000-2005 which are given in Table 2 are accurate and result in sensible trends with the final energy intensities given for 2006-2010, we chose to separate these two periods (2000-2006 and 2006-2010) in the decomposition analysis to prevent the uncertainty related to the aforementioned calculation to affect the decomposition analysis results.

As explained in the methodology section, additive non-changing decomposition analysis was used for this study. Since there are three different scenarios, we conducted the decomposition analysis for each scenario separately. It should be noted that the results of the decomposition analysis of historical data (2010-2010) are the same across all scenarios and only the results of decomposition for future years (2010-2015, 2015-2020, and 2020-2030) vary across the three scenarios because of different assumptions used (see Table 7).

Figures 5 show the results of the decomposition analysis of total final energy use of key medium- and large-sized steel enterprises for during the 10th and 11th FYP, separately. During the 10th FYP (2000-2005) and 11th FYP (2006-2010), the activity effect increased the final energy use by 3,225 PJ and 3,738 PJ, respectively due to rapid increase in crude steel production in these two periods. The structural effect slightly increased the final energy use of key enterprises in these two periods (7 PJ in 10th FYP and 69 PJ in 11th FYP) because of slight decrease in EAF steel production share (hence, increase in more energy-intensive BF-BOF steel production share) of key enterprises in 2005 compared to 2000 and in 2010 compared to 2006 (see Table 3). The pig iron ratio effect increases the final energy use by 80 PJ during 10th FYP and decreases it slightly by 17 PJ during 11th FYP. This is because the ratio of pig iron used as a feedstock in EAF increases in 2005 compared to 2000 and slightly decreases in 2010 compared to 2006 (see table 3). The pig iron ratio effect is small because the share of EAF steel production in China is low; hence, the changes in pig iron ratio used in EAF do not affect the total final energy use of the industry significantly. After the intensity effect, which reduces the final energy use by 256 PJ and 573 PJ during 10th and 11th FYP, respectively, is taken into account, the total change in key steel enterprises final energy use during 10th and 11th FYP is equal to an increase of 3,056 PJ and 3,215 PJ, respectively.

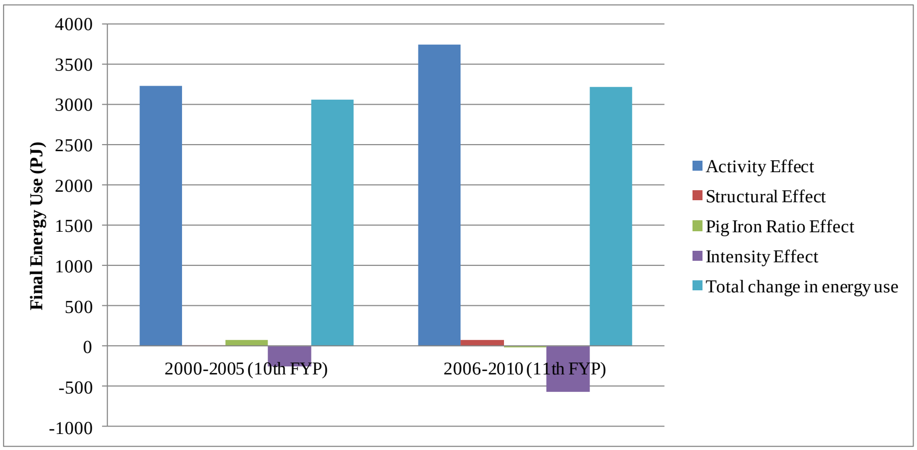


Figure 5. Results of retrospective decomposition of final energy use of key medium- and large-sized steel enterprises during the 10th and 11th Five Year Plans

Figure 5 shows that in both periods the activity and intensity effects were the two dominant influences working against each other to drive energy use upward (activity effect) or downward (intensity effect). The intensity effect during the 10th FYP (2000-2005) is the smaller compared to the 11th FYP because of a very small decline in combined final energy intensity of key enterprises during this period (see Figure 2). This was due to the sudden boom in steel production capacity and construction of steel plants in China and the rapid increase in production without enough attention to energy efficiency. During the 11th FYP, in an attempt to control the energy intensity of manufacturing, the Chinese government implemented series of policies and programs to reduce the energy intensity of manufacturing sectors, especially the energy-intensive industries like the steel industry. Programs like the “Top-1000 Enterprises Energy Saving Program” and the “10 Key Energy Saving Projects Program” implemented during the 11th FYP substantially helped to control the energy intensity of the manufacturing (Price et al. 2011).

Figures 6 to 8 show the results of the prospective decomposition analysis for 2010 – 2030 (the 12th, 13th, and 14th plus 15th Five Year Plan periods). The differences between the three scenarios and the primary reasons for such differences are summarized below.

Overall, the future activity effects are almost similar across the scenarios due to the similar steel production forecast for all three scenarios (see Table 9).

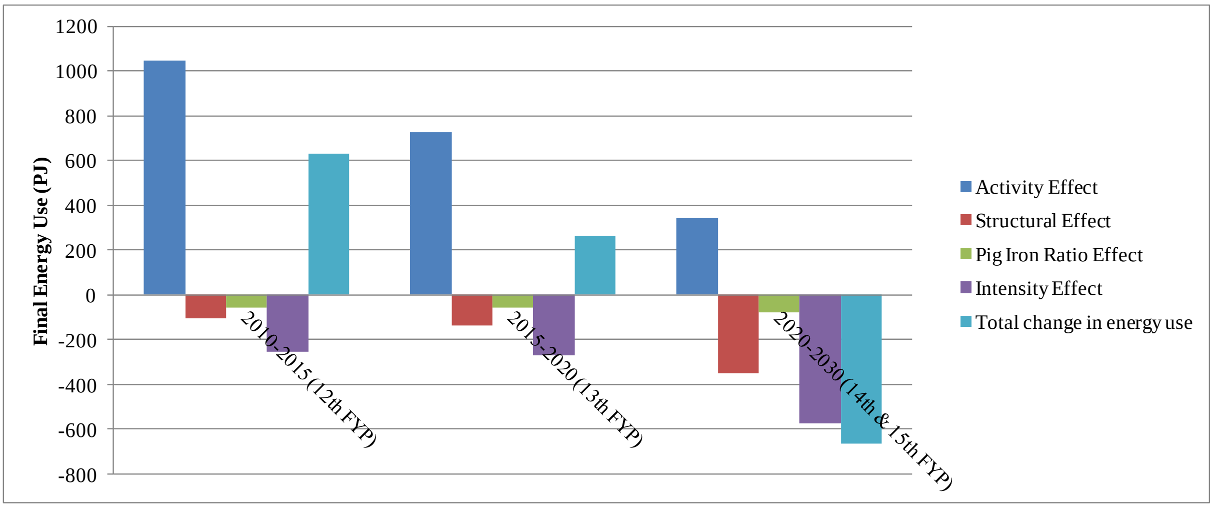


Figure 6. Scenario 1. Results of prospective decomposition of final energy use of key medium- and large-sized steel enterprises during the 12th, 13th, and 14th plus 15th Five Year Plans

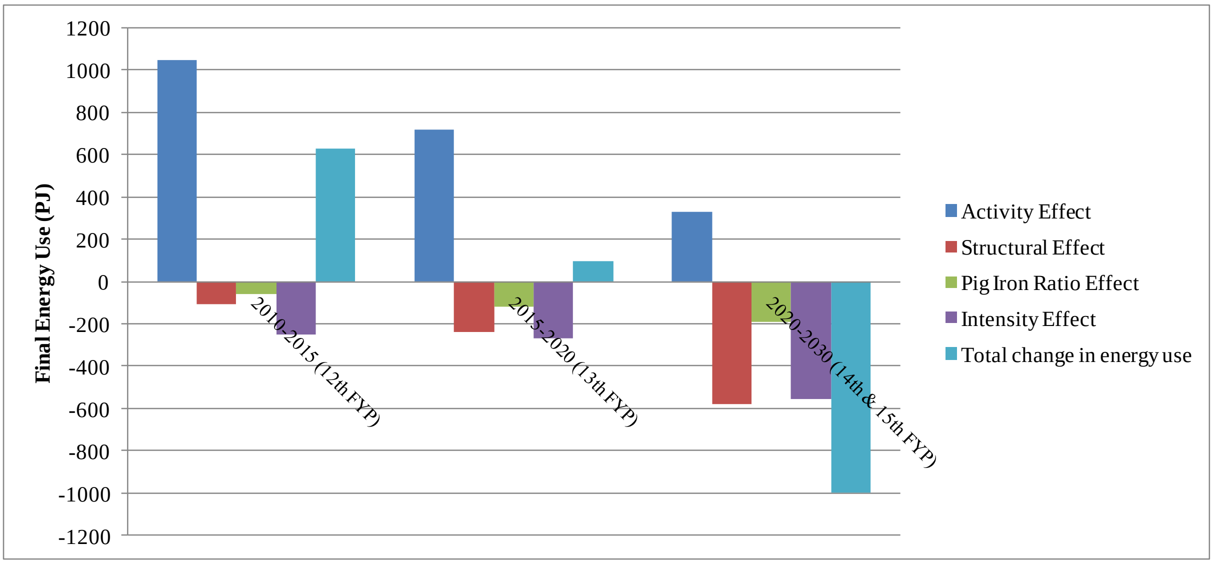


Figure 7. Scenario 2. Results of prospective decomposition of final energy use of key medium- and large-sized steel enterprises during the 12th, 13th, and 14th plus 15th Five Year Plans

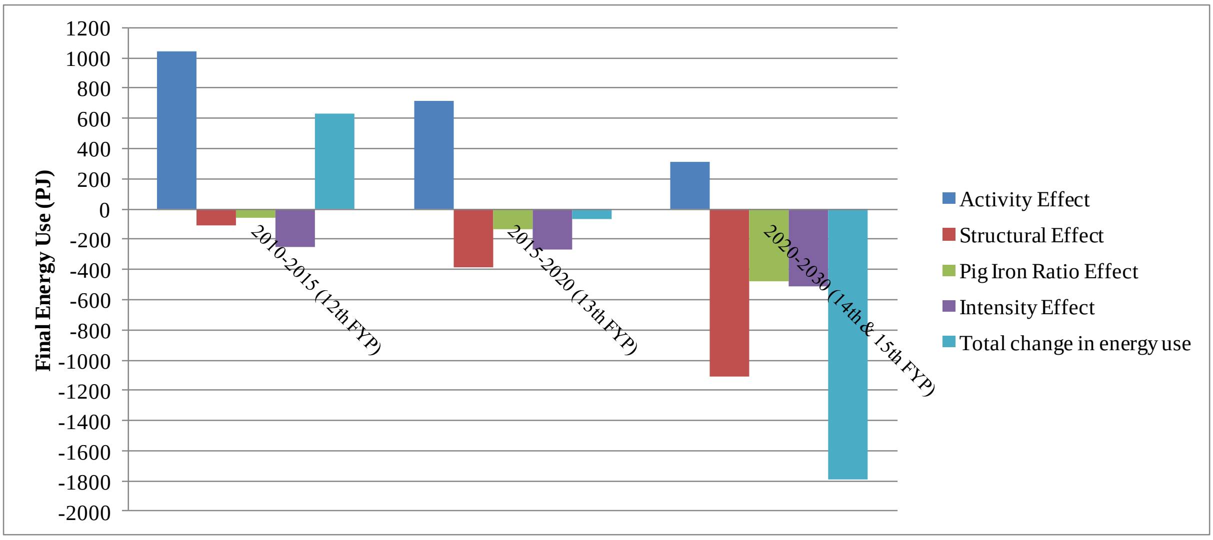


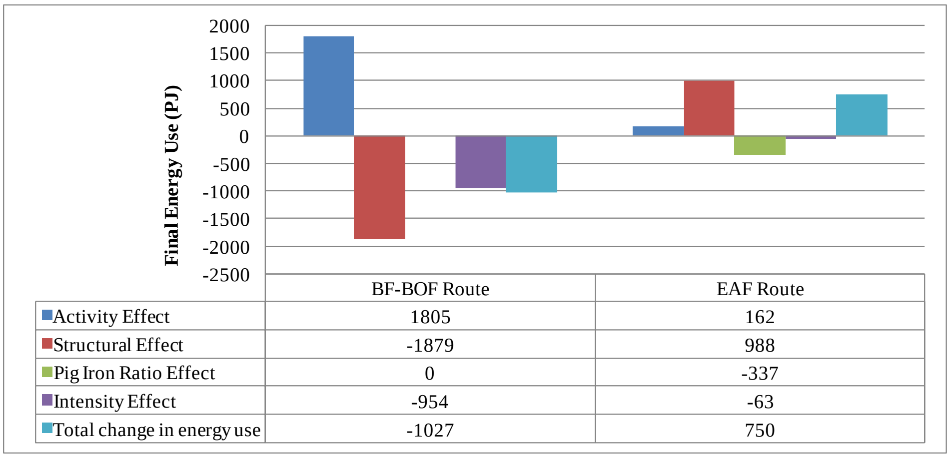
Figure 8. Scenario 3. Results of prospective decomposition of final energy use of key medium- and large-sized steel enterprises during the 12th, 13th, and 14th plus 15th Five Year Plans

Contrary to 10th and 11th FYP periods, the structural effect is negative (i.e. reducing the final energy use) during 2010-2030 because of our assumption of the increase in the EAF share of steel production in this period. The structural effect is the smallest in scenario 1 and largest in scenario 3 because of lower EAF steel production share in scenario 1 and higher share in scenario 3 (Table 7). If China wants to adjust the structure of its steel industry and move towards less energy-intensive and lower polluting steel manufacturing, the shift from BF-BOF steel production to EAF steel production is essential. However, steel scrap availability, the scrap price, and the retirement rate of the BF-BOF plants (most of which were built after 2000) limits the ability of China to increase its EAF steel production significantly in the short term. Even in the current EAF steel production, the share of pig iron used as feedstock in EAF instead of scrap in China is among the highest in the world. The pig iron use in EAF increases the total energy and $CO_2$ emissions footprint of the steel produced by EAFs because of the high energy used for pig iron production. As the Chinese economy becomes more mature there will be more recycled scrap available which will make it possible for China to produce more steel by EAFs and less by BF-BOF and also to decrease the use of pig iron as feedstock in EAFs.

The pig iron ratio effect reduces the final energy use during 2010-2030. This reduction is the smallest in scenario 1 and largest in scenario 3 because of higher pig iron ratio used as EAFs feedstock in scenario 1 and lower ratio in scenario 3 (Table 7). Also, the pig iron ratio effect increases as the share of EAF steel production from total steel production by key enterprises increases from scenario 1 to scenario 3.

During 2010 - 2030, the intensity effect is almost in the same range across all three scenarios, with scenario 1 having slightly greater (in negative value) energy intensity effect. This is mainly because we assumed a similar energy intensity reduction rate during the 12th FYP, 13th FYP, and 14th plus 15th FYP periods for all three scenarios (Table 6). The slight differences between intensity effects across scenarios comes from the differences in absolute energy use in key enterprises in 2015, 2020, and 2030 under each scenario which is the result of different assumptions for the EAF share of steel production in each scenario. As can be seen in Eq. 12 and Eq. 15, absolute energy use in each production route ($E_{PI,i}$ or $E_{Oth,i}$) plays a role in the calculation of the intensity effect in addition to the energy intensity of the production route. Nonetheless, the intensity effect plays a significant role in reducing final energy use of steel manufacturing during the 12th FYP, 13th FYP, and 14th plus 15th FYP periods. This is primarily because of reduction in energy intensities of production processes in 2020 and 2030. While the realization of such energy intensity reduction is uncertain and remains to be seen in the future, the aggressive policies of the Chinese government to reduce the energy use per unit of product of the energy intensive sectors, especially the steel sector, are a promising sign that the Chinese steel industry in moving towards those energy intensity targets. The “Top-1000 Enterprises Energy Saving Program” and the “10 Key Energy Saving Projects Program” implemented during the 11th FYP have both been extended to the 12th FYP with the Top 1000 program expanding to the “Top-10,000 Enterprises Energy Saving Program”. These programs along with other policies and incentives in the coming years will be helping to reduce the energy intensity of the steel industry in China; hence we see a strong intensity effect in the decomposition analysis.

Breaking down the decomposition analysis results by BF-BOF and EAF production routes shows the contribution of each production route to the overall results. Figure 9 shows the results of the analysis for scenario 2 (medium scrap usage) for the period of 2010-2030 for the decomposition analysis by production routes. Similar results for scenario 1 and scenario 3 are presented in Appendix 1.



| | BF-BOF Route | EAF Route |
|---|---|---|
| ■ Activity Effect | 1805 | 162 |
| ■ Structural Effect | -1879 | 988 |
| ■ Pig Iron Ratio Effect | 0 | -337 |
| ■ Intensity Effect | -954 | -63 |
| ■ Total change in energy use | -1027 | 750 |

Figure 9. Scenario **2**: Results of additive non-changing decomposition of final energy use of key medium- and large-sized steel enterprises by production route type, 2010-2030

In scenario 2, both production routes have a positive activity effect during the 2010 to 2030 period. The activity effect of the EAF production route is minimal because of the lower share of steel production by EAFs compared to the BF-BOF route. The structural effect of the BF-BOF route is negative, while it is positive for the EAF route. This is because of the decrease in the BF-BOF share of total steel production and subsequent increase in the EAF share. However, since the BF-BOF steel production is more energy-intensive than the EAF steel production, we can see that the reduction in energy use from structural effect in the BF-BOF route is greater than increase in energy use because of the EAF structural effect. Hence, the result in net reduction in final energy use (-1879 PJ+988 PJ = -891 PJ).

The pig iron ratio effect is zero for the BF-BOF route because the assumption on one t pig iron per one t crude steel remained constant during 2010-2030 for the BF-BOF route. For the EAF route, however, since the pig iron ratio as a feedstock to EAFs declines between 2010 and 2030, we see a reduction in final energy use because of the EAF pig iron ratio effect. Both production routes have negative intensity effects. This confirms that the final energy intensities of BF-BOF and EAF steel production are projected to decrease in 2030 compared to energy intensities in 2010.

There are number of limitations and sources of uncertainty in this study and most other studies that try to forecast the future production for manufacturing sectors as well as their future energy intensities. For example, the projected AAGRs for steel production, the energy intensity reduction rates, pig iron feed ratio in EAFs, and the EAF steel production share between 2010 and 2030 given in Tables 6, 7, 8 are sources of uncertainty. Even so, the scenario development and decomposition analysis in this study can help to understand how changes in these influential factors can affect overall energy consumption of key medium- and large-sized steel enterprises in the future. Therefore, the result of such studies should be reviewed and interpreted with caution keeping in mind the limitations and uncertainties.

## 5. Conclusions

In this study, a bottom-up analysis of the energy use of key medium- and large-sized Chinese steel enterprises is performed using data at the process level. Both retrospective and prospective analyses are conducted in order to assess the impact of factors that influence the energy use of the steel industry in the past (2000-2010) and estimate the likely impact in the future (2010-2030).

Throughout this report all of the data presented are for the key medium- and large-sized steel enterprises unless it is mentioned otherwise. The aggregate energy intensity of the key medium- and large-sized steel enterprises tends to be lower than the energy intensity of the entire Chinese steel industry. We focus the analysis on the key medium- and large-sized steel enterprises because the energy intensity data by process for various years, which are used in our analysis, are only reported for the key medium- and large-sized steel enterprises in China.

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

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

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

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

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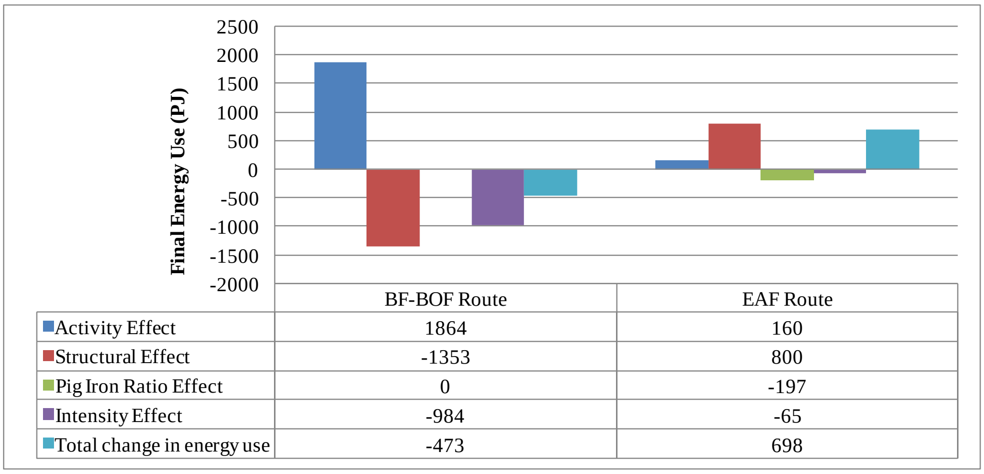
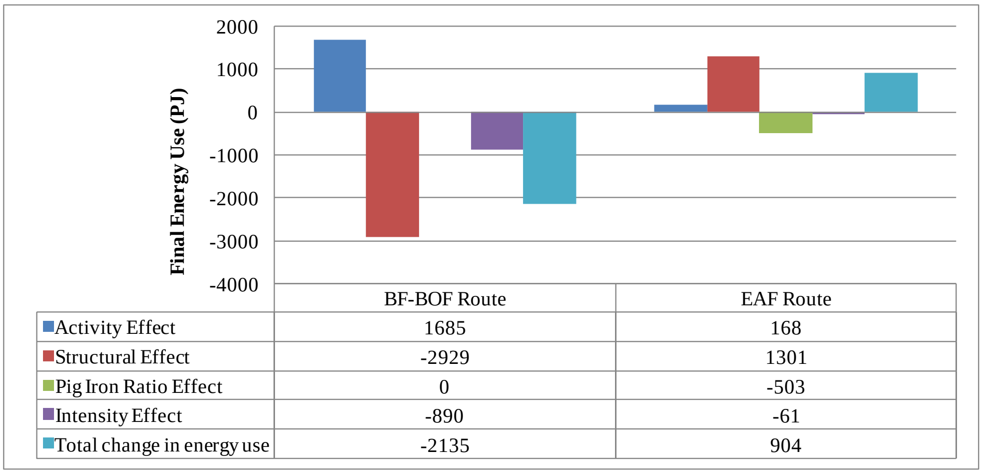
# Appendixes

## Appendix 1. Results of decomposition analysis by production route type



| | BF-BOF Route | EAF Route |
|---|---|---|
| 🟦Activity Effect | 1864 | 160 |
| 🟥Structural Effect | -1353 | 800 |
| 🟩Pig Iron Ratio Effect | 0 | -197 |
| 🟪Intensity Effect | -984 | -65 |
| 🟦Total change in energy use | -473 | 698 |

Figure A.1. Scenario **1**: Results of additive non-changing decomposition of final energy use of key medium- and large-sized steel enterprises by production route type, 2010-2030



| | BF-BOF Route | EAF Route |
|---|---|---|
| 🟦Activity Effect | 1685 | 168 |
| 🟥Structural Effect | -2929 | 1301 |
| 🟩Pig Iron Ratio Effect | 0 | -503 |
| 🟪Intensity Effect | -890 | -61 |
| 🟦Total change in energy use | -2135 | 904 |

Figure A.2. Scenario **3**: Results of additive non-changing decomposition of final energy use of key medium- and large-sized steel enterprises by production route type, 2010-2030