

**ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY**

A Comparison of Iron and Steel Production Energy Intensity in China and the U.S

Lynn Price, Ali Hasanbeigi, Nathaniel Aden
China Energy Group
Environmental Energy Technologies Division
Lawrence Berkeley National Laboratory

Zhang Chunxia, Li Xiuping, Shangguan Fangqin
China Iron & Steel Research Institute

*Reprint version of proceedings of the American Council for an
Energy-Efficient Economy's 2011 Summer Study on Energy
Efficiency in Industry, held in Niagara Falls, New York, U.S.A.,
on July 26-29, 2011*

June 2012

This work was supported by the China Sustainable Energy Program of the Energy Foundation through the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Disclaimer

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor The Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or The Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, or The Regents of the University of California.

Ernest Orlando Lawrence Berkeley National Laboratory is an equal opportunity employer.

.

A Comparison of Iron and Steel Production Energy Intensity in China and the U.S.

Lynn Price¹, Ali Hasanbeigi¹, Nathaniel Aden¹
Zhang Chunxia², Li Xiuping², Shangguan Fangqin²

¹ Lawrence Berkeley National Laboratory; ² China Iron & Steel Research Institute

Abstract

The goal of this study was to develop a methodology for making an accurate comparison of the energy intensity of steel production in China and the U.S. The methodology addresses issues related to boundary definitions, conversion factors, and industry structure. In addition to the base case analysis, six scenarios were developed to assess the effect of different factors such as the share of electric arc furnace (EAF) steel production, conversion factors for the embodied energy of imported and exported intermediary and auxiliary products, and the differences in net calorific values of the fuels. The results of the analysis show that for the whole iron and steel production process, the final energy intensity in 2006 was equal to 14.90 GJ/tonne crude steel in the U.S. and 23.11 GJ/tonne crude steel in China in the base scenario. In another scenario that assumed the Chinese share of electric arc furnace production in 2006 (i.e. 10.5%) in the U.S., the energy intensity of steel production in the U.S. increased by 54% to 22.96 GJ/tonne crude steel. Thus, when comparing the energy intensity of the U.S. and Chinese steel industry, the structure of the industry should be taken into account.

1. Introduction

Production of iron and steel is an energy-intensive manufacturing process. In 2006, the iron and steel industry accounted for 13.6% and 1.4% of primary energy consumption in China and the U.S., respectively (Zhang et al., 2010; U.S. DOE/EIA, 2010a). The energy efficiency of steel production has a direct impact on overall energy consumption and related carbon dioxide (CO₂) emissions. The goal of this study is to develop a methodology for making an accurate comparison of the energy intensity (energy use per unit of steel produced) of steel production in China and the U.S. The methodology addresses issues related to boundary definitions, conversion factors, and indicators in order to develop a common framework for comparing steel industry energy use in these two countries.

2. Methodology

This study uses a bottom-up, physical-based methodology to compare the energy intensity of China and U.S. crude steel production in 2006. This year was chosen in order to maximize the availability of comparable steel-sector data. However, data published in China and the U.S. are not always consistent in terms of analytical scope, conversion factors, and information on adoption of energy-saving

technologies. This study is primarily based on published annual data from the China Iron and Steel Association and National Bureau of Statistics in China and the Energy Information Agency in the U.S.

2.1. Boundaries

In this study, the iron and steel industry includes all coke making, pelletizing, sintering, iron making, steel making, steel casting, hot rolling, cold rolling, and processing such as galvanizing or coating (Figure 1). This boundary definition is used for the calculations of energy use and energy intensity for both the Chinese and U.S iron and steel industries.

Regarding accounting for energy used for coke production within the iron and steel industry, there are a few special considerations. This study includes the total coal input used as a feedstock for coke making and also as a fuel in other parts of the steel making process. Only net imported coke (either produced in other domestic industries or imported from other countries) is included as a source of input energy to the iron and steel industry. Net imported coke is total imported coke minus total exported coke. The energy value of the coke produced in the coke making process within the iron and steel industry and used in the iron making process is not included since the coal initially used to produce the coke is already accounted for within the boundary. This study does not count the coke trade that occurs within the boundary, as the total coal input to the industry is already taken into account. This study takes net imported (to the boundary of the industry defined in Figure 1) pig iron, direct-reduced iron (DRI), pellets, lime, oxygen, and ingots, blooms, billets, and slabs into account by adding the energy used for production of these products to the total energy input to the iron and steel industry.

In addition, this study does not include energy consumption associated with other energy-intensive products manufactured for the industry (e.g., electrodes, ferroalloys, refractories, etc.). These products could be included in a more extensive, life-cycle analysis study of the industry, but are excluded here because the focus of this study is on iron and steel production. This is the approach taken by Stubbles (2000). This study also does not take into account the embodied energy of the scrap used in the iron and steel industry. Finally, energy demand for mining and beneficiation of iron ores is not included in this analysis.

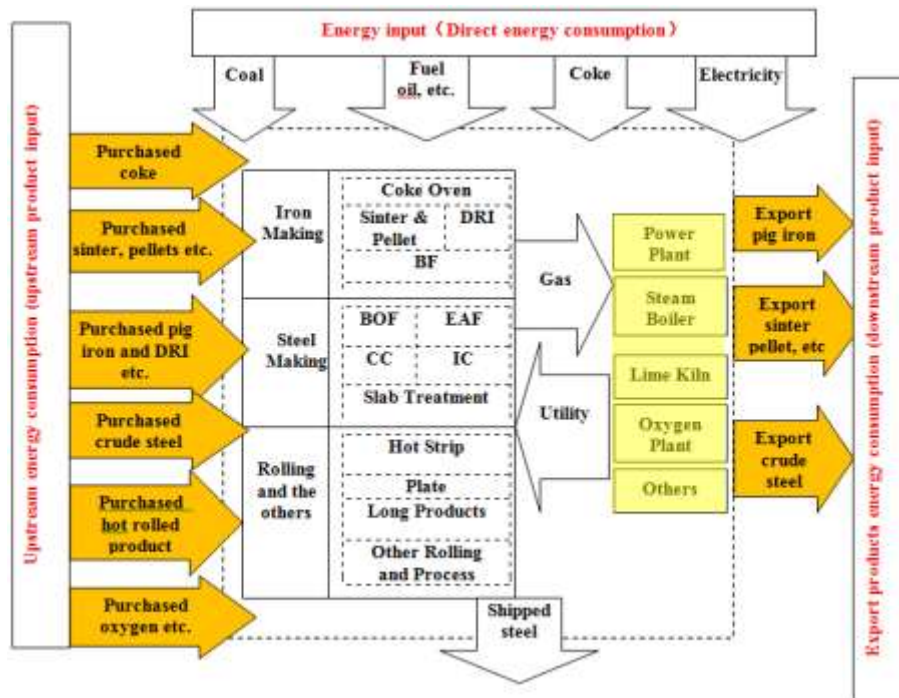


Figure 1: Flowchart of Iron and Steel Sector Boundaries Used in this Study

2.2. Conversion Factors

In order to calculate comparable energy use and energy intensity values, common conversion factors must be used to convert the physical quantities of fuels consumed to produce steel to energy values. In addition, common conversion factors must also be used to calculate electricity values. These conversion factors are explained below.

2.2.1. Fuel Conversion Factors

The heating value or calorific value of a fuel source represents the amount of heat released during combustion. This study uses the lower heating value – or net calorific value (NCV) – to convert physical quantities of fuel to a common energy unit. NCV conversion factors for China are provided in the China Energy Statistics Yearbook 2006 and 2009 (NBS 2007, 2010a) and for the U.S. are provided in the EIA’s Annual Energy Review (U.S. DOE/EIA 2007, 2009). Where available, the NCV of the fuels in 2006 is used. In addition, the typical NCVs for fuels are also provided in various IEA publications. Table 1 provides the NCV conversion factors for different fuels for China and the U.S.

Table 1: Fuel Conversion Factors for China and the U.S.

| Fuel | IEA-Typical | | Country-Specific | | | | Unit |
|--------------------------------------|-------------|-----------|------------------|----------|-------|----------|-------------------|
| | IEA-Typical | Source | China | Source | U.S. | Source | |
| Other Bituminous coal (used as fuel) | 24.05 | IEA 2005 | 20.91 | NBS 2007 | 25.65 | EIA 2009 | MJ/kg |
| Coking coal | 28.20 | IEA 2005 | 26.34 | NBS 2007 | 30.56 | EIA 2009 | MJ/kg |
| Coke oven coke | 27.45 | IEA 2005 | 28.44 | NBS 2007 | 28.85 | EIA 2009 | MJ/kg |
| Natural gas | 35.04 | IEA 2008c | 38.93 | NBS 2007 | 38.33 | EIA 2009 | MJ/m ³ |
| Residual Fuel oil | 42.18 | IEA 2005 | --- | | 44.18 | EIA 2007 | MJ/kg |
| Distillate Fuel Oil | 40.19 | IEA 2008c | 41.82 | NBS 2007 | 40.94 | EIA 2007 | MJ/kg |
| LPG | 46.15 | IEA 2005 | 50.18 | NBS 2007 | 45.81 | EIA 2009 | MJ/kg |
| Other washed coal | - | | 10.47 | NBS 2007 | | | MJ/kg |
| Crude oil | 42.85 | IEA 2008c | 41.82 | NBS 2007 | | | MJ/kg |
| Gasoline | 47.10 | IEA 2005 | 43.07 | NBS 2007 | | | MJ/kg |
| Kerosene | 46.22 | IEA 2005 | 43.07 | NBS 2007 | | | MJ/kg |
| Diesel | 45.66 | IEA 2005 | 42.65 | NBS 2007 | | | MJ/kg |
| Other petroleum products | - | | 35.17 | NBS 2007 | | | MJ/kg |
| Tar | - | | 33.45 | NBS 2009 | | | MJ/kg |
| Benzene | | | 41.82 | NBS 2009 | | | MJ/kg |

2.2.2. Electricity Conversion Factors

Final (or site) electricity is the electricity consumed at the production facility. This value does not include the primary energy used to generate, transmit, and distribute electricity to the site. To convert final electricity to primary energy, the average efficiency of power generation and transmission and distribution (T&D) losses must be taken into account. The conversion factors to convert electricity from final to primary energy for the U.S. and China in 2006 are calculated based on net heat rates and T&D in both countries along with World Steel Association (WORLDSTEEL) conversion factor are presented in Table 2.

Table 2: Final to Primary Energy Conversion Factor in 2006

| | China | U.S | WORLDSTEEL |
|--|-----------------------------------|---------------------|------------------|
| Final Conversion Factor <u>with</u> T&D losses (kgce/kWh) | 0.376 | 0.379 | 0.334 |
| Final Conversion Factor <u>without</u> T&D losses (kgce/kWh) | 0.350 | 0.354 | |
| Sources | NBS 2009; Anhua and Xingshu, 2006 | EIA 2010a; EIA 2008 | WORLDSTEEL 2008b |

2.2.3. Conversion Factors for Purchased Auxiliary/Intermediary Products

For this study, the international average energy conversion factors are used for products that are purchased externally and imported or exported by the iron and steel industry since imported products can be from different countries and will thus vary in their energy consumption during production due to differences in production technology and energy structure. The energy conversion factors for external products in this study are provided by the World Steel Association (WORLDSTEEL) (WORLDSTEEL, n.d.;

WORLDSTEEL, 2008b). Table 3 provides energy conversion factors for purchased fuels and materials as well as imported auxiliary/intermediary products along with the share of electricity use for production of each product.

Table 3: Conversion Factors for Purchased Fuels & Auxiliary/Intermediary Products

| | Coke ^a | Pig Iron ^a | Coal based ^a DRI | Gas based ^a DRI | Pellets ^a | Crude Steel ^b | Lime ^a | Oxygen ^a |
|--|-------------------|-----------------------|--------------------------------|----------------------------|----------------------|--------------------------|-------------------|---------------------|
| | MJ/kg | MJ/kg | MJ/kg | MJ/kg | MJ/kg | MJ/kg | MJ/kg | MJ/m ³ |
| WORLDSTEEL Factors (Primary Energy) | 4.0 | 20.9 | 17.9 | 14.1 | 2.1 | 18.9 | 4.5 | 6.9 |
| China-specific value | | | | | | 18.54 | | |
| WORLDSTEEL Factors (Final Energy) ^c | 3.7 | 19.8 | 17.0 | 13.4 | 2.1 | 16.5 | 4.1 | 2.5 |
| China-specific value | | | | | | 17.4 | | |
| Electricity share in total Primary Energy | 11% | 8% | 8% | 8% | 0 | 20% | 15% | 100% |
| China-specific value | | | | | 0 | 10% | | |

^a WORLDSTEEL, n.d. ^b WORLDSTEEL, 2008a

^c The 9.8 MJ/kWh conversion factor from WORLDSTEEL was used to convert the WORLDSTEEL conversion factors for Purchased Fuels & Auxiliary/Intermediary Products from primary to final energy using the percentages of electricity use for the production of each product given in the table above.

3. Base Year Production, Trade and Energy Use Data

3.1. Production and Trade Data

3.1.1. Production Data for the U.S.

Table 4 shows the production data for pig iron, DRI, crude steel, ingots, blooms, billets, slabs, and steel products (finished steel). For the calculation of the energy intensities, crude steel production is used as the denominator. However, it should be noted that the casting, rolling and finishing processes are also within the boundary of the analysis.

Table 4: Production and Trade Data for Pig Iron, DRI, Crude Steel, Ingot, Blooms, Billets, and Slabs, and Steel Products in U.S in 2006 (Mt) (USGS, 2008)

| Product | Production | Exports | Imports | Net Imports | Used in industry |
|--------------------------------|------------|---------|---------|-------------|------------------|
| Pig Iron | 37.9 | 0.813 | 6.73 | 5.92 | 43.8 |
| DRI | 0.24 | - | 2.61 | 2.61 | 2.85 |
| Crude Steel | 98.2 | - | - | - | - |
| Ingots, Blooms, Billets, Slabs | - | 0.20 | 8.46 | 8.26 | - |
| Steel Products | 99.3 | 8.83 | 41.1 | 32.3 | - |

3.1.2. Production and Trade Data for China

Table 5 lists China's production, exports and imports of pig iron, DRI, crude steel, and steel products in 2006. Net exports are 0.7 Mt of pig iron and 8.67 Mt of steel billets. Net imports are 0.3 Mt of DRI, and 0.1 Mt of steel ingots.

Table 5: Production, Imports and Exports of Pig Iron, DRI, Crude Steel, Ingots, Billets, and Steel Products in China, 2006 (Mt)

| Product | Production | Imports | Exports | Net Imports | Used in industry |
|----------------|------------|---------|---------|-------------|------------------|
| Pig Iron | 413.64 | 0.17 | 0.87 | -0.70 | 412.94 |
| DRI | 0.21 | 0.31 | 0.01 | 0.30 | 0.51 |
| Crude Steel | 421.02 | - | - | - | - |
| Steel Ingots | - | 0.14 | 0.04 | 0.10 | - |
| Steel Billets | - | 0.37 | 9.04 | -8.67 | - |
| Steel Products | 399.97* | 18.51 | 43.01 | -24.50 | 375.47 |

Source: Editorial Board of the China Iron and Steel Industry Association Yearbook, 2006.

* In order to avoid double-counting of steel products, this number was calculated as 95% of crude steel.

3.2. Energy Use Data

3.2.1. Energy Use of the U.S. Iron and Steel Industry Based on EIA Reported Data

In addition to the first use of energy, which is the energy used as fuel and nonfuel (feedstock), the energy use for the production of net imported coke, lime, pellets, pig iron, DRI, oxygen, and ingots, blooms, billets, and slabs is also included in the calculation of energy intensity for this study in order to have a more accurate and fair comparison of the energy intensity of the industry in both countries. This is done to eliminate the effect of differences in the share of imported coke, lime, DRI, and pig iron on the energy intensity of the industry in the two countries. For the base case scenario of this study, the WORLDSTEEL conversion factors for these auxiliary/intermediary products used in the iron and steel industry are used.

The total electricity and fuel consumption for the production of iron and steel in the U.S. based on the defined boundary of this study are presented in Table 6. The first row of the table is energy use in 2006 based on the EIA fuel conversion factors from U.S. DOE/EIA (2010e, f, g). For details of the calculation we refer you to Hasanbeigi et al. (2011).

Table 6: Total Electricity and Fuel Consumption for Iron and Steel Production in the U.S. Based on Study Boundaries

| Item | Electricity Use (GWh) | Fuel Use (TJ) | Final (TJ) | Primary (TJ) * |
|---|-----------------------|------------------|------------------|------------------|
| Energy use reported for the iron and steel industry in EIA (excluding the energy use for production of intermediary products given below) | 51,198 | 912,623 | 1,096,936 | 1,481,942 |
| Energy used for the production of net imported** oxygen | 4,750 | 0 | 17,101 | 52,824 |
| Energy used for the production of net imported pig iron | 2,603 | 107,784 | 117,157 | 136,735 |
| Energy used for the production of net imported direct reduced iron | 809 | 33,473 | 36,383 | 42,463 |
| Energy used for the rolling and finishing of net imported ingots, blooms, billets, and slabs | 4,396 | 43,257 | 59,083 | 92,141 |
| Embodied energy of net imported ingots, blooms, billets, and slabs | 7,509 | 109,109 | 136,141 | 192,608 |
| Energy used for the production of net imported coke | 351 | 10,237 | 11,502 | 14,145 |
| Energy used for the production of net imported lime | 334 | 6,816 | 8,019 | 10,532 |
| Energy used for the production of net imported pellets | 0 | 103,530 | 103,530 | 103,530 |
| Total Energy Consumption based on EIA fuel conversion factor | 71,951 | 1,326,830 | 1,585,853 | 2,126,919 |

* In final energy, electricity use is equal to the electricity consumption at the end-use. In primary energy with T&D losses, electricity use at the end-use is converted to the primary energy sources by taking into account the power generation efficiency (average net heat rate of power plants) and transmission and distribution losses.

** : Net import is to the steel industry based on the defined boundary.

3.2.2. Energy Use Data for the Chinese Iron and Steel Industry

According to the boundaries presented in Figure 1, the energy consumption of steel production is calculated and included in this analysis. The upstream energy consumption of net imported coke, pig iron, DRI, steel ingots and steel billets is presented in Table 7. Total energy use is adjusted for net trade in auxiliary and intermediate products. The first row of the table is energy use in 2006 based on the NBS (2010a). For details of the calculation we refer you to Hasanbeigi et al. (2011).

Table 7: Total Energy Consumption of China's Steel Industry Production in 2006

| Component | Electricity Use (GWh) | Fuel Use (TJ) | Final (TJ) | Primary (TJ) |
|---|-----------------------|---------------|------------|--------------|
| Reported energy consumption | 174,293 | 8,593,558 | 9,221,013 | 10,515,967 |
| Energy used for the production of purchased coke | 5,883 | 488,395 | 509,574 | 553,283 |
| Energy used for the production of net exports of pig iron | -114 | -13,412 | -13,822 | -14,669 |
| Energy used for the production of net imports of coal-based DRI | 42 | 4,934 | 5,085 | 5,397 |
| Energy used for the production of net imports of steel ingots | 17 | 1,589 | 1,650 | 1,776 |
| Energy used for the production of net exports of steel billets/slabs | -2,082 | -192,304 | -199,799 | -215,268 |
| Total energy consumption of steel industry with embodied energy of net imported/exported auxiliary/intermediary products included | 178,039 | 8,882,760 | 9,523,701 | 10,846,487 |

Note 1: The negative values indicate the energy use by export products was subtracted.

Note 2: The reason that there is no energy use data given separately for lime and pellets is that the energy use for the production of these products is included in the reported energy consumption of the steel industry in China (first row of this table) and there is no import or export of these two products.

4. Comparison of Energy Intensity of Iron and Steel Production in China and the U.S.

In this study, “energy intensity” is chosen as the index of comparison for the Chinese and U.S. iron and steel industries. It presents, within the prescribed boundary (as illustrated in Figure 1), the index of energy consumption per tonne of crude steel during production.

$$\text{Energy intensity} = \frac{\text{Energy Consumption of the iron and steel industry within the prescribed boundary}}{\text{Crude steel production within the prescribed boundary}}$$

The energy intensity of steel production is influenced by industry structure, technology, fuel choice, and materials-e.g., availability of scrap steel. The effects of these variables are isolated in this study's scenario analyses as well as explanatory variables section. Section 4.3 of the paper presents six scenarios to compare a range of effects within the steel industry of China and the U.S.

4.1. Energy Intensity of Iron and Steel Production in the U.S.

Final energy intensity (energy use per tonne of crude steel) for the U.S. iron and steel industry in 2006 is provided in Table 8. This value is calculated using the production data and the electricity and fuel consumption data. Crude steel production in the U.S. in 2006 was 98.2 Mt. In addition, there were 8.261 Mt of net imported ingots, blooms, billets, and slabs in 2006. Since the energy use for the production of net imported ingots, blooms, billets, and slabs are included in the calculation of energy intensities, the amount of net imported ingots, blooms, billets, and slabs should be added to the crude steel production in the U.S. for energy intensities calculation. Thus, total crude steel production used for the calculation of energy intensities in 2006 was 106.461 Mt. Under the base case scenario, the total electricity and fuel

consumption in iron and steel industry in U.S. in 2006 based on the defined boundary of this study explained above are 71,948 million kWh and 1,326,830 TJ, respectively. If these energy uses are divided by the production of crude steel given above, the electricity and fuel intensity can be calculated separately. The sum of the electricity and fuel intensity is given as the total final energy intensity.

Table 8: Base Case - Energy Intensity of the U.S. Iron and Steel Industry in 2006

| Scenario | Electricity Intensity (kWh/t crude steel) | Fuel Intensity (GJ/t crude steel) | Final Energy Intensity (GJ/t crude steel) | Primary Energy Intensity with T&D (GJ/t crude steel) | Primary Energy Intensity without T&D (GJ/t crude steel) |
|-----------|---|-----------------------------------|---|--|---|
| Base case | 675.84 | 12.46 | 14.90 | 19.98 | 19.47 |

² In primary energy without transmission and distribution losses (T&D), electricity use at the end-use is converted to the primary energy sources by taking into account *only* the power generation efficiency (average net heat rate of power plants). This is done because in Chinese statistics it is common to do the conversion for electricity from final to primary energy without taking into account the T&D losses. Thus, for consistency, we have reported both types of primary energy calculated with international standard (with T&D losses) and Chinese standard (without T&D losses).

Total final energy intensity of the US iron and steel industry using the U.S. country-specific energy conversion factors for the purchased coke and auxiliary/intermediary products instead of WORLDSTEEL conversion factor would be 14.5 GJ/tonne crude steel, which is around 2.7% less than the intensity calculated above (see Table 8) using WORLDSTEEL conversion factors.

4.2. Energy Intensity of Iron and Steel Production in China

Table 9 shows the energy intensity (energy consumption per tonne crude steel) calculated based on the 2006 revised energy data given in the China Energy Statistical Yearbook 2009 (NBS, 2010a). The same methodology applied to the U.S. for taking into account the embodied energy of auxiliary/intermediary products is also applied to China. As can be seen from Table 8 and Table 9, the electricity intensity of the steel production in U.S. is significantly higher compared to China. This is because of higher share of EAF steel production in the U.S. (56.9% in 2006) compared to that in China (10.5% in 2006). The fuel and final energy intensity in the U.S., however, is much lower compared to China mainly because of higher share of EAF steel production in the U.S. Other factors causing the differences between energy intensities are the level of penetration of energy-efficient technologies, the age of the equipments, the scale of production equipment, fuel shares in the iron and steel industry, and the final steel product mix in both countries. These variables are discussed in our main report (Hasanbeigi et al. 2011).

Table 9: 2006 Energy Consumption and Intensity of Iron and Steel Production in China

| Scenario | Electricity Intensity (kWh/t crude steel) | Fuel Intensity (GJ/t crude steel) | Final Energy Intensity (GJ/t crude steel) | Primary Energy Intensity with T&D (GJ/t crude steel) | Primary Energy Intensity without T&D (GJ/t crude steel) |
|-----------|---|-----------------------------------|---|--|---|
| Base case | 431.66 | 21.54 | 23.11 | 26.30 | 25.97 |

4.3. Scenario Analyses

In addition to the base case presented above, six variations to the base case were calculated to examine the impact of different assumptions on the iron and steel production energy intensity value for each country. The purpose of this scenario analysis is to determine which variables are most important for explaining energy intensity differences between China and the U.S. The first scenario uses IEA typical fuel conversion factors (instead of country-specific fuel conversion factors used in the base case), country-specific electricity conversion factors, and WORLDSTEEL conversion factors for auxiliary/intermediary products. This scenario is intended to isolate the impact of the use of country-specific conversion factors on the overall comparative intensity.

The second scenario uses the country-specific fuel conversion factors, WORLDSTEEL electricity conversion factors for converting electricity from final to primary energy (9.8 MJ/kWh) (instead of country-specific electricity conversion factors used on the base case), and WORLDSTEEL conversion factors for auxiliary/intermediary products. This scenario is intended to analyze the impact on energy intensity caused by change of electric power conversion factor.

The third scenario uses the IEA typical fuel conversion factors (instead of country-specific fuel conversion factors used in the base case), WORLDSTEEL electricity conversion factors (9.8 MJ/kWh) ((instead of country-specific electricity conversion factors used on the base case), and the WORLDSTEEL conversion factors for auxiliary/intermediary products. The purpose of this scenario is to remove the effect of country-specific conversion factors and focus the intensity comparison on structural and efficiency effects.

The fourth scenario uses the country-specific fuel conversion factors, country-specific electricity conversion factors, WORLDSTEEL conversion factors for auxiliary/intermediary products, and China's EAF ratio in 2006 used for U.S. energy intensity calculation. This scenario is intended to analyze the impact on energy consumption caused by a change of the EAF ratio.

The fifth scenario uses the IEA typical fuel conversion factors, WORLDSTEEL electricity conversion factors (9.8MJ/kWh), WORLDSTEEL conversion factors for auxiliary/intermediary products, and China's EAF ratio in 2006 used for U.S. energy intensity calculation. This scenario is the same as the third scenario, but takes into account the impact on energy consumption caused by a change of EAF ratio.

Finally, the sixth scenario uses the country-specific fuel conversion factors, WORLDSTEEL conversion factors for auxiliary/intermediary products, and China's final to primary electricity conversion factor for U.S. energy intensity calculation. This scenario shows the impact of the different power generation efficiencies in each country on the primary energy intensity. Table 10 shows the results for all scenarios developed for China and the U.S. One of the most interesting scenarios that gives useful insight into the effect of industry structure on the energy intensity is scenario 4. Scenario 4 for the U.S. should be compared with the base case for China and scenario 4 for China should be compared with base case in

the U.S. This comparison presents the results of the base case and the six scenarios, providing information on the calculated electricity intensity, fuel intensity, final energy intensity, and primary energy intensity for the U.S. and China.

4.4. Explanatory Variables

The purpose of the analysis presented in this study is to develop and test a methodology for quantifying and comparing the energy intensity of steel production in China and the U.S. with defined boundaries and conversion factors. This section provides a discussion of some possible reasons that the energy intensity values differ in the two countries. Two explanatory variables are discussed in this paper: 1) the share of EAF steel in total steel production, 1) the age of steel manufacturing facilities in each country.

Table 10: Energy Intensity for the Iron and Steel Industry in China and the U.S. (2006)

| No. | Scenarios | Country | Final Energy Intensity | | Primary Energy Intensity* | |
|------|--|---------|------------------------|--------------------|---------------------------|--------------------|
| | | | GJ/t crude steel | kgce/t crude steel | GJ/t crude steel | kgce/t crude steel |
| Base | Country-specific fuel conversion factors Country-specific electricity conversion factors WORLDSTEEL conversion factors aux/intermediary products | U.S. | 14.90 | 508.69 | 19.98 | 681.68 |
| | | China | 23.11 | 788.53 | 26.30 | 897.29 |
| 1 | IEA typical fuel conversion factors Country-specific electricity conversion factors WORLDSTEEL conversion factors aux/intermediary products | U.S. | 14.83 | 506.49 | 19.91 | 679.48 |
| | | China | 22.65 | 769.87 | 25.75 | 878.49 |
| 2 | Country-specific fuel conversion factors WORLDSTEEL electricity conversion factors WORLDSTEEL conversion factors aux/intermediary products | U.S. | 14.90 | 508.69 | 19.09 | 651.24 |
| | | China | 23.11 | 788.69 | 25.77 | 879.45 |
| 3 | IEA typical fuel conversion factors WORLDSTEEL electricity conversion factors WORLDSTEEL conversion factors aux/intermediary products | U.S. | 14.83 | 506.49 | 19.02 | 649.04 |
| | | China | 22.65 | 769.87 | 25.23 | 860.88 |
| 4a | Country-specific fuel conversion factors Country-specific electricity conversion factors WORLDSTEEL conversion factors aux/intermediary products China 2006 EAF ratio used for U.S. | U.S. | 22.96 | 783.32 | 26.08 | 889.94 |
| | (Base Scenario) Country-specific fuel conversion factors Country-specific electricity conversion factors WORLDSTEEL conversion factors aux/intermediary products | China | 23.11 | 788.53 | 26.30 | 897.29 |
| 4b | (Base Scenario) Country-specific fuel conversion factors Country-specific electricity conversion factors WORLDSTEEL conversion factors aux/intermediary products | U.S. | 14.90 | 508.69 | 19.98 | 681.68 |
| | Country-specific fuel conversion factors Country-specific electricity conversion factors WORLDSTEEL conversion factors aux/intermediary products U.S. 2006 EAF ratio used for China | China | 18.44 | 629.19 | 22.54 | 769.24 |
| 5a | IEA typical fuel conversion factors WORLDSTEEL electricity conversion factors | U.S. | 23.04 | 786.03 | 26.09 | 890.27 |

| No. | Scenarios | Country | Final Energy Intensity | | Primary Energy Intensity* | |
|-----|--|---------|------------------------|--------------------|---------------------------|--------------------|
| | | | GJ/t crude steel | kgce/t crude steel | GJ/t crude steel | kgce/t crude steel |
| | WORLDSTEEL conversion factors aux/intermediary products China 2006 EAF ratio used for U.S. | | | | | |
| | (Scenario 3) IEA typical fuel conversion factors WORLDSTEEL electricity conversion factors WORLDSTEEL conversion factors aux/intermediary products | China | 22.65 | 769.87 | 25.23 | 860.88 |
| 5b | (Scenario 3) IEA typical fuel conversion factors WORLDSTEEL electricity conversion factors WORLDSTEEL conversion factors aux/intermediary products | U.S. | 14.83 | 506.49 | 19.02 | 649.04 |
| | IEA typical fuel conversion factors WORLDSTEEL electricity conversion factors WORLDSTEEL conversion factors aux/intermediary products U.S. 2006 EAF ratio used for China | China | 17.90 | 610.76 | 21.38 | 729.50 |
| 6 | Country-specific fuel conversion factors WORLDSTEEL conversion factors aux/intermediary products China final to primary electricity conversion factor for U.S. energy intensity calculation | U.S. | 14.90 | 508.69 | 19.92 | 679.60 |
| | Country-specific fuel conversion factors WORLDSTEEL conversion factors aux/intermediary products U.S. final to primary electricity conversion factor for China energy intensity calculation | China | 23.11 | 788.53 | 26.33 | 898.51 |

* For the base Scenario and Scenarios 1, 4 and 6 the primary energy value includes T&D losses, whereas for Scenarios 2, 3, and 5 the primary energy value is calculated based on the WORLDSTEEL conversion factor which excludes T&D losses. T&D losses will be added to this calculation if the values can be identified.

4.4.1. Structure of the Steel Manufacturing Sector

The structure of the steel manufacturing sector is one of the key variables that explains the difference in energy intensity values in China and the U.S. since EAF steel production uses significantly less energy for the production of one tonne of steel. In 2006, the share of EAF steel production in total steel production was 10.5% in China and 56.9% in the U.S. The world average EAF production in 2006 was 31.6%. Scenarios 4 and 5 calculate the total U.S. energy intensity using the share of EAFs in China and the total Chinese energy intensity using the share of EAFs in the U.S., respectively.

Scenario 4a, which relies on country-specific fuel and electricity conversion factors and WORLDSTEEL conversion factors for auxiliary and intermediate products, found that if the U.S. iron and steel industry had the same structure as the Chinese iron and steel industry in terms of the shares of EAF steel, the final energy intensity of U.S. steel production would be 22.96 GJ/tonne crude steel using the same conversion factors. This value should be compared to the Base Scenario for China which resulted in a final energy intensity of 23.11 GJ/tonne crude steel using the same conversion factors. Conversely, Scenario 4b shows that if the Chinese steel industry had the same structure as the U.S. steel industry in terms of shares of EAF steel, the final energy intensity of Chinese steel production would be 18.44

GJ/tonne crude steel using the same conversion factors. This value should be compared to the Base Scenario for the U.S which resulted in a final energy intensity of 14.9 GJ/tonne crude steel.

Scenario 5a, which uses IEA typical fuel conversion factors and WORLDSTEEL conversion factors for electricity and auxiliary and intermediate products, found that if the U.S. iron and steel industry had the same structure as the Chinese iron and steel industry in terms of the shares of EAF steel, the final energy intensity of U.S. steel production would be 23.04 GJ/tonne crude steel. This value should be compared to Scenario 3 for China, in which the resulting steel energy intensity was calculated to be 22.65 GJ/tonne crude steel using the same conversion factors. Conversely, Scenario 5b shows that if the Chinese steel industry had the same structure as the U.S. steel industry in terms of shares of EAF steel, the final energy intensity of Chinese steel production would be 17.9 GJ/tonne crude steel using the same conversion factors. This value should be compared to Scenario 3 for the U.S which resulted in a final energy intensity of 14.83 GJ/tonne crude steel using the same conversion factors.

4.4.2. Age of Steel Manufacturing Facilities

Most of China's steel production capacity has been constructed since 2000, when annual production jumped from 129 Mt to 630 Mt in 2010. During that same time, production in the U.S. dropped from 102 Mt to 90 Mt. While there are no data available on the exact age of each steel production line (e.g. BF, BOF, or EAF) in China, we can infer from the growth in production capacity between 2000 and 2010 that in 2011, about 500 Mt of production (or about 80%) is from production lines that are 10 years old or younger. In contrast, the average age of BOF vessels in the U.S. is 31.5 years (AIST, 2010a) and the average age of EAF furnaces in the U.S. is 30.9 years (AIST, 2010b). Even though the vessels have been relined and other upgrades have been made to the U.S. facilities, they are overall older than most of the steel production facilities in China. However, it should also be noted that not all of the new Chinese plants have necessarily installed the most energy-efficient technologies.

5. Findings

A key finding of this analysis is that it is possible to develop a methodology in which the energy intensity of steel production of different countries can be compared. The methodology must clearly define the boundaries and energy conversion factors used in the analysis. The boundary definition must address how to account for imported and exported inputs and intermediate products.

Another key finding is that it is not possible to accurately compare the energy intensity of steel production of different countries without considering multiple scenarios. There is no single scenario that best compares different countries; each scenario presents different issues in terms of the accuracy and "fairness" of the comparison. For example, for this comparison of the U.S. and Chinese steel industries, the results change when the difference in production structure is taken into account when comparing the energy intensity values. For other countries, key differences might be found in the fuel or electricity conversion factors. Thus, it is necessary to present multiple scenarios to accurately convey the reasons behind the calculated energy intensities.

Acknowledgements

This work was supported by the China Sustainable Energy Program of the Energy Foundation through the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. The authors gratefully acknowledge the insightful review comments and suggestions of Ernst Worrell and Deger Saygin of Utrecht University, Christopher Weber of Science and Technology Policy Institute, Joan Pelligrino and Keith Jamison of Energetics, Lawrence Kavanagh of American Iron and Steel Institute, Henk Reimink of World Steel Association, and Wang Yanjia of Tsinghua University. At LBNL, the authors gratefully acknowledge Hongyou Lu and Cecilia Fino-Chen for their valuable research assistance on this project.

References

- Anhua, Z. and Xingshu, Z. 2006. *Efficiency Improvement and Energy Conservation in China's Power Industry*. Available at: <http://www.dfld.de/Presse/PMitt/2006/061030cl.pdf>
- Association for Iron and Steel Technology (AIST). 2010a. 2010 North American BOF Roundup. Iron & Steel Technology. November.
- Association for Iron and Steel Technology (AIST). 2010b. 2010 EAF Roundup. Iron & Steel Technology. February.
- Hasanbeigi, A.; Price, L.; Aden, N.; Zhang C.; Li X.; Shangguan F., (2011). A Comparison of Iron and Steel Production Energy Use and Energy Intensity in China and the U.S. Berkeley, CA: Lawrence Berkeley National Laboratory.
- National Bureau of Statistics (NBS). 2007. China Energy Statistics Yearbook 2006. Beijing: China Statistics Press.
- National Bureau of Statistics (NBS). 2009. China Energy Statistics Yearbook 2007. Beijing: China Statistics Press.
- National Bureau of Statistics (NBS). 2010a. China Energy Statistical Yearbook 2009. Beijing: China Statistics Press.
- International Energy Agency (IEA). 2005. Energy Statistics Manual. Paris: IEA.
http://www.iea.org/textbase/nppdf/free/2005/statistics_manual.pdf
- International Energy Agency (IEA). 2008. Key World Energy Statistics 2008. Paris: IEA.
http://www.iea.org/textbase/nppdf/free/2008/key_stats_2008.pdf
- Ruth M, et al. 2000. "Impacts of Market-based Climate Change Policy on the US Iron and Steel Industry," Energy Sources, Vol. 22, No. 3, pp. 269 - 280.
- Tornell A. 1997. Rational Atrophy: The US Steel Industry. Working Paper 6084. Cambridge: National Bureau of Economic Research.
- U.S. Department of Energy, Energy Information Administration (U.S. DOE/EIA). 2007. Annual Energy Review 2006, App. A: Thermal Unit Conversion Factors. Washington, DC: EIA.
- U.S. Department of Energy, Energy Information Administration (U.S. DOE/EIA). 2008. United States Electricity Profile (2008 Edition)- Table 10. Supply and Disposition of Electricity, 1990 Through 2008. Washington, DC: EIA. <http://www.eia.doe.gov/aer/>
- U.S. Department of Energy, Energy Information Administration (U.S. DOE/EIA). 2009. Annual Energy Review 2008, Appendix A: Thermal Unit Conversion Factors. Washington, DC: EIA.
<http://www.eia.doe.gov/aer/pdf/aer.pdf>
- U.S. Department of Energy, Energy Information Administration (U.S. DOE/EIA). 2010a. Manufacturing Energy Consumption Survey (MECS)-2006 data (Table 1.2). Washington, DC: EIA.
<http://www.eia.doe.gov/emeu/mecs/mecs2006/2006tables.html>
- U.S. Department of Energy, Energy Information Administration (U.S. DOE/EIA), 2010e. Manufacturing Energy Consumption Survey (MECS)-2006 (Table 2.2). Washington, DC: EIA.
<http://www.eia.doe.gov/emeu/mecs/mecs2006/2006tables.html>
- U.S. Department of Energy, Energy Information Administration (U.S. DOE/EIA). 2010f. Manufacturing Energy Consumption Survey (MECS)-2006 (Table 3.2). Washington, DC: EIA.
<http://www.eia.doe.gov/emeu/mecs/mecs2006/2006tables.html>

- U.S. Department of Energy, Energy Information Administration (U.S. DOE/EIA). 2010g. Electric Power Industry 2008: Year in Review. (Table 2.1 and Table 5.3). Washington, DC: EIA.
http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html
- U.S. Geological Survey (USGS), 2007. 2006 Minerals Yearbook- Lime.
<http://minerals.usgs.gov/minerals/pubs/commodity/lime/myb1-2006-lime.pdf>
- U.S. Geological Survey (USGS), 2008. 2006 Minerals Yearbook- Iron and Steel.
http://minerals.er.usgs.gov/minerals/pubs/commodity/iron_&_steel/myb1-2006-feste.pdf
- U.S. Geological Survey (USGS). 2010a. Iron and Steel Mineral Commodity Summary.
http://minerals.usgs.gov/minerals/pubs/commodity/iron_&_steel/mcs-2010-feste.pdf.
- U.S. Geological Survey (USGS), 2010b. Iron and Steel Statistics.
<http://minerals.usgs.gov/ds/2005/140/ironsteel.pdf>
- U.S. Geological Survey (USGS). 2011. Iron and Steel Mineral Commodity Summary.
http://minerals.usgs.gov/minerals/pubs/commodity/iron_&_steel/mcs-2011-feste.pdf
- Stubbles J. 2000. Energy Use in the U.S. Steel Industry: A Historical Perspective and Future Opportunities. U.S. Department of Energy, Office of Industrial Technologies, Washington, DC.
http://www1.eere.energy.gov/industry/steel/pdfs/steel_energy_use.pdf
- World Steel Association (WORLDSTEEL). 2010. Steel in Figures.
http://www.worldsteel.org/?action=stats_search&keuze=steel&country=63&from=2009&to=2009
- World Steel Association (WORLDSTEEL). 2008a. Sustainability Report of the World Steel Industry.2008.
http://www.worldsteel.org/pictures/publicationfiles/Sustainability%20Report%202008_English.pdf
- World Steel Association (WORLDSTEEL). 2008b. World Steel Sustainability Indicator Methodology.
<http://www.worldsteel.org/pictures/storyfiles/SR08%20mthodology.pdf>
- World Steel Association (WORLDSTEEL). n.d. CO2 Emissions Data Collection – User Guide, Version 6,
<http://www.worldsteel.org/climatechange/files/2/2/Data%20collection%20user%20guide.pdf>
- Zhang CX, Shangguan FQ, Changqing H. 2010. "Steel Process Structure and Its Impact on CO2 Emission," Iron & Steel, 2010, 45(5):10-15 [in Chinese]