LBNL-47205

ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

Energy use and carbon dioxide emissions from steel production in China

L. Price[a,*]*, J. Sinton*[a]*, E. Worrell*[a]*, D. Phylipsen*[b]*, X. Hu*[c]*, J. Li*

Environmental Energy Technologies Division

2001

This work was supported by the Climate Protection Division, Office of Air and Radiation, U.S. Environmental Protection Agency through the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Disclaimer

Published in Energy 27 (2002) 429–446 www.elsevier.com/locate/energy

Energy use and carbon dioxide emissions from steel production in China

L. Price [a,*], J. Sinton [a], E. Worrell [a], D. Phylipsen [b], X. Hu [c], J. Li [d]

[a] *International Energy Studies Group, Energy Analysis Department, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, MS 90-4000, Berkeley, CA 94720, USA*
[b] *Ecofys Energy and Environment, The Netherlands*
[c] *Center for Energy, Environment and Climate Change Research, Energy Research Institute People's Republic of China*
[d] *Center for Energy Economics and Development Strategy, Energy Research Institute, People's Republic of China*

30 May 2001

Abstract

In 1996, China manufactured just over 100 Mt of steel and became the world's largest steel producer. Official Chinese energy consumption statistics for the steel industry include activities not directly associated with the production of steel, 'double-count' some coal-based energy consumption, and do not cover the entire Chinese steelmaking industry. In this paper, we make adjustements to the reported statistical data in order to provide energy use values for steel production in China that are comparable to statistics used internationally. We find that for 1996, official statistics need to be reduced by 1365 PJ to account for non-steel production activities and double-counting. Official statistics also need to be increased by 415 PJ in order to include steelmaking energy use of small plants not included in official statistics. This leads to an overall reduction of 950 PJ for steelmaking in China in 1996. Thus, the official final energy use value of 4018 PJ drops to 3067 PJ. In primary energy terms, the official primary energy use value of 4555 PJ is reduced to 3582 PJ when these adjustments are made. Published by Elsevier Science Ltd.

1. Introduction

The industrial sector is the most important end-use sector in developing countries, and was responsible for 50% of primary energy use and 53% of associated carbon dioxide emissions in 1995 in these countries [1]. The industrial sector is extremely diverse, encompassing the extraction of natural resources, conversion into raw materials, and manufacture of finished products. Five energy-intensive industrial subsectors account for the bulk of industrial energy consumption and related carbon dioxide emissions (iron and steel, chemicals, petroleum refining, pulp and paper, and cement).

Iron and steel production consumes large quantities of energy, especially in developing countries and countries with economies in transition where outdated, inefficient technologies are often still used to produce iron and steel. Production of steel in developing countries has grown at an average annual rate of 6.6% in recent years [2] and is expected to continue to grow at similar levels due to the current low per capita steel consumption levels in these countries. In contrast to industrialized countries, where steel consumption averages over 425 kg/capita, key steel-producing developing countries have extremely low average per capita consumption levels of 80 kg/capita in 1995.

China is the world's largest producer of steel. Most of China's steel industry developed through a system of state-owned 'enterprises', in which an entire community was devoted to the production of steel. As a result, data collection and reporting regarding the energy used to produce steel in China also contains energy used for a variety of other functions at the enterprise level, both directly and indirectly related to the production of steel.[1] In addition, a share of China's steel is produced by small steel mills that do not report energy use data to government statistical sources.

In this paper, we discuss our methodology and results of separating the reported data on Chinese energy use for steel production into values for actual production of steel and values for the other enterprise functions. It is important to disaggregate these data so that Chinese energy use values can be fairly evaluated, especially when comparing Chinese steel industry energy consumption and energy intensity values to those of other countries or to particular 'best practice' examples. We note that even with these adjustments, it is possible that the data still include inaccuracies due to Chinese energy production and consumption statistics reporting issues.

2. Energy use for steelmaking

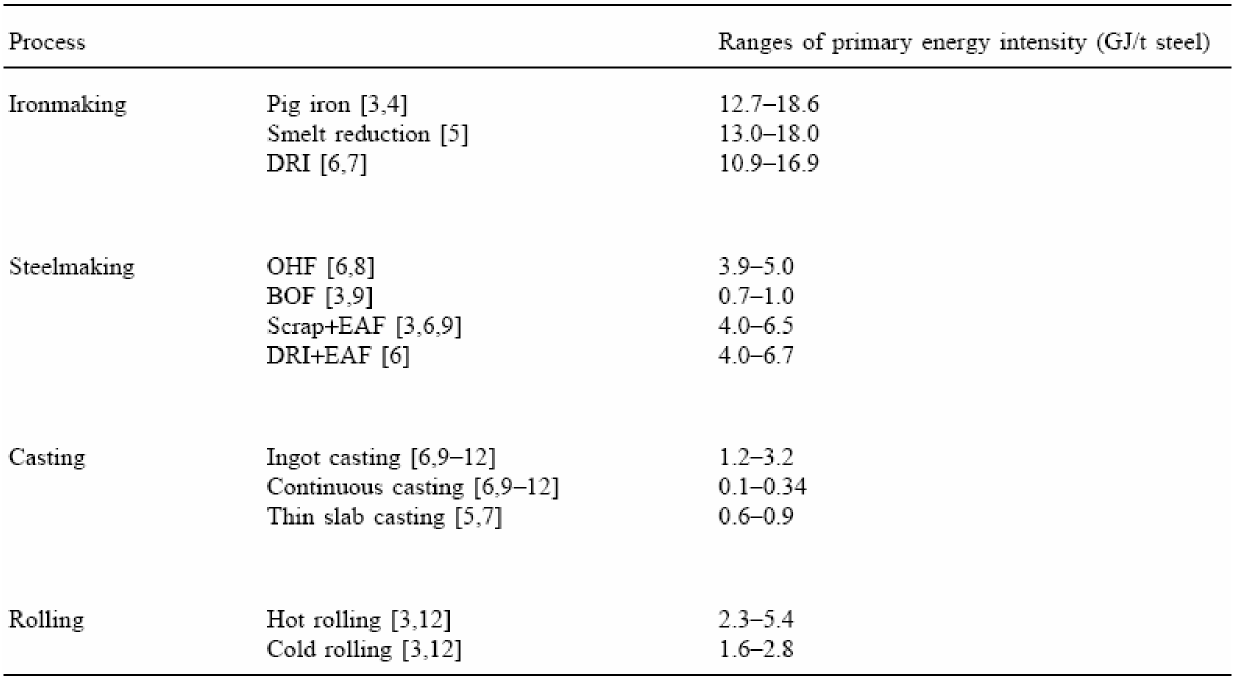
Greenhouse gas emissions in the steel sector are primarily the result of burning fossil fuels during the production of iron and steel. Currently there are two main routes for the production of steel: production of primary steel using iron ores and scrap and production of secondary steel using scrap only. A wide variety of steel products are produced by the industry, ranging from slabs and ingots to thin sheets, which are used in turn by a large number of other manufacturing industries. Table 1 provides information on typical primary energy intensities of the key iron and steelmaking processes [3–12].

Ironmaking. During the ironmaking process, sintered or pelletized iron ore is reduced using coke (produced in coke ovens) in combination with injected coal or oil to produce pig iron in a blast furnace. Limestone is added as a fluxing agent. Reduction of the iron ore is the largest energy-consuming process in the production of primary steel. In 1994, this process was responsible for over 45% of the CO2 emissions from US integrated steelmaking and had a primary energy intensity of 18.6 GJ/t of steel produced (including the energy used for ore preparation and cokemaking) [3]. Other countries, such as Finland and Luxembourg, use significantly less energy for ironmaking, consuming 12.7 and 12.9 GJ/t, respectively [4].

---

[1] A significant percentage of enterprise's energy use is for transportation and non-industrial buildings, including worker housing, offices, schools, hospitals, and other service organizations, as explained in Section 4.

Table 1 Ranges of primary energy intensities of key iron and steelmaking processes (note: ironmaking includes energy used for ore preparation and cokemaking. Ironmaking — DRI and Steelmaking — DRI+EAF assume 80% DRI and 20% scrap)



Process		Ranges of primary energy intensity (GJ/t steel)
Ironmaking	Pig iron [3,4]	12.7–18.6
	Smelt reduction [5]	13.0–18.0
	DRI [6,7]	10.9–16.9
Steelmaking	OHF [6,8]	3.9–5.0
	BOF [3,9]	0.7–1.0
	Scrap+EAF [3,6,9]	4.0–6.5
	DRI+EAF [6]	4.0–6.7
Casting	Ingot casting [6,9–12]	1.2–3.2
	Continuous casting [6,9–12]	0.1–0.34
	Thin slab casting [5,7]	0.6–0.9
Rolling	Hot rolling [3,12]	2.3–5.4
	Cold rolling [3,12]	1.6–2.8

Smelt reduction processes are the latest development in pig iron production, omitting coke production by combining the gasification of coal with the melt reduction of iron ore. Processes under development include COREX, CCF, DIOS, AISI, and HISmelt. Currently, only the COREX process (Voest-Alpine, Austria) is commercial and operating in South Africa and South Korea, with plants under construction in India, South Korea, and South Africa [13]. The COREX process uses agglomerated ore, which is prereduced by gases coming from a hot bath. The prereduced iron is then melted in the bath. The process produces excess gas, which is used for power generation, DRI-production, or as fuel gas. The COREX process is estimated to use 15–18 GJ/t steel net energy consumption, while the CCF process is estimated to use 13 GJ/t steel net energy consumption [5].

Direct reduced iron (DRI), hot briquetted iron (HBI) and iron carbide are all alternative iron making processes [14]. DRI is produced by reduction of the ores below the melting point in small-scale plants (<1 Mt/year) and has different properties than pig iron. Production of DRI typically requires between 10.9 and 16.9 GJ/t of steel, including the energy used for ore preparation [6,7]. DRI production is growing and nearly 4% of the iron in the world is produced by direct reduction, of which over 90% uses natural gas as a fuel [15]. DRI serves as a high-quality alternative for scrap in secondary steelmaking (see subsequently).

Primary steel is produced by two processes: open hearth furnace (OHF) and basic oxygen furnace (BOF). Steelmaking using a BOF has a relatively low energy intensity (0.7–1.0 GJ/t) compared to the 3.9–5.0 GJ/t energy intensity of OHFs, which are much more common in developing countries [3,6,8,9]. The OHF is still used in Eastern Europe and some developing countries. While the OHF uses more energy, this process can also use more scrap than the BOF process. However, the BOF process is rapidly replacing the OHF worldwide, because of its greater productivity and lower capital costs [16]. In addition, this process needs no net input of energy and can even be a net energy exporter in the form of BOF-gas and steam. The process operates through the injection of oxygen, oxidizing the carbon in the hot metal. Several configurations exist depending on the way the oxygen is injected. The steel quality can be improved further by ladle refining processes used in the steel mill. The scrap input is rather small for the BOF-route, typically 10–25%.

Secondary steel is produced in an electric arc furnace (EAF) using scrap. In this process, the coke production, pig iron production, and steel production steps are omitted, resulting in much lower energy consumption and a primary energy intensity of 4.0–6.5 GJ/t [3,6,9]. To produce secondary steel, scrap is melted and refined, using a strong electric current. The EAF can also be fed with iron from the DRI route, but energy consumption increases due to the added carbon, resulting in an EAF primary energy intensity of 4.0–6.7 GJ/t [6]. DRI is used to enhance steel quality, or if high-quality scrap is scarce or expensive. Several process variants exist, using either AC or DC currents, and fuels can be injected to reduce electricity use. Energy optimizing furnaces (EOFs) can also be used to produce steel from scrap. This process is essentially an oxygen steelmaking process using combined side blowing. The heat from the carbon–oxygen reaction is used to preheat scrap [17].

Casting can be a batch (ingots) or a continuous process (slabs, blooms, billets). Ingot casting is the classical process and is rapidly being replaced by continuous casting machines (CCM). In 1998, 83% of global crude steel production was cast continuously [18]. Continuous casting is a significantly more energy-efficient process for casting steel than the older ingot casting process. Continuous casting uses 0.1–0.34 GJ/t of steel, significantly less than the 1.2–3.2 GJ/t required for ingot casting [6,9–12].

Rolling of the cast steel begins in the hot rolling mill where the steel is heated and passed through heavy roller sections reducing the thickness of the steel. Hot rolling typically consumes between 2.3 and 5.4 GJ/t of steel [3,12]. The sheets may be further reduced in thickness by cold rolling. Finishing is the final production step, and may include different processes such as annealing, pickling, and surface treatment. Cold rolling and finishing add 1.6–2.8 GJ/t to the rolling energy use [3,12].

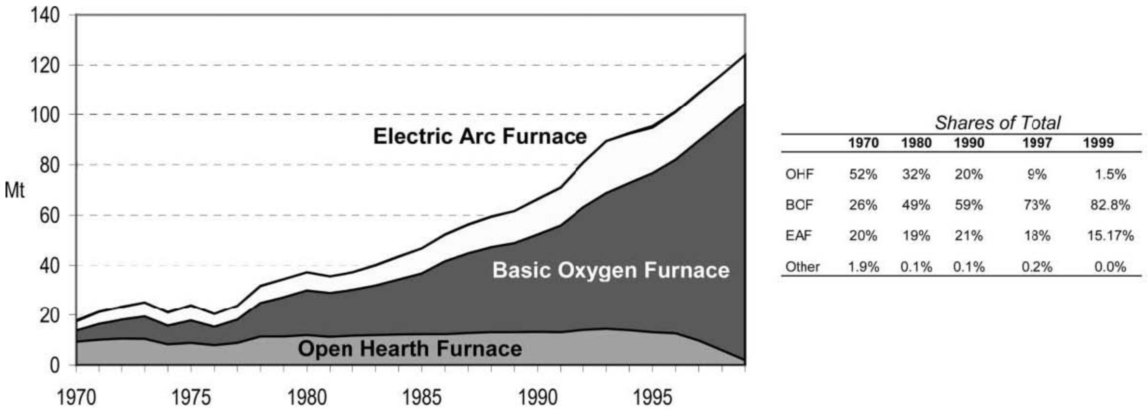
Thin slab or near net shape casting are more advanced casting techniques which reduce the need for hot rolling because products are initially cast closer to their final shape. Primary energy used for casting and rolling using thin slab casting is 0.6–0.9 GJ/t [5,18].

3. The Chinese steel industry

The Chinese steel industry has grown rapidly since the founding of the People’s Republic of China in 1949. In 1996, China manufactured just over 100 Mt of steel and became the world’s largest producer of steel. In 1999, China produced 124 Mt of steel in 1999, the majority of which was primary steel using a BOF (82.8%) [19]. In addition, 15.7% of the steel was secondary steel produced using EAF technology and only 1.5% was produced using the outmoded and energy-intensive OHF technology (see Fig. 1 [19,20]). It is predicted that the OHF technology will be phased-out completely by the end of 2000 [21]. In 2000, China's steel output continued to rise to over 126 Mt despite a government campaign to reduce output, and steel demand is likely to keep growing [22,23].

In 1999, there were 33 *key iron and steel enterprises* in China operated by the regulatory agency that inherited the duties of the former Ministry of Metallurgical Industry (MMI).[2] These key enterprises produced 76 Mt of crude steel in 1999 (see Table 2 [19,24–26]). These plants are generally old, ranging from 17 to 89 years old and averaging about 50 years old (although the age of the plant does not give adequate information regarding later equipment upgrades). Overall, continuous casting was used for 79% of the steel produced by these key plants in 1999.

Along with these key enterprises, MMI supervised an additional 56 *major local iron and steel enterprises* that produced 37.7 Mt, or 30.4% of crude steel in 1999. Over two-thirds of these plants were built in the 1950s; the most recently constructed plant was built in 1972. Continuous casting is used for 83% of the steel produced in these plants [19]. A small percentage of steel is produced by *small enterprises* in the MMI system. These plants mainly operate small EAFs, or produce only iron. Some steel is manufactured in *non-MMI enterprises*, i.e. iron and steel plants outside of MMIs supervision. Of the nearly 124 Mt of crude steel produced in 1999, 96% came from enterprises in the MMI system, and 91.5% from MMIs key enterprises and major local enterprises.[3]



Shares of Total

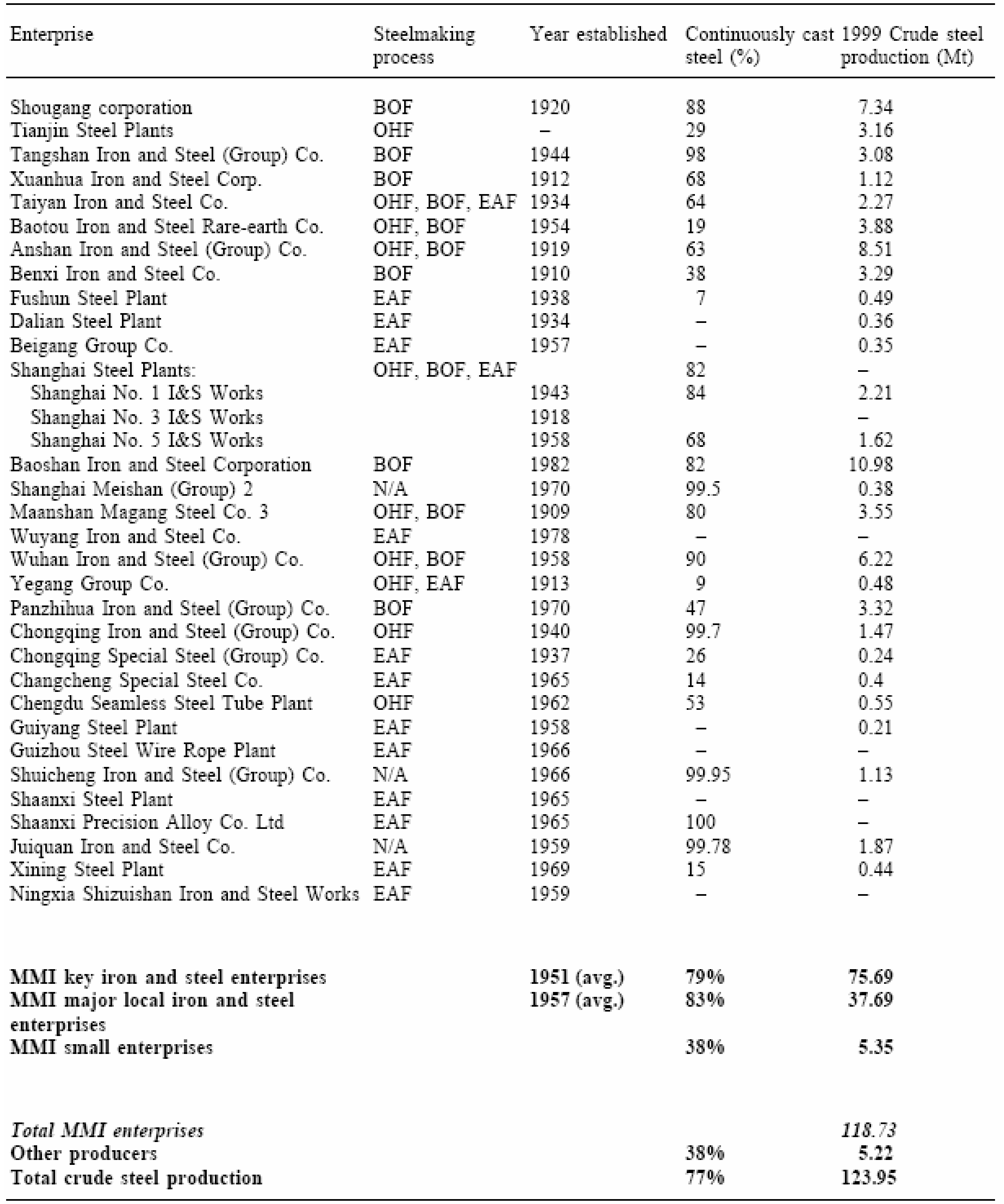
	1970	1980	1990	1997	1999
OHF	52%	32%	20%	9%	1.5%
BOF	26%	49%	59%	73%	82.8%
EAF	20%	19%	21%	18%	15.17%
Other	1.9%	0.1%	0.1%	0.2%	0.0%

Fig. 1. Steel production in China by process, 1970–1999 [19,20] (Note: Less than 1% of crude steel is produced by methods in the 'Other' category).

[2] In the 1998 reorganization of the central government, the decades-old Ministry of Metallurgical Industry was demoted to the status of a bureau and placed under the State Economic and Trade Commission (SETC), the body responsible for coordinating day-to-day administration of the government's economic regulatory activities. In 2000, most industrial bureaus, including that responsible for iron and steel, were combined into a single Sectoral (or Industrial) Management Bureau (*hangye guanlisi*). Throughout these administrative changes of the past several years, the regulatory staff and duties have evolved, but remained fundamentally similar. For convenience in presentation and continuity with historical practice and reference materials, we refer to the governmental body engaged in overseeing the iron and steel sector as 'MMI' throughout this document.

[3] Since 1990s, iron output from non-MMI enterprises has risen rapidly, from a 4.8% share of national iron output in 1989 to 17% in 1997. The annual output of pig iron produced by non-MMI enterprises is now over 10 Mt [20]. However, a central government campaign to close down small, inefficient iron and steel producers shut down over 100 mills in 2000, and aims to close over 100 more in 2001 [27,28]. Since many of these small plants are non-MMI plants, it is likely that their share of iron and steel output will fall.

Table 2 Crude steel production in China by enterprise, 1999 [19,24–26]



Enterprise	Steelmaking process	Year established	Continuously cast steel (%)	1999 Crude steel production (Mt)
Shougang corporation	BOF	1920	88	7.34
Tianjin Steel Plants	OHF	–	29	3.16
Tangshan Iron and Steel (Group) Co.	BOF	1944	98	3.08
Xuanhua Iron and Steel Corp.	BOF	1912	68	1.12
Taiyan Iron and Steel Co.	OHF, BOF, EAF	1934	64	2.27
Baotou Iron and Steel Rare-earth Co.	OHF, BOF	1954	19	3.88
Anshan Iron and Steel (Group) Co.	OHF, BOF	1919	63	8.51
Benxi Iron and Steel Co.	BOF	1910	38	3.29
Fushun Steel Plant	EAF	1938	7	0.49
Dalian Steel Plant	EAF	1934	–	0.36
Beigang Group Co.	EAF	1957	–	0.35
Shanghai Steel Plants:	OHF, BOF, EAF		82	–
Shanghai No. 1 I&S Works		1943	84	2.21
Shanghai No. 3 I&S Works		1918		–
Shanghai No. 5 I&S Works		1958	68	1.62
Baoshan Iron and Steel Corporation	BOF	1982	82	10.98
Shanghai Meishan (Group) 2	N/A	1970	99.5	0.38
Maanshan Magang Steel Co. 3	OHF, BOF	1909	80	3.55
Wuyang Iron and Steel Co.	EAF	1978	–	–
Wuhan Iron and Steel (Group) Co.	OHF, BOF	1958	90	6.22
Yegang Group Co.	OHF, EAF	1913	9	0.48
Panzhihua Iron and Steel (Group) Co.	BOF	1970	47	3.32
Chongqing Iron and Steel (Group) Co.	OHF	1940	99.7	1.47
Chongqing Special Steel (Group) Co.	EAF	1937	26	0.24
Changcheng Special Steel Co.	EAF	1965	14	0.4
Chengdu Seamless Steel Tube Plant	OHF	1962	53	0.55
Guiyang Steel Plant	EAF	1958	–	0.21
Guizhou Steel Wire Rope Plant	EAF	1966	–	–
Shuicheng Iron and Steel (Group) Co.	N/A	1966	99.95	1.13
Shaanxi Steel Plant	EAF	1965	–	–
Shaanxi Precision Alloy Co. Ltd	EAF	1965	100	–
Juiquan Iron and Steel Co.	N/A	1959	99.78	1.87
Xining Steel Plant	EAF	1969	15	0.44
Ningxia Shizuishan Iron and Steel Works	EAF	1959	–	–
MMI key iron and steel enterprises		**1951 (avg.)**	**79%**	**75.69**
MMI major local iron and steel enterprises		**1957 (avg.)**	**83%**	**37.69**
MMI small enterprises			**38%**	**5.35**
Total MMI enterprises				*118.73*
Other producers			**38%**	**5.22**
Total crude steel production			**77%**	**123.95**

4. Adjusting Chinese steelmaking energy consumption statistics

We analyzed steel energy use data for 1996 as provided in the *Yearbook of Iron and Steel Industry of China*, published by MMI.[4] These official Chinese energy statistics indicate that final energy use for steelmaking in 1996 was 4018 PJ [29]. The reported energy consumption statistics include energy use for activities not directly associated with the production of steel, 'doublecount' some coal-based energy consumption, and do not cover the entire Chinese steelmaking industry. In 1991, Ross and Liu [30] pointed out the inclusion of this non-steelmaking energy use in Chinese energy statistics, but explained that data on energy use for these other services were not available. They estimated that this 'living energy use' (for households and social services) should be reduced by about 20 kgce per ton product, which in 1987 was 5.6% of energy used for steel production in all plants in China [30].

Below, we modify the reported statistical data in order to provide energy use values for steel production in China that are comparable to statistics used internationally [20]. This allows us to compare China's energy consumption and energy intensity to those of other countries or to best practice energy use values.

4.1. Removing non-steelmaking energy use from MMI energy consumption values

Energy consumption statistics for the Chinese steel industry are only reported for the key iron and steel enterprises, the major local iron and steel enterprises, and the small enterprises operated or supervised by MMI. In 1994, 17% of reported MMI energy use for steelmaking was for auxiliary production process such as ore mining (4%), manufacturing of refractory materials (6%), carbon products (4%), and byproducts (2%), as well as machine repair (1%) [20]. These activities, while related to steel production, are not typically included in the strict definition of 'steelmaking', especially among analysts making international comparisons [31]. Of the 4% used for ore mining in 1996, coal accounted for 18%, coke for 25.5%, oil for 5%, and electricity for 51.5% [20]. In 1996, final energy use for ore mining was 38 PJ. Final energy use for the remaining auxiliary production processes was 440.5 PJ that year.

MMI steelmaking energy use statistics also include on-site 'livelihood' energy use. On-site livelihood includes energy used in buildings, cafeterias, hospitals, preschools, and other non-steelproducing activities within the enterprise. Further refinement of the non-energy use estimate of Ross and Liu [30] was made by ERI researchers who estimated that in 1994 on-site livelihood energy use was

---

[4] *The Yearbook of Iron and Steel Industry of China*, edited by the Ministry of Metallurgical Industry (MMI), is an annual publication that records the historical development of the iron and steel industry of China. The major data and information presented in this publication are obtained from the collected annual reports from plants in the system of metallurgical industry of China. The output data in the publication are for the whole country, while the energy data only include key enterprise and local enterprise within MMIs system. The data do not include the Hong Kong Special Administrative Region, Taiwan and Macao.

7.6% of reported MMI energy use for steel production [20]. Of this, it was estimated that about 70% was electricity and the remainder was coal. Using this information for 1996, final energy use for on-site livelihood is calculated to be 258 PJ.

Finally, MMI statistics include energy used for off-site transportation. Approximately 50% of motor gasoline use reported as energy use for steelmaking was for off-site transportation [20]. In 1996, energy use for off-site transportation was 8 PJ.

4.2. Correcting for double-counting of energy use for coal, coking coal, and steam coal

MMI steelmaking energy use statistics include energy consumption values for coal, coking coal and steam coal as well as for coke oven gas, blast furnace gas, heat, and other electricity produced for own use on-site. Coke oven gas and blast furnace gas are waste gases that result from burning coking coal during the cokemaking and steelmaking processes, respectively. Heat is captured from the use of steam coal in furnaces and boilers and on-site electricity is generated using coal. Thus, these process waste gases, heat, and on-site electricity all derive from fuels already included in the energy consumption statistics under ‘coking coal,’‘steam coal,’ and ‘coal’ and thus are being double-counted when all of these categories are summed. In 1996, the energy value of coke oven gas, blast furnace gas, heat, and other electricity produced for own use on-site was 621 PJ.

4.3. Adding non-MMI steelmaking energy use to calculate a national steelmaking energy consumption value

Approximately 5% of Chinese steel production is not included in the MMI data. To account for the other producers not included in the MMI data, we first gathered iron and steel production data for these other producers, including data on steel production by process, from the *Statistics of Iron and Steel Industry of* China [32,33][5] and the *China Energy Statistical Yearbook* [34–37].[6] We then estimated energy use by fuel for ironmaking and steelmaking in non-MMI steel mills. For ironmaking, we calculated solid fuel consumption assuming that the energy intensity per ton of iron produced by non-MMI steel mills is equivalent to 75% of overall solid fuel intensity for iron and steel and 25% of electricity intensity for iron and steel at MMI mills.[7] For steelmaking, we assumed that the energy intensity per ton of steel produced was equivalent to the average MMI energy intensity. These energy intensities were then multiplied by non-MMI iron and steel

---

[5] Data in *Statistics of Iron and Steel Industry of China* are obtained from annual statistical reports of MMIs Department of Planning, and from industrial surveys. The output data presented in the publication are for the whole country, while energy data only include key enterprise and local middle and small enterprises within MMIs system. The data in this book do not include the Hong Kong Special Administrative Region, Taiwan Province and Macao.

[6] The *China Energy Statistical Yearbook* has been published four times, in 1986, 1989, 1991 and 1997. This yearbook is an essential reference for decision-makers at all levels, economists and energy researchers. It provides information on the energy situation in China as well as the relationship between energy and social economic development. The output data presented in the publication are for whole country. The national data in this book do not cover the Hong Kong Special Administrative Region, Taiwan Province and Macao. Also, the data in the energy balance tables does not cover non-commercial energy.

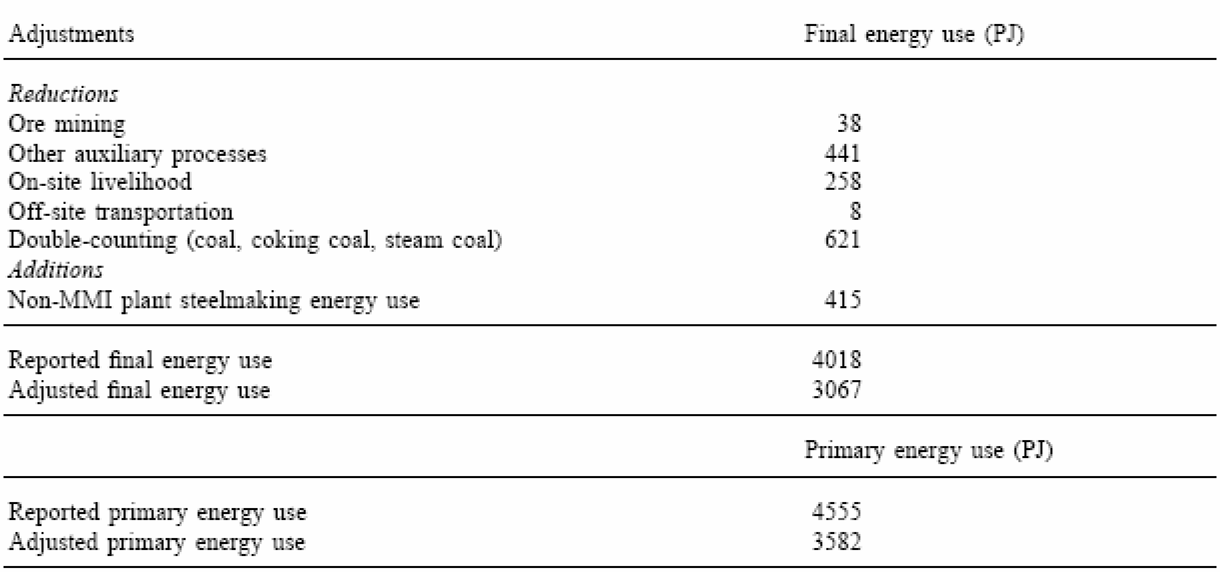
[7] We chose these approximate percentages to reflect the fact that ironmaking is the most fuel-intensive process in iron and steel production, but accounts for a relatively small fraction of electricity use.

production data to calculate non-MMI steelmaking energy consumption values. In 1996, non-MMI energy use for steel production is estimated to be 415 PJ to produce approximately 6 Mt of crude steel. This adjustment is likely to be smaller for 2000 and future years, due to the government-mandated closure of hundreds of small iron and steel plants.

4.4. Summary of adjustments

Table 3 provides a summary of the adjustments we made to reported final energy use in China for 1996. As discussed, reductions were made for ore mining, other auxiliary processes, on-site livelihood, off-site transportation, and double-counting of coal, coking coal, and steam coal. Non-MMI plant steelmaking energy use was added to the reported final energy use. The result is a reduction of 1365 PJ and addition of 415 PJ, leading to a net reduction of 950 PJ in final energy. Thus, the reported final energy use value of 4018 PJ in 1996 drops to 3067 PJ. In primary energy terms, the reported primary energy use value of 4555 PJ drops to 3582 PJ when these adjustments are made. To analyze historic trends and make international comparisons, similar adjustments were made for energy use for steelmaking from 1980 to 1995, assuming the same shares of livelihood energy use, non-MMI output, and so on.[8,9]

Table 3 Adjustments to reported steelmaking energy use in China, 1996 (note: primary energy use calculated using a 33% electricity conversion factor)



Adjustments	Final energy use (PJ)
Reductions	
Ore mining	38
Other auxiliary processes	441
On-site livelihood	258
Off-site transportation	8
Double-counting (coal, coking coal, steam coal)	621
Additions	
Non-MMI plant steelmaking energy use	415
Reported final energy use	4018
Adjusted final energy use	3067
	Primary energy use (PJ)
Reported primary energy use	4555
Adjusted primary energy use	3582

---

[8] Ideally, these adjustments should be made on a year-by-year basis.

[9] Recent concerns regarding the accuracy and reliability of China's energy statistics [38] focus mostly on coal consumption reporting issues. Problems with reporting are most acute in the non-state sectors. Thus, we believe that the statistics reported here are as accurate as any national-level statistics [39] since 95% of iron and steel production is state-owned (by MMI) and steelmaking enterprises are not experiencing the same political pressures that are forcing coal mines to under-report [38].

5. Primary and final energy use and carbon dioxide emissions from steel production in China

Based on the adjustments in reported energy consumption data described above, primary energy use for steel production in China more than doubled between 1980 and 1996, growing from 1603 to 3582 PJ (see Fig. 2). This growth, which averaged 5.2% per year, was slower than the 6.5% average annual growth in steel production experienced during this period, resulting in a drop in energy intensity (energy used per ton of steel produced) from 43 to 35 GJ/t.

In 1996, final energy use for steel production in China was 3067 PJ. Solid fuels accounted for 74% of final energy use (after accounting for all adjustments). Among solid fuels, coking coal accounted for over two-thirds, purchased coke for nearly 9%, and steam coal for the balance.[10] The proportion of purchased coke has been rising; in 1981 purchased coke accounted for about 4% of solid fuels.

Gas fuels were used for 8% of final steel energy consumption in 1996. This was composed mainly of coke oven gas (79%). The remaining gas fuels were blast furnace gas (16%) and a small amount of natural gas (5%).[11] In China, natural gas is preferentially supplied to residential customers and a few large chemical fertilizer plants.

In 1996, liquid fuels accounted for 5% of steelmaking energy use, a drop from the 9% share used in 1980. Fuel oil accounted for over three-quarters of the liquid fuels consumed in 1996, and diesel and gasoline for nearly all the rest.[12] This was a great change from the early 1980s,

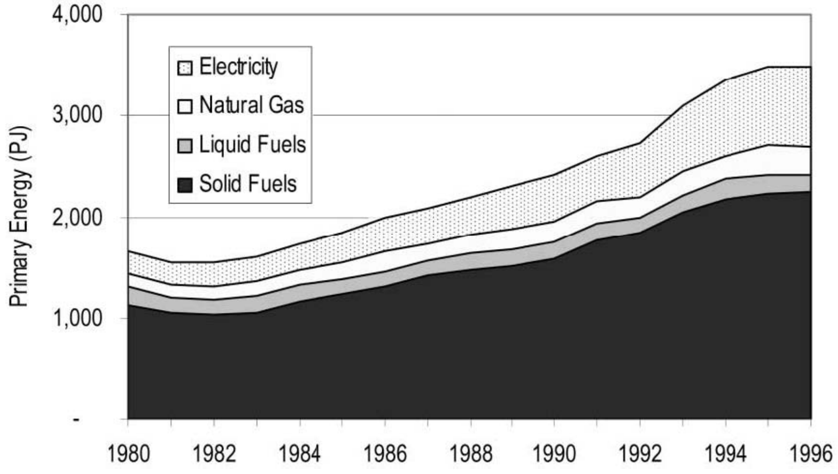


Fig. 2. Adjusted end-use energy consumption for steel production in China, 1980–1996.

[10] Nearly all (96%) of steam coal consumed in the iron and steel sector is used in manufacturing, 1% for railway transport on-site, and 3% for building heating in winter [20]. The adjustments above excluded use of steam coal not directly related production of iron and steel and used at iron and steel mills.

[11] The major use of collected coke oven gas is in manufacturing. A small portion is used as residential cooking fuel, and a negligible amount for power generation. The major use of collected blast furnace gas is in manufacturing. Currently about 15% is used for power generation.

[12] The major use of diesel is on-site transportation. Approximately half of gasoline consumption is used for on-site transportation, and the remainder for off-site transportation. This is reflected in our adjusted figures for energy consumption.

when 15% of the liquid fuel used was crude oil, a consequence of the great faith China then had that it would continue to find large onshore oilfields.

Electricity accounted for 8% of final energy use (22% of primary energy use) for steel production in 1996. Four-fifths of this electricity was purchased, and the remainder generated on-site. China's largest integrated iron and steel plants run their own conventional power plants, and an increasing number generate power using energy byproducts of the manufacturing process, such as coke oven gas, blast furnace gas, and by using blast furnace top pressure recovery turbines.

Carbon dioxide emissions from steel production grew from 37.8 MtC in 1980 to 84.6 MtC in 1996.[13] The structure of emissions mirrors energy use, with coal and coke dominating, followed by electricity (mainly from coal-fired power plants), then fossil liquids, and a small amount of natural gas. No biomass fuels are used in China's steel industry. Carbon dioxide emissions from steel production accounted for 9% of total carbon dioxide emissions in China in 1995.

The carbon dioxide intensity of steel production is simply sectoral carbon dioxide emissions (expressed in metric tons of carbon) divided by an indicator of total output, in this case crude steel. Carbon intensity declined steadily from 1980 to the early 1990s, and has recently begun to fall again after a short rise, reaching 1.03 tC/t steel in 1996 (see Fig. 3 [20,41]).

6. Energy use and carbon dioxide emissions of the Chinese steel sector in an international context

During the past decade, interest in comparing energy use and greenhouse gas emissions trends between countries has grown in response to the many issues raised as a result of the United National Framework Convention on Climate Change (UNFCCC). The UNFCCC was signed in

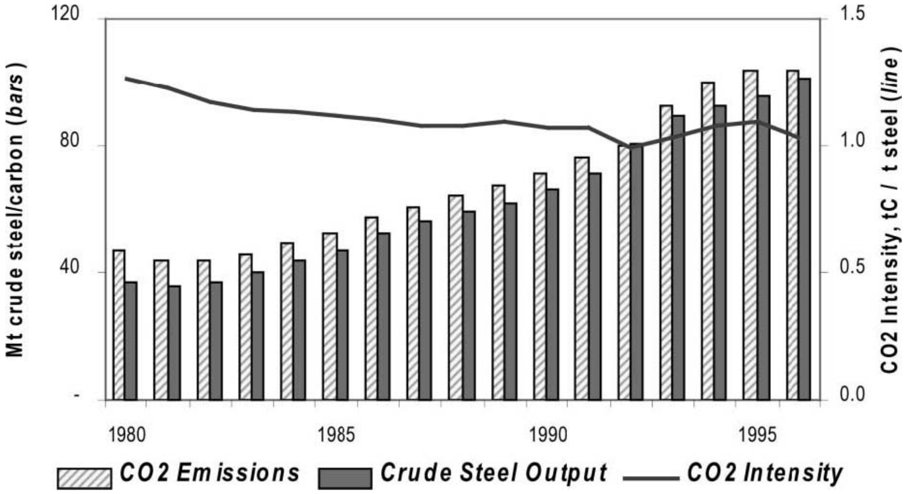


Fig. 3. Carbon dioxide emissions, crude steel output, and carbon dioxide intensity of steel production in China, 1980– 1996 [20,41].

---

[13] CO2 emissions factors based on IPCC [40].

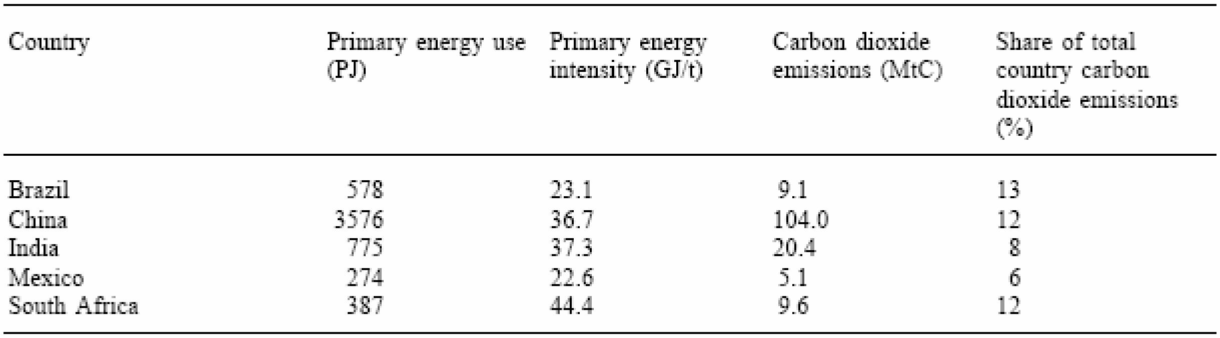
1992 by over 150 countries that committed to the goal of stabilizing greenhouse gas concentrations ‘at a level that would prevent dangerous anthropogenic interference with the climate system’ [42]. In 1997, at the third Conference of the Parties (COP-3) to the UNFCCC in Kyoto, Japan, the signatories agreed to the Kyoto Protocol that outlined emissions reduction targets for the Annex I countries, but not for developing countries. Even so, it is generally acknowledged that developing countries have a role to play in abating global climate change since greenhouse gas emissions are growing rapidly in many of these countries. Thus, in order to fairly compare and assess greenhouse gas emissions trends and reduction opportunities, it is important to develop a consistent methodology for making international comparisons.

The international comparisons made in this paper follow the methodological recommendations from two workshops and a handbook on international comparisons of industrial energy efficiency [31,43,44]. These comparisons can be used to analyze differences in trends between countries as well as to identify opportunities for energy efficiency improvement and greenhouse gas emissions reductions.

When compared to other major developing countries, China is clearly the largest producer of steel and thus consumes a significantly larger amount of primary energy and has equally large related carbon dioxide emissions (see Table 4 [20,41,45]).[14] Primary energy consumption does not correlate exactly with steel production levels, however, due to changes in production technology structure and in the energy efficiency of steelmaking equipment.

Table 4 provides primary energy use, primary energy intensity (primary energy consumption per ton of crude steel), and carbon dioxide emissions for five key developing countries: Brazil, China, India, Mexico, and South Africa. China and India have high primary energy intensity compared to the other countries. Brazil and Mexico have the lowest energy intensities of the five developing countries, but their intensity values are still higher than those found in many European countries and some rapidly developing countries (e.g. South Korea). Intensity in South Africa was quite high in the 1970s, and has since declined rapidly, though it rebounded somewhat in recent years.

Table 4 Primary energy use and carbon dioxide emissions from the steel industry in five developing countries, 1995 [20,41,45]



Country	Primary energy use (PJ)	Primary energy intensity (GJ/t)	Carbon dioxide emissions (MtC)	Share of total country carbon dioxide emissions (%)
Brazil	578	23.1	9.1	13
China	3576	36.7	104.0	12
India	775	37.3	20.4	8
Mexico	274	22.6	5.1	6
South Africa	387	44.4	9.6	12

[14] Primary energy consumption is calculated by using a constant conversion efficiency of 33% in order to exclude differences in electricity generating efficiency between countries, thus highlighting only differences in energy efficiency in the production of steel.

Steel-related carbon dioxide emissions closely mirror primary energy use, with China clearly dominating, followed by India, Brazil, and Mexico. Carbon dioxide emissions from steel production are responsible for 13% of total emissions in Brazil, 12% of total emissions in South Africa and in China, 8% of total emissions in India, and 6% of total emissions in Mexico [45].

Carbon intensity trends are closely related to energy intensity trends but are also dependent upon the fuel mix used by the iron and steel industry in each country.[15] South Africa, India and China have the highest carbon intensities from iron and steel production, while Brazil and Mexico have relatively low carbon intensities.

Between 1980 and 1996, primary energy used per ton of steel produced in China dropped from 43 to 35 GJ/t, based on the adjusted energy consumption values described above. Other studies of China's steelmaking energy intensity, which also made various adjustments to China's steelmaking energy use in order to account for differences from international practices, show similar declines. For example, a 1997 study by the Asian Development Bank indicates that in 1996, overall energy intensity for key plants in China was 33.2 GJ/t steel (compared to a national average of 40.8 GJ/t), while the 'comparable' energy intensity for key plants was 28.3 GJ/t [46] (see Table 5 [19,24,25,29,32,33,46,47]).[16] Another study indicates that the comparable energy consumption per ton of steel in large and medium sized steel enterprises is 27.5 GJ/t while the international advanced level is 19.3 GJ/t in 1998 [49].

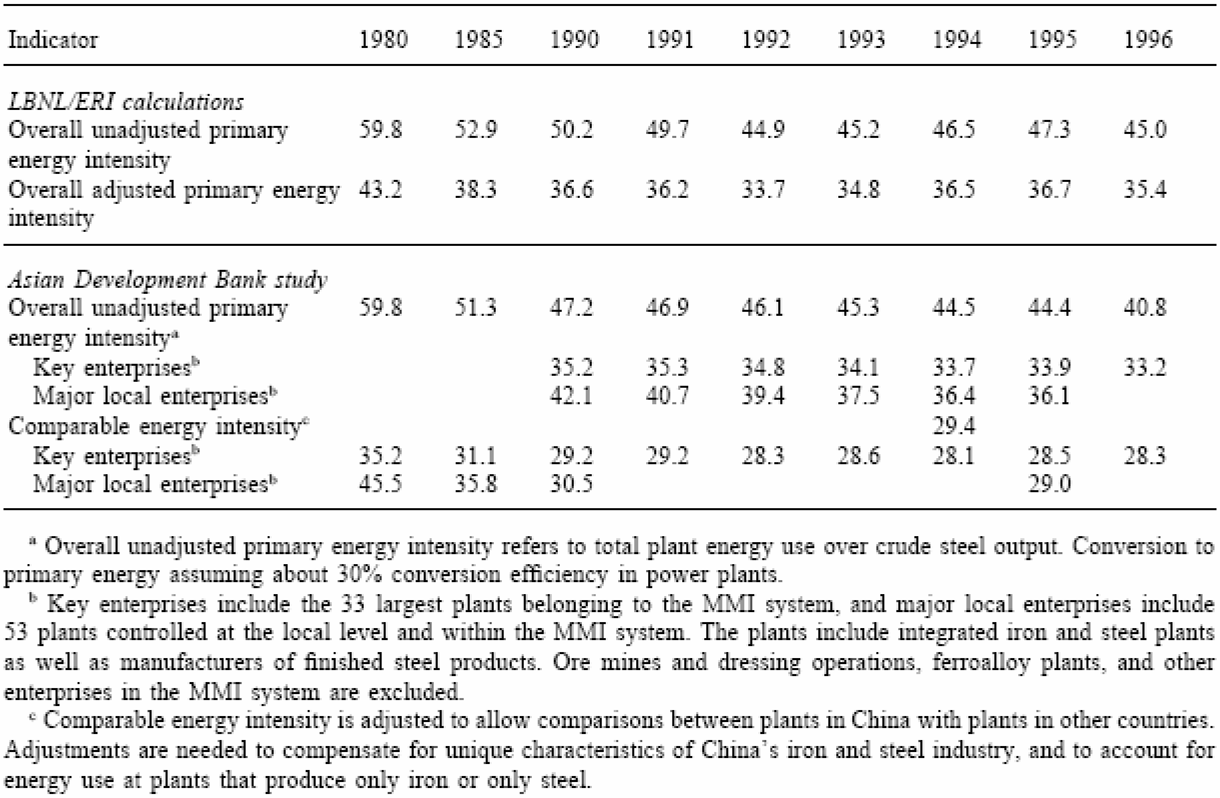
Another study comparing energy use for steel production in China and the US in 1987 made a small adjustment to remove 5.6% of living energy use from steelmaking data. This study found that the US relied more heavily on the efficient pellet-based process for iron production while China used the less energy-efficient sinter-based process. China used less energy per ton for cokemaking than the US due to the long-standing experience of the Chinese with cokemaking as well as the energy loss in the US related to emissions controls and more extensive processing of coke byproducts. Other differences included the high electricity intensity in the blast furnace operation in China, the low use of scrap in China, and the low complexity and quality of many Chinese steel products. Overall, the study found that the energy intensity of China's key steel-producing plants was about 20% higher than that for US integrated plants in 1987 [30].

---

[15] Carbon emissions factors are from the Intergovernmental Panel on Climate Change [40].

[16] 'Comparable energy intensity' is a calculation made to allow for comparisons between plants in China and with plants in other countries. It refers to the 'total energy necessarily consumed by certain defined major processes for producing one tonne of steel, deducting process energy consumed by iron-ore mining and auxiliary processes, etc.' [48].

Table 5 Energy intensity of steel production in China (GJ/t) [19,24,25,29,32,33,46,47] (these figures represent overall sectoral consumption of energy divided by crude steel output. Coverage is for MMI system only)



Indicator	1980	1985	1990	1991	1992	1993	1994	1995	1996
LBNL/ERI calculations									
Overall unadjusted primary energy intensity	59.8	52.9	50.2	49.7	44.9	45.2	46.5	47.3	45.0
Overall adjusted primary energy intensity	43.2	38.3	36.6	36.2	33.7	34.8	36.5	36.7	35.4
Asian Development Bank study									
Overall unadjusted primary energy intensity[a]	59.8	51.3	47.2	46.9	46.1	45.3	44.5	44.4	40.8
Key enterprises[b]			35.2	35.3	34.8	34.1	33.7	33.9	33.2
Major local enterprises[b]			42.1	40.7	39.4	37.5	36.4	36.1	
Comparable energy intensity[c]							29.4		
Key enterprises[b]	35.2	31.1	29.2	29.2	28.3	28.6	28.1	28.5	28.3
Major local enterprises[b]	45.5	35.8	30.5					29.0	

[a] Overall unadjusted primary energy intensity refers to total plant energy use over crude steel output. Conversion to primary energy assuming about 30% conversion efficiency in power plants.

[b] Key enterprises include the 33 largest plants belonging to the MMI system, and major local enterprises include 53 plants controlled at the local level and within the MMI system. The plants include integrated iron and steel plants as well as manufacturers of finished steel products. Ore mines and dressing operations, ferroalloy plants, and other enterprises in the MMI system are excluded.

[c] Comparable energy intensity is adjusted to allow comparisons between plants in China with plants in other countries. Adjustments are needed to compensate for unique characteristics of China's iron and steel industry, and to account for energy use at plants that produce only iron or only steel.

A more recent study comparing energy consumption for steel production in China to that in Japan shows that China's primary energy intensity of 36.5 GJ/t in 1995 is 17 GJ/t higher than that of Japan's steel industry [50]. Most of the higher energy consumption can be explained by the higher relative iron production in China, relatively poorer material quality, a poorer electric utility transmission and delivery system, higher relative iron alloy production, lower waste energy recovery, smaller scale of equipment, lower conversion efficiency of steam and oxygen, and other miscellaneous factors [50].

7. Estimating potential energy savings and carbon dioxide emissions reductions in the steel industry in China

Differences in physical energy intensities between countries are due to differences in energy efficiency as well as structural differences. In order to account for the structural differences, a best practice benchmark energy intensity using best practice energy intensities for the actual product mix and feedstocks used in each country can be calculated. The best practice benchmark energy intensity is calculated to reflect the sector structure for each year for each country, based on that country's product mix and feedstock. This methodology accounts for the share of both primary and secondary steel produced in the country each year. In the iron and steel industry product mix is defined as the share of iron, slabs, hot rolled steel, cold rolled steel and wire. Feedstocks (e.g. scrap, iron ore) are important because the product quality can be influenced by the scrap input due to contaminations from other metals (i.e. product mix is influenced) [31]. Also, the quality of the ore (i.e. the iron content) can slightly affect energy use in the blast furnace. These best practice benchmark energy intensities are then compared to actual energy intensities. To make this comparison, we use an energy efficiency index (EEI) which is the ratio of the actual energy intensity to the best practice energy intensity, where the best practice equals 100.

As with energy intensity, the structural differences between countries can be taken into account by calculating a carbon intensity index, which compares the actual level of emissions per ton of product to a best practice benchmark level of emissions. The best practice benchmark carbon intensity for each of the processes and products is calculated by multiplying the actual carbon intensities with the best practice carbon intensities and the carbon emission factor for each process.

The sectoral best practice benchmark carbon intensity is calculated as a weighted average based on the shares of the processes and products in each country. The carbon intensity index is the ratio of the actual carbon intensity to the best practice benchmark carbon intensity, where a carbon intensity of 100 represents best practice and the higher the carbon intensity index the higher the emission reduction potential for a given sector structure.

Compared to the EEI there is one complicating factor in calculating the carbon intensity index. In addition to sector structure and energy efficiency, fuel mix also influences CO2 emissions per ton of product. Using the fuel mix associated with the best practice technology in the carbon intensity index calculation implies a fuel switch from actual fuel mix to this best practice fuel mix. Because of constraints on the availability of indigenous resources this is not always economically feasible. Therefore, we have excluded the influence of fuel mix in our calculations of the carbon intensity index. This is done by using a national average fuel mix, instead of the best practice fuel mix, to calculate the benchmark carbon intensity.[17] This means that the index is an indication of the emission reduction potential by efficiency improvements only. Additional emissions reductions can be accomplished through fuel switching.

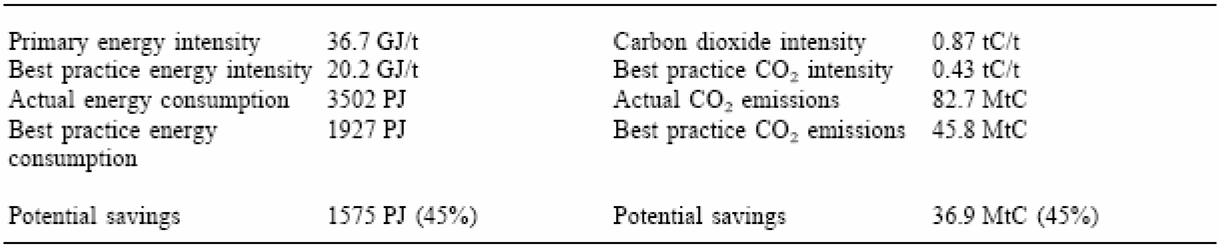
Identification of the technical potential primary energy savings and carbon dioxide emissions reductions provides a rough estimate of the savings potential available in various countries. While the technical potential is based on actual energy use and carbon dioxide emissions from plants in commercial operation, country and plant-specific conditions will determine what portion of the technical potential can be realized in any given country.

---

[17] This assumes that the efficiency of the best practice technology does not change with changing fuel mix.

Table 6 shows the results of the energy efficiency and carbon intensity index calculations for China in 1995 [51]. That year, China had an actual primary energy intensity of 36.7 GJ/t. If best practice technology had been used to produce the same amount and types of steel in China that year, then the energy intensity would have been 20.2 GJ/t, resulting in energy savings of 16.5 GJ/t. Based on the amount of steel produced that year, 95.4 Mt, China could have consumed only 1927 PJ for steel production, or 45% below the actual consumption of 3502 PJ. China's carbon dioxide intensity in 1995 was 0.87 tC/t steel produced. Using best practice technologies would have reduced this intensity value to 0.43 tC/t, resulting in a savings of 0.39 tC/t steel. These best practice technologies would have almost cut actual carbon dioxide emissions of 82.7 MtC almost in half, to 45.8 MtC in 1995.

Table 6 Potential energy savings and carbon dioxide emissions reductions using best practice technologies in China in 1995 [51]



Primary energy intensity	36.7 GJ/t	Carbon dioxide intensity	0.87 tC/t
Best practice energy intensity	20.2 GJ/t	Best practice CO_2 intensity	0.43 tC/t
Actual energy consumption	3502 PJ	Actual CO_2 emissions	82.7 MtC
Best practice energy consumption	1927 PJ	Best practice CO_2 emissions	45.8 MtC
Potential savings	1575 PJ (45%)	Potential savings	36.9 MtC (45%)

8. Summary and conclusions

Steelmaking is a very energy-intensive manufacturing process and accounts for over 10% of China's primary energy use and related carbon dioxide emissions. To understand the potential for saving energy and reducing emissions in this industry, it is important to clearly understand how the energy is used and to correctly account for the energy consumed for actual steelmaking. We have made a number of adjustments to the official Chinese energy consumption statistics for the steel industry in order to remove energy use for activities not directly associated with the production of steel, to correct for double-counting of some coal-based energy consumption, and to add energy use for a small portion of the steelmaking industry that is not included in official statistics. Using these adjusted values, we find that Chinese energy use and associated carbon dioxide emissions are still very high when compared to other countries and to best practice energy consumption values. If best practice technology had been used to produce the same amount and types of steel in China in 1995, energy savings and carbon dioxide emissions reductions of 45% could have been achieved.

Acknowledgements

Funding for this work was provided by the China Sustainable Energy Program of the Energy Foundation, and the Climate Protection Partnerships Division, Office of Atmospheric Programs, Office of Air and Radiation, US Environmental Protection Agency through the US Department of Energy under Contract No. DE-AC03-76SF00098.

References

[1] Price L, Michaelis L, Worrell E, Khrushch M. Sectoral trends and driving forces of global energy use and greenhouse gas emissions. Mitigation Adapt Strategies Global Change 1998;3:263–319.
[2] International Iron and Steel Institute. Steel statistics of developing countries, 1996 ed. IISI: Brussels, 1997.
[3] Worrell E, Martin N, Price L. Energy efficiency and carbon dioxide emissions reduction opportunities in the U.S. iron and steel sector. Berkeley, CA: Lawrence Berkeley National Laboratory, 1999 (LBNL Report 41724).
[4] International Iron and Steel Institute. Statistics on energy in the steel industry. Brussels, Belgium: IISI, 1996 (1996 update).
[5] Worrell E, Moore C. Energy efficiency and advanced technologies in the iron and steel industry. In: Proceedings 1997 ACEEE Summer Study on Energy Efficiency in Industry. Washington, DC: ACEEE; 1997.
[6] World Energy Council. Energy efficiency improvement utilising high technology, an assessment of energy use in industry and buildings. London, UK: WEC, 1995.
[7] International Iron and Steel Institute. Energy use in the steel industry. Brussels: IISI, 1998.
[8] Kudrin V. Steelmaking. Moscow: Mir, 1985.
[9] Energetics. Energy and environmental profile of the U.S. steel industry. Washington, DC: Energetics, 2000 (Prepared for the US DOE, Office of Industrial Technologies).
[10] Brown H, Hamel B, Hedman B. Energy analysis of 108 industrial processes. Washington, DC: US DOE, 1985.
[11] Energetics. The U.S. steel industry: an energy perspective. Washington, DC: Energetics, 1988.
[12] Worrell E, de Beer JG, Blok K. Energy conservation in the iron and steel industry. In: Pilavachi PA, editor. Energy efficiency in process technology. Amsterdam/London: Elsevier; 1993.
[13] Voest Alpine Industrieanlagenbau. COREX, revolution in ironmaking. Linz, Austria: VAI, 1996.
[14] McAloon TP. Alternate ironmaking update. Iron Steelmaker 1994;21(2):37–9(+55).
[15] Midrex Direct Reduction Corporation. 1994 World direct reduction statistics. Charlotte, NC: Midrex, 1995.
[16] International Iron and Steel Institute. Statistics on energy in the steel industry. Brussel: IISI, 1990 (1990 update).
[17] Chatterjee A. The steel industry in India. Ironmaking Steelmaking 1996;23(4):293–302.
[18] International Iron and Steel Institute (IISI). IISI web site: http://www.worldsteel.org/steeldatacentre/lgcountry.htm. Brussels: IISI; 1999.
[19] Ministry of Metallurgical Industry. Yearbook of iron and steel industry of China. Beijing: MMI, 2000.
[20] Energy Research Institute. Chinese steel input data for INEDIS database. Beijing: Energy Research Institute, State Development Planning Commission of China, 1999.
[21] Li S, Wang Z. Present and future status of Chinese steel industry in the 21st century. Iron Steel Eng. 1999;August.
[22] China Online. China ranks No. 1 in iron and steel output in '00. 9 February 2001. http://www.chinaonline.com.
[23] South China Morning Post (SCMP). Consumption seen outpacing demand in rest of world. 5 October 2000. http://www.scmp.com.
[24] Ministry of Metallurgical Industry. Yearbook of iron and steel industry of China. Beijing: MMI, 1994.
[25] Ministry of Metallurgical Industry. Yearbook of iron and steel industry of China. Beijing: MMI, 1998.
[26] Joint Study Team. China: issues and options in greenhouse gas control. Washington, DC: The World Bank, 1994.
[27] China Daily. China to close down 50 small steelworks. 29 June 2000. http://www.chinadaily.com.cn.
[28] China Online. Steel industry growth down from average. 4 October 2000. http://www.chinaonline.com.
[29] Ministry of Metallurgical Industry. Yearbook of iron and steel industry of China. Beijing: MMI, 1999.
[30] Ross M, Liu F. The energy efficiency of the steel industry of China. Energy 1991;16(5):833–48.
[31] Phylipsen GJM, Blok K, Worrell E. Handbook on international comparisons of energy efficiency in the manufacturing industry. Utrecht, The Netherlands: Department of Science, Technology and Society, Utrecht University, 1998.
[32] Ministry of Metallurgical Industry. Statistics of the iron and steel industry of China. Beijing: MMI, 1986.
[33] Ministry of Metallurgical Industry. Statistics of the iron and steel industry of China. Beijing: MMI, 1993.
[34] State Statistical Bureau. China energy statistical yearbook. Beijing: China Statistical Publishing House, 1986.
[35] State Statistical Bureau. China energy statistical yearbook. Beijing: China Statistical Publishing House, 1989.
[36] State Statistical Bureau. China energy statistical yearbook. Beijing: China Statistical Publishing House, 1991.
[37] State Statistical Bureau. China energy statistical yearbook. Beijing: China Statistical Publishing House, 1997.
[38] Sinton JE. Accuracy and reliability of China's energy statistics. China Econ Rev 2001; December.
[39] Farla JCM, Blok K. The quality of energy intensity indicators for international comparisons in the iron and steel industry. Energy Policy 2001;29:523–43.

[40] Intergovernmental Panel on Climate Change. Revised 1996 IPCC guidelines for national greenhouse gas inventories: workbook. Geneva: IPCC, 1996.

[41] Price L, Worrell E, Khrushch M. Sectoral trends and driving forces of global energy use and greenhouse gas emissions: focus on buildings and industry. Berkeley, CA: Lawrence Berkeley National Laboratory, 1999 (LBNL Report 42817).

[42] United Nations. United Nations framework convention on climate change. Geneva: United Nations Environment Program/World Meteorological Organization, 1992.

[43] Martin N, Worrell E, Schipper L, Blok K. International Comparisons of Energy Efficiency: Workshop Proceedings. Berkeley, CA: Lawrence Berkeley National Laboratory, 1994 (6–9 March).

[44] Phylipsen GJM, Nyboer J, Oliver JT, Pape A, Worrell E, Blok K. Proceedings of the Workshop on Methodologies for International Comparisons of Industrial Energy Efficiency. Vancouver, BC: Simon Fraser University, 1996 (1–2 April).

[45] Maarland G, Andres RJ, Boden TA, Johnston C, Brenkert A. In: Global, regional, and national CO2 emission estimates from fossil fuel burning, cement production, and gas flaring. Oak Ridge, TN: Oak Ridge National Laboratory ; 1999. p. 1751–996 (http://cdiac.esd.ornl.gov/ndps/ndp030.html).

[46] Asian Development Bank. Market-based industrial energy conservation and environmental improvement project (final report). TA No. 2675-PRC. Manila: Asian Development Bank; 1998.

[47] Li GT, Jiang HH. Tigao jieneng jiangdi chengben tigao gangtie qiye jingzhengli (Raise competitiveness of iron and steel enteprises by raising energy efficiency and reducing costs). Zhongguo Nengyuan (Energy of China) 1999;110:26–8.

[48] Liu Z, Liu J, Wang Y. Energy consumption in the iron and steel industry in P.R. China. Energy Sustainable Dev 1996;III(3), September.

[49] Li G, Zeng G. Overview of the energy efficiency policies and regulations in energy-intensive sectors of China. In: Proceedings of Learning from International Best Practice Energy Policies in the Industrial Sector. 2000. (Beijing, 22–23 May).

[50] Hu XL, Xin DG, Qu sY. Comparative study on standard energy consumption in high energy using industries between China and other countries. Beijing, 1997: Center for Energy, Environment and Climate Change Research, Energy Research Institute, 1997.

[51] Price L, Phylipsen D, Worrell E. Energy use and carbon dioxide emissions in the steel sector in key developing countries. Berkeley: Lawrence Berkeley National Laboratory, 2001 (LBNL-46987).