ENERGY EFFICIENCY IN THE UNITED STATES IRON AND STEEL INDUSTRY: AN INTERNATIONAL PERSPECTIVE

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ABSTRACT

Energy consumption of the U.S. iron and steel industry is compared to that in Brazil, China, France, Germany, Japan, Korea, and Poland. We show that there was a general trend towards a reduction in the energy used per tonne of steel produced between 1971 and 1994 in most countries. However, in the U.S., Japan, France, and Poland this decreasing trend appears to have reversed in the early 1990s and we recommend further analysis to determine the factors contributing to this reversal. Using a decomposition analysis based on physical indicators for process type and product mix, we show that specific energy consumption decreased significantly in the U.S., Germany, and China between 1980 and 1991. In the U.S., about two-thirds of this decrease was due to efficiency improvements, while the remainder was due to structural changes. A structural/efficiency analysis shows that China, Brazil, Poland, and the U.S. have the largest potential for energy savings in the iron and steel industry.

INTRODUCTION

In this paper, we compare energy consumption in iron and steelmaking in the U.S. to that in Brazil, China, France, Germany, Japan, Korea, and Poland.* Steelmaking is one of the largest energy-using and most energy-intensive industrial subsectors and more than half of the world's steel production occurs in the eight countries analyzed in this paper.[2] Data on production levels, processes, and energy use are generally available for the iron and steel subsector, making it possible to analyze national trends and produce international comparisons of the energy intensity of steelmaking on a physical basis (e.g. per tonne of product).[3] We make international comparisons following the methodological recommendations from two workshops and a handbook on international comparisons of industrial energy efficiency.[4,5,6] These comparisons can be used to analyze differences in trends between countries as well as to identify opportunities for efficiency improvement, both of which are especially important in light of the current international climate change treaty negotiations.

To make such comparisons, we calculate the specific energy consumption or SEC (energy used per tonne of steel produced) for the eight countries between 1971 and 1993/94 to observe both national trends and the relative differences between countries. We also calculate a structure-adjusted SEC to make the same comparisons holding structure constant. We then perform a decomposition analysis to distinguish changes in activity, structure, and energy intensity among the countries. One example of intra-sectoral structural change – increased use of scrap in steelmaking – is also examined using a structure/efficiency analysis. Finally, we conclude with a discussion of the trends and developments in this industry in the U.S.

DATA COLLECTION, DEFINITIONS, AND METHODOLOGY

We examine three basic elements of energy use in iron and steelmaking: activity, structure, and energy intensity. Activity is defined as production of crude steel. Structural factors include the feedstock type (iron ore and scrap) and product mix (slabs, hot rolled steel, cold rolled steel). Energy intensity, or specific energy consumption (SEC) (e.g. GJ/tonne), is the result of the efficiency of the steelmaking process used. Steel is produced using iron ore (with some scrap additions) in an old-fashioned open hearth furnace (OHF) or a basic oxygen furnace (BOF). Scrap-based steel production relies on the use of an electric arc furnace (EAF).

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* Data are for the former Federal Republic of Germany until 1990; from 1991 to 1994 German data also include former East Germany. Portions of this paper are based on an article that is forthcoming in Energy Policy.[1]

Energy is measured as the consumption of primary energy carriers. Fuel inputs (coal, oil products, gas) are calculated on the basis of lower heating values, as is common in International Energy Agency (IEA) statistics. Cokemaking has not been taken into account in the analysis as coke production is a separate sector in many statistics. Energy consumption of cokemaking may vary, as well as the coke input rates in the blast furnaces.[7] We use data from the International Iron and Steel Institute (IISI)[2] and national statistics for energy use and production data for Brazil, China, France, Germany, Japan, Korea, Poland, and the U.S.[1]

Primary values for electricity generation were calculated by multiplying electricity consumption by the world average efficiency (33% in 1990),[8] in order to highlight the changes and differences in energy intensities in the iron and steel industry, rather than those in the electricity sector of a country. Using such a standard conversion efficiency makes the comparisons of trends in the iron and steel sector more transparent, but can obscure changes in electricity generation efficiencies over time and differences between countries. This can be problematic for countries like Brazil that produce electricity predominantly from hydroelectric sources. The effects of cogeneration (also referred to as combined heat and power, CHP) are also obscured with a standard electricity conversion efficiency. Varying the electricity generation efficiency will change the analysis results (see "Decomposition analysis" and Table 4).

Specific energy consumption

Specific energy consumption (SEC) is defined as the amount of energy needed to execute a certain activity (e.g. the production or processing of a specific product) expressed in physical terms. For this study, activity is the production of a tonne of a certain steel product. The aggregated SEC is calculated by dividing total primary energy consumption in the iron and steel industry by total production. The SEC is influenced by the production process (including feedstock), the type of products produced, and the energy efficiency of the production process. The primary energy carrier used can also affect the energy efficiency (e.g. in boilers). We do not consider the variety of fuels available, but treat fuels as one single energy carrier in determining the potential for energy efficiency improvement, since most iron and steel industries are assumed to have market access to most types of energy carriers in the selected countries, and coal and coke are the dominant fuels in this sector.

The most important input-factor influencing energy consumption in the iron and steel industry is the feedstock: iron ore and scrap for primary steel or scrap only for secondary steel. We do not include direct reduction in this study because of its small contribution to iron production in the investigated countries.[2] The production of primary steel consumes more energy but produces a higher quality steel. In the BOF-process the amount of scrap used is different for each plant. Scrap use (instead of pig iron) is both a technical and an economic issue. The quality of the steel may be influenced by impurities in the scrap, although the introduction of ladle refining technologies improves quality control of the product. Scrap prices have increased due to the increasing share of EAF production in steelmaking worldwide, making pig iron relatively less expensive.

The main output-factor influencing energy consumption is the product type. We have aggregated the various product types into three categories that represent the most important product categories, from the perspective of energy consumption: ingots and slabs, hot rolled steel (including plates, strip, wire (rod), and long steel products) and cold rolled products (cold rolled sheet and strip). Production is defined as the total output of usable ingots, continuously cast semi-finished products, and liquid steel for castings. Steel production is allocated to categories on the basis of deliveries.[2] Finishing (e.g. galvanizing, annealing) has not been accounted for in the analysis. This introduces an uncertainty in the calculations, depending on the share of finished product and the SEC of annealing or galvanizing (roughly equal to 0.4 GJ/tonne finished steel).[9] For the selected countries the uncertainty in the SEC due to finishing is less than 1%.[1]

Decomposition analysis methodology

We have followed the simple average parametric Divisia decomposition methodology to understand the factors that contribute to the SEC.[10] Because product types change over time and differ by country, a weighting factor is used to calculate a physical production index (PPI) instead of simply summing all steel products (Formula 1):

$$PPI = \sum_{x=1}^{n} (P_X \times W_X) \qquad (1)$$

In this calculation, production (P) of commodity *x* is weighted with a weight factor (W). The weight factors are based on the energy used to produce each steel product using existing best practice. We assign weight factors for production of slabs and ingots by both the BOF and EAF processes, for production of hot rolled steel, and for production of cold rolled steel. The weighting factors are provided in Table 1. Thus, for any given year and country, the amount of steel produced through the BOF (or OHF) process is multiplied by 15.3 GJ/tonne, the amount of steel produced through the electric arc process is multiplied by 5.4 GJ/tonne, the amount of hot rolled steel is multiplied by 2.9 GJ/tonne, and the amount of cold rolled steel is multiplied by 2.7 GJ/tonne.

Table 1. "Best Practice" Weighting Factors for Various Steel Products Used in the Decomposition Analysis.

Product	Fuel (GJ/tonne)	Electricity (GJ/tonne)	Primary energy (GJ/tonne)[c]
Basic Oxygen Furnace - Slab[a]	14.24	0.36	15.3
Electric Arc Furnace - Slab[b]	0.79	1.52	5.4
Hot Rolling[c]	1.82	0.37	2.9
Cold Rolling[d]	1.10	0.53	2.7

Notes:

a Equivalent to the 1988 SEC of an integrated steel plant in The Netherlands, assuming 10% scrap addition in the BOF.[11]

b Equivalent to the SEC of an EAF plant in Germany[12] and the SEC for continuous casting equivalent to the integrated steel plant.[11]

c Equivalent to the 1988 SEC of a hot strip mill at an integrated steel plant in The Netherlands.[11] The SEC of wire rod production is comparable to the given SEC.[13]

d Equivalent to the 1988 SEC of a cold rolling mill at an integrated steel plant.[11]

c Calculated SEC assuming an electricity generation efficiency of 33%.

The total energy consumption of the sector is a function of the volume of the output (activity), the process and product mix (structure), and the energy efficiency of the production processes (efficiency). This is expressed by formula 2, in which P, a simple summation of the production outputs, is the parameter for activity, PPI/ΣP reflects the process and product mix of the output (structure), and ΣE/PPI is an indicator for the energy efficiency of the manufacturing processes:

$$\sum E = \sum P \times \frac{PPI}{\sum P} \times \frac{\sum E}{PPI} \quad (2)$$

With the index decomposition, the influences of changes in activity (ACT), structure or product mix (STR), and efficiency (EFF) on the energy consumption can be calculated according to the following relationship (between year 0 and year T) given by formula 3, in which R is a residual term:

$$\Delta E_{0,T} = \Delta E_{0,T}(ACT) + \Delta E_{0,T}(STR) + \Delta E_{0,T}(EFF) + R \quad (3)$$

Structure/efficiency analysis methodology

We use a structure/efficiency analysis to show the SEC as a function of the share of scrap.[14] We plot both the actual SEC and a "best practice" SEC (SEC_{BP}) which is calculated on the basis of the physical production index (PPI) and the SEC_{BP} for each of the products, as presented in Table 2.* The difference between the actual SEC and estimated SEC_{BP} for a given year presents an estimate of the energy efficiency improvement potential (relative to the chosen "best practice" technologies in a specific year), and hence measurement of the energy efficiency.[14] The structure/efficiency analysis helps to explain the observed changes in energy use in a sector and countries, as a function of intra-sectoral structural changes and inter-country differences.

* In the analysis of the SEC_{BP} (and the weighting factors used) we assumed a hot metal charge rate of 90% in the BOF. For most countries the hot metal charge is lower (except for Japan), which leads to lower pig iron use per tonne of steel, and hence a lower SEC_{BP} for a country or year. As we have assumed a constant charge rate changes in the hot metal charge rate are accounted as an efficiency effect in the decomposition analysis. For most countries the hot metal charge rate has not changed much,[7] and hence in most cases we underestimate the potential for energy savings. However, in France for the period 1980 - 1991 the hot metal charge rate increased from 79% to 86%.[7] This constitutes an important contribution to the negative development of the energy efficiency shown in Figure 4.

ANALYSIS RESULTS

Steel production

Steel production, as shown in Figure 1, varied significantly in the eight countries between 1971 and 1994. In the U.S., steel production dropped by an average of 2.4% per year during that period. U.S. production fluctuated between 104 and 138 Mtonnes until 1982 when it dropped to 68 Mtonnes due to collapsing markets, bankruptcies, and mill closings.[15] Production slowly increased to 91 Mtonnes in 1994, but over the entire 1971 to 1994 period production dropped 1% per year on average. In contrast, steel production remained nearly constant in Germany and Japan and increase dramatically in Korea (on average 19.7% per year), China and Brazil (6.5%/yr. in both countries). Both France and Poland experienced decreases in production (of 1% and 0.6% per year, respectively) over the period. The decrease in Poland is a result of the economic restructuring that began in the late 1980s that lead to a considerable decreased capacity utilization.

Crude steel production volumes and shares of the different production processes in 1994 for the countries analyzed in this paper are given in Table 2. With the exception of China and Poland, the countries studied have abandoned the old-fashioned, energy-intensive OHF method of steelmaking. The U.S. has the highest share of scrap-based electric arc furnaces, followed closely by Korea, France, and Japan. Over 90% of steel is produced using the more energy-efficient continuous casting process in France, Germany, Japan, and Korea. The U.S. has a slightly lower amount of continuous casting (89%). The amount of steel continuously cast in Brazil, China, and especially Poland, is significantly less.

Figure 1. Steel Production in Selected Countries, 1971 to 1994 (Mt).

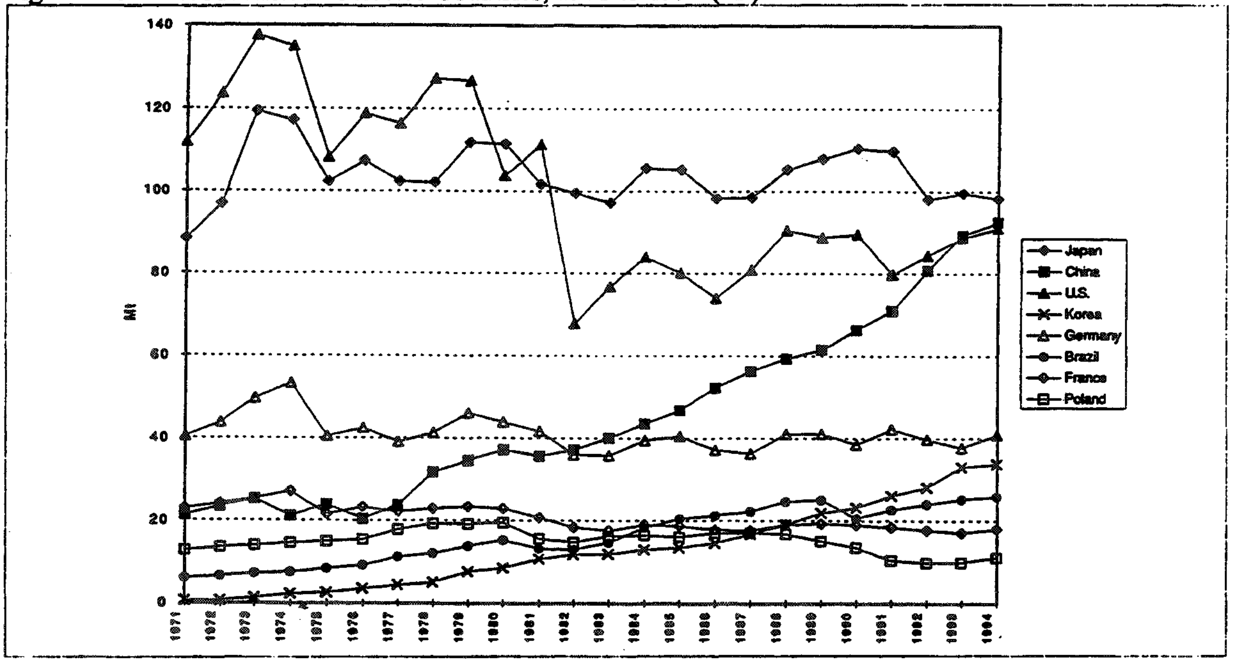


Table 2. Crude Steel Production and Shares of Iron and Steel Production Processes in Selected Countries in 1994.[2]

	Crude steel (Mtonnes)	Open Hearth Furnace	Basic Oxygen Furnace	Electric Arc Furnace	Continuous Casting
Brazil	25.75	2%[a]	78%	20%	59%
China	92.61	15%	64%	21%	34%[b]
France	18.03	0%	66%	34%	96%
Germany	40.84	0%	78%	22%	96%
Japan	98.30	0%	69%	31%	96%
Korea	33.74	0%	64%	36%	92%
Poland	13.63	29%	53%	18%	8%
U.S.	91.23	0%	61%	39%	89%

Notes:

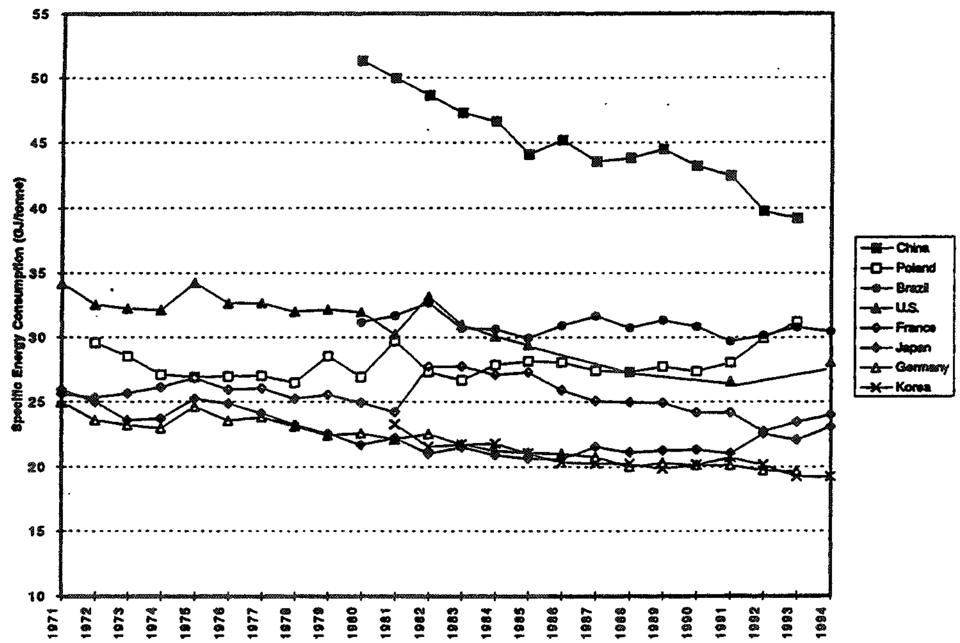
a The Brazilian industry includes 2% of other (not Open Hearth Furnace) steelmaking processes.

b Data are from 1993.

Specific energy consumption trends

We calculate the SEC for iron and steel production in the eight countries by dividing primary energy consumption in the iron and steel industry by total crude steel production. These SECs are plotted in Figure 2 and show a general trend towards a reduction in SECs in most countries over the study period. We found that iron and steel production is least energy-intensive in Korea, Germany, Japan, and France and most energy-intensive in China.* The SEC for the U.S. dropped over 20%, from 34.2 GJ/tonne to 26.9 GJ/tonne, between 1971 and 1994. However, the 1994 SEC is slightly higher than the 26.5 GJ/tonne value in 1991, indicating a change in the longer-term trend of decreasing energy use per tonne of steel.** Japan, Poland, and France also show a slight increase in SECs in recent years. Further research is needed to determine the reasons behind these increased intensity levels.

Figure 2. Specific Energy Consumption for Steel Production in Selected Countries (GJ/tonne).



We also calculated structure-adjusted SECs for most of these countries for the period 1980 to 1991 to account for differences in structure (feedstock and product mix) between countries and over time as measured by the PPI. Such structure-adjusted SECs, which hold each country's structure constant at its 1980 level, make it possible to more closely compare the energy intensities without the disturbance of differences and changes in structure. The SECs and the structure-adjusted SECs were essentially the same for all countries except the U.S. and France, two countries where structural change towards increasing use of scrap had a major influence on the SEC. The structure-adjusted SECs for these two countries are about 1 to 2 GJ/tonne higher than the unadjusted SECs, indicating that a large portion of the decrease in SEC in these countries came through increased production of secondary steel.

Decomposition analysis

The decomposition analysis summarizes the relative influence of changes in structure and efficiency on the SEC in iron and steelmaking. Figure 3 and Table 3 present the relative changes in the primary energy consumption between 1980 and 1991. The first bar for each country represents the aggregate change in SEC

* In comparing the efficiency of the Chinese steel industry to the other countries, it should be noted that the use of cast iron is relatively high in China and that energy is also used for so-called "non-productive use" such as residential energy use by employees and energy use for mining of raw materials. Correcting for the latter two factors may lead to 5-6% lower energy consumption in the Chinese iron and steel industry.[16]

** This SEC is calculated using energy use data from the U.S. Manufacturing Energy Consumption Survey (MECS).[17] We note that energy use data of the American Iron and Steel Institute show a continuing decline in SEC between 1990 and 1994.[18]

between 1980 and 1991. The second and third bars represent the contribution of efficiency and structural changes, respectively, to the overall change in SEC during the period. The sum of the efficiency and structural changes equals the change in the overall SEC for the period. Table 3 presents the changes in actual values (GJ/tonne), as well as relative percentage changes. Of the countries which experienced the largest decline in intensity (China, Germany, U.S.), energy efficiency improvements accounted for the majority of the change. Efficiency improvements played a major role in Brazil, China, Germany, and the United States, while structural changes were the major driver for energy savings in France and Japan.

Figure 3. Relative Changes in SEC, Structure, and Efficiency Between 1980 and 1991 for Selected Countries.

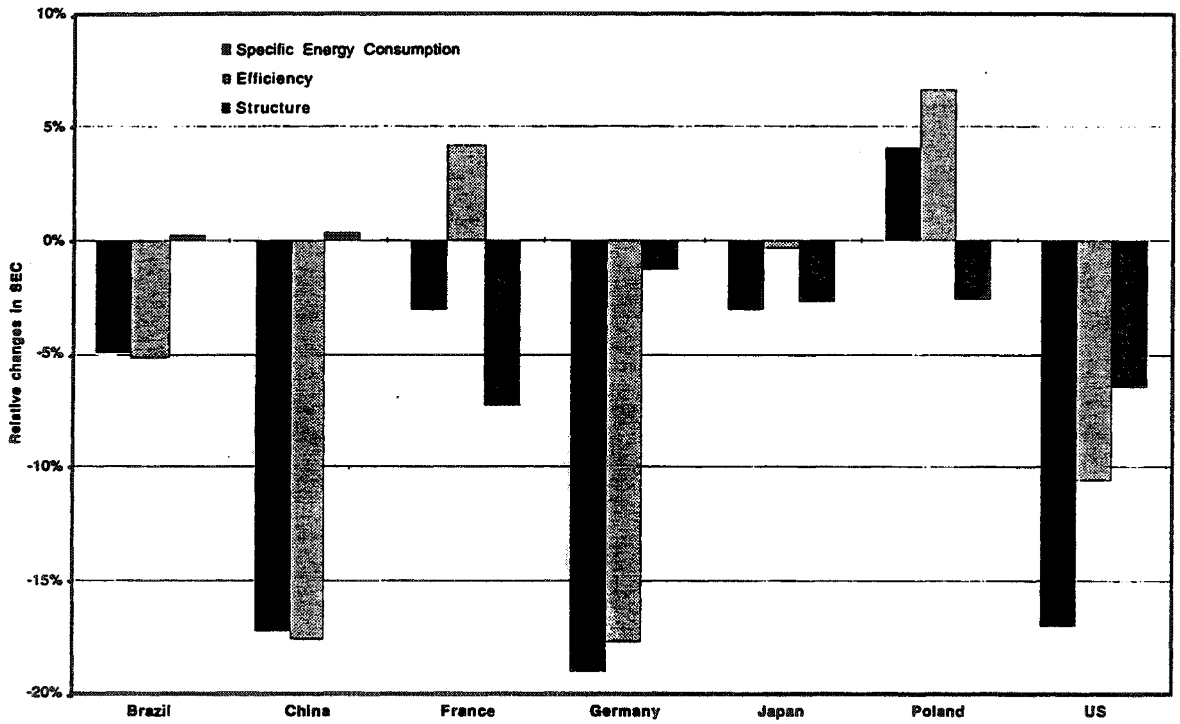


Table 3. Changes in Specific Energy Consumption (SEC) Between 1980 and 1991 and the Influence of Structure and Efficiency Developments in Seven Countries (Relative Changes in Percents).

	SEC 1980 (GJ/tonne)	Structure (GJ/tonne)	Efficiency (GJ/tonne)	SEC 1991 (GJ/tonne)
Brazil	31.2	0.1 (+0%)	-1.6 (-5%)	29.7 (-5%)
China	51.3	0.2 (+0%)	-9.0 (-18%)	42.4 (-17%)
France	24.9	-1.8 (-7%)	1.1 (4%)	24.2 (-3%)
Germany	22.6	-0.3 (-1%)	-4.0 (-18%)	18.3 (-19%)
Japan	21.7	-0.6 (-3%)	-0.1 (-0%)	21.0 (-3%)
Poland	26.9	-0.7 (-3%)	1.8 (7%)	28.0 (4%)
U.S.	32.0	-2.1 (-6%)	-3.4 (-11%)	26.5 (-17%)

Note: The figures are based on an electricity generation efficiency of 33% across countries during the study period.

We have analyzed the effects of changing the electricity generation efficiency on the results of the decomposition analysis.[1] The results, provided in Table 4, show that a higher electricity generation efficiency will increase the total change in SECs for all countries, leading to a larger difference between the observed SECs of 1980 and 1991. Both the effects of structural change and efficiency improvement increase. Higher electricity generation efficiency generally seems to lead to a larger contribution of structural change to the total savings in the observed SEC. However, for Japan it leads to a higher contribution of energy efficiency improvement, although the role of structural change in total development remains dominant.

Table 4. Effects of Varying Electricity Generation Efficiency on the 1980-1991 Results of the Decomposition Analysis.

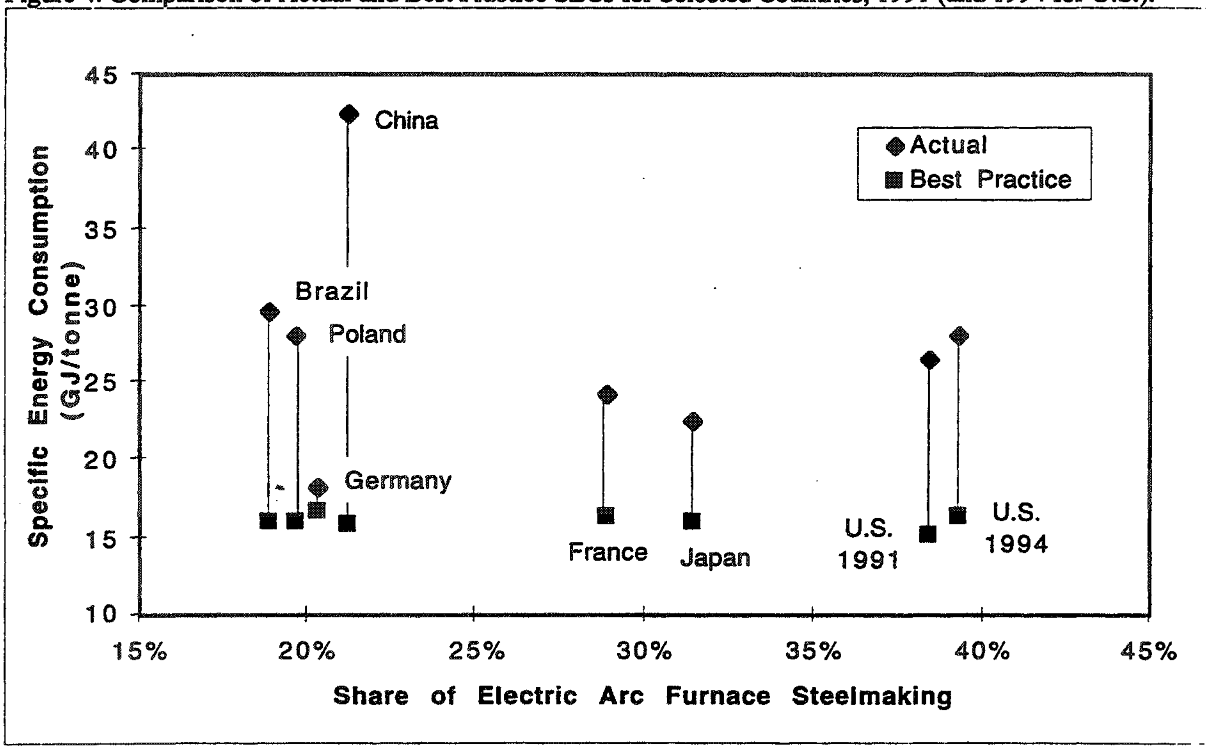
	Specific Energy Consumption		Structure		Efficiency	
Electricity Efficiency	30%	50%	30%	50%	30%	50%
Brazil	-1.6%	-1.6%	-0.1%	1.4%	-1.5%	-3.0%
China	-17.0%	-18.3%	+0.4%	-0.0%	-17.4%	-18.3%
France	-2.9%	-3.7%	-6.7%	-9.3%	+3.9%	+5.6%
Germany	-18.5%	-20.4%	-1.1%	-2.1%	-17.4%	-18.3%
Japan	-2.6%	-4.5%	-2.5%	-3.8%	-0.2%	-0.7%
Poland	+4.9%	+1.8%	-2.3%	-3.2%	+7.2%	+5.0%
U.S.	-16.8%	-17.6%	-6.1%	-7.8%	-10.7%	-9.9%

Note: The effects are expressed for the observed developments for electricity generation efficiencies of 30% and 50% for the seven studied countries. Compare the results to Table 3.

Structure/efficiency analysis

The share of secondary (EAF) steelmaking is used as an indication of the changes in the structure (scrap as a feedstock) in the structure/efficiency analysis. Figure 4 depicts the actual SEC and the "best practice" SEC for 1991 relative to the share of secondary (EAF) steelmaking for the studied countries. The U.S. has the highest share of EAF steelmaking (38% in 1991, 39% in 1994), while Germany, Poland, Brazil, and China have relatively low shares. The difference between the SEC and SEC_{BP} reflects the potential energy savings relative to the "best practice" technologies as applied to each country's product mix. China, Brazil, Poland, and the U.S. have the largest potential energy savings, while France, Japan, and especially Germany have lower potentials. Potential energy savings for Germany may have increased since 1991 due to the unification with former East Germany.

Figure 4. Comparison of Actual and Best Practice SECs for Selected Countries, 1991 (and 1994 for U.S.).



TRENDS IN THE U.S. IRON AND STEEL INDUSTRY

Crude steel production in the U.S. decreased dramatically in the beginning of the 1980s, dropping from 111 Mtonnes in 1981 to 68 Mtonnes in 1982. Bankruptcies and mill closings characterized the industry in the 1980s. However, there has been steady growth since then, leading to production of 91 Mtonnes in 1994. Current capacity utilization is over 90%.

Between 1971 and 1994, the SEC in the U.S. iron and steel industry dropped 21%. About two-thirds of this decrease was due to efficiency improvements, while the remainder was due to structural changes. The most important change was the growing use of scrap-based electric arc furnaces, which grew from 17% to 39% of total steel production during this period. Efficiency improvement can be explained mainly by the increasing continuous casting ratio (from 0% in 1971 to 89% in 1994) and the closing of inefficient OHF steelmaking (the production share decreased from 30% in 1971 to 0% after 1991). Also the increased use of pellets as blast furnace feed contributed to the energy savings.[2]

Despite these overall improvements, the SEC increased slightly between 1991 and 1994, growing from 26.5 GJ/tonne to 26.9 GJ/tonne, reversing the long-term downward trend. During that period, annual production grew from 80 Mtonnes to 91 Mtonnes. Based on trends in three key areas (increased share of electric arc furnaces from 38% to 39%, retirement of all remaining OHF plants, and increase in the continuous casting ratio from 76% in 1991 to 89% in 1994), we would expect the overall energy intensity to decrease. However, it appears that U.S. energy use per tonne of steel is high in the blast furnace, the basic oxygen furnace (due to the lack of BOF gas recovery), the reheating furnace, and in the hot strip mill when compared to best practice in other countries.[11, 18] Other trends that may have contributed to the increased energy use include a move toward more extensively treated (cold rolled) steel and increased capacity utilization leading to the use of older, less-efficient integrated steel mills.

CONCLUSION

We found that although the U.S. experienced a significant decline in energy used per tonne of steel produced between 1971 and 1994, this trend has reversed slightly in the 1990s. In addition, we found that the U.S. SEC is high compared to that of other industrialized countries, including Korea. Further, we found that despite the high share of electric arc furnace use, the U.S. still has a large gap between the 1994 SEC of 27 GJ/tonne and the best practice SEC of 16 GJ/tonne that we calculated based on the U.S. steel industry characteristics.

From this analysis it appears that the general downward trend in energy used to produce a tonne of steel has also reversed in a number of other countries in the 1990s. While this reversal can be explained for Poland (due to the economic restructuring), further analysis is needed to more clearly understand the forces underlying this trend in the U.S., Japan, and France.

ACKNOWLEDGMENTS

This work was supported by both the Climate Policies and Programs Division in the Office of Economy and the Environment, U.S. Environmental Protection Agency and the U.S. Department of Energy Climate Change Research Assessment Program through the U.S. Department of Energy under Contract Number DE-AC03-765F00098. We would like to thank Bart Davis, Daniel Einstein, Marta Khrushch, Jonathan Sinton, and Mike Ting (all from Lawrence Berkeley National Laboratory), Grazyna Berent-Kowalska (Gtówny Urzad Statystyczny), Jeong-Shik Shin (Korean Energy Economics Institute), and Wolfgang Eichhammer (Fraunhofer-ISI) for help with data collection. We would also like to thank Marc Ross (University of Michigan), Lee Schipper (Lawrence Berkeley National Laboratory, on leave to the International Energy Agency), Kornelis Blok (Utrecht University), and Anthony Martocci (Bethlehem Steel Corporation) for comments on previous versions of this paper.

REFERENCES

1. Worrell, E., Price, L., Martin, N., Farla, J., Schaeffer, R., 1997 (forthcoming). "Energy Intensity in the Iron and Steel Industry: A Comparison of Physical and Economic Indicators," *Energy Policy*.

2. International Iron and Steel Institute, 1996. *Steel Statistical Yearbook 1995*, Brussels: IISI.

3. Phylipsen, G.J.M., Blok, K., Worrell, E., 1997 (forthcoming). "Methodologies for International Comparisons of Energy Efficiency in the Manufacturing Industry," *Energy Policy*.

4. Martin, N., Worrell, E., Schipper, L., Blok, K., 1994. *Workshop Proceedings: International Comparisons of Energy Efficiency*, Berkeley, CA: Lawrence Berkeley National Laboratory, March 6-9.

5. Phylipsen, G.J.M., Nyboer, J., Oliver, J.T., Pape, A., Worrell, E., Blok, K., eds. 1996. *Proceedings of the Workshop on Methodologies for International Comparisons of Industrial Energy Efficiency*, Vancouver, BC: Simon Fraser University, April 1-2.

6. Phylipsen, G.J.M., Blok, K., Worrell, E., 1996 (draft). *Handbook on International Comparisons of Energy Efficiency in the Manufacturing Industry*. Utrecht: Utrecht University.

7. International Iron and Steel Institute, 1990. *Statistics on Energy in the Steel Industry (1990 Update)*, Brussels: IISI.

8. Faaij, A., Blok, K., and Worrell, E., 1995. *Worldwide Comparison of Efficiency and Carbon Dioxide Emissions of Public Generation*, Dept. Of Science Technology & Society, Utrecht University, Utrecht, The Netherlands.

9. Novem, 1991. Stralingsverhitter met Warmteterugwinning (Radiative Heater with Heat Recovery) Demonstration Project Result 282, Novem bv, Utrecht, The Netherlands.

10. Farla, J., Blok, K. and Schipper, L., 1997 (forthcoming). "Energy Efficiency Developments in the Pulp and Paper Industry: A Cross-Country Comparison Using Physical Production Data," *Energy Policy*.

11. Worrell, E., de Beer, J. and, Blok, K., 1993. "Energy Conservation in the Iron and Steel Industry" in: P.A. Pilavachi (ed.), *Energy Efficiency in Process Technology*, Amsterdam: Elsevier Applied Science.

12. Teoh, L., 1989. "Electric Arc Furnace Technology: Recent Developments and Future Trends," *Ironmaking and Steelmaking*, **16** (303).

13. International Iron and Steel Institute, Committee on Technology, 1982. *Energy and the Steel Industry*, Brussels, Belgium.

14. Worrell, E., Cuelenaere, R., Blok, K. and Turkenburg, W., 1994. "Energy Consumption of Industrial Processes in the European Union" *Energy, the International Journal* **19** (11) 1113-1129.

15. U.S. Environmental Protection Agency, 1995. *Profile of the Iron and Steel Industry*, Washington, DC: U.S. EPA (EPA/310-R-95-005).

16. Ross, M. and Feng, L., 1991. "The Energy Efficiency of the Steel Industry in China," *Energy* **16** (5) 833-848.

17. U.S. Department of Energy, Energy Information Administration, 1997. *Manufacturing Energy Consumption Survey, 1994*, Form EIA 846, Washington, DC: U.S. EIA.

18. U.S. Department of Energy, Office of Industrial Technologies, 1996. *Energy and Environmental Profile of the U.S. Iron and Steel Industry*. Prepared by Nancy Margolis of Energetics, Inc. Washington, DC: U.S. DOE.