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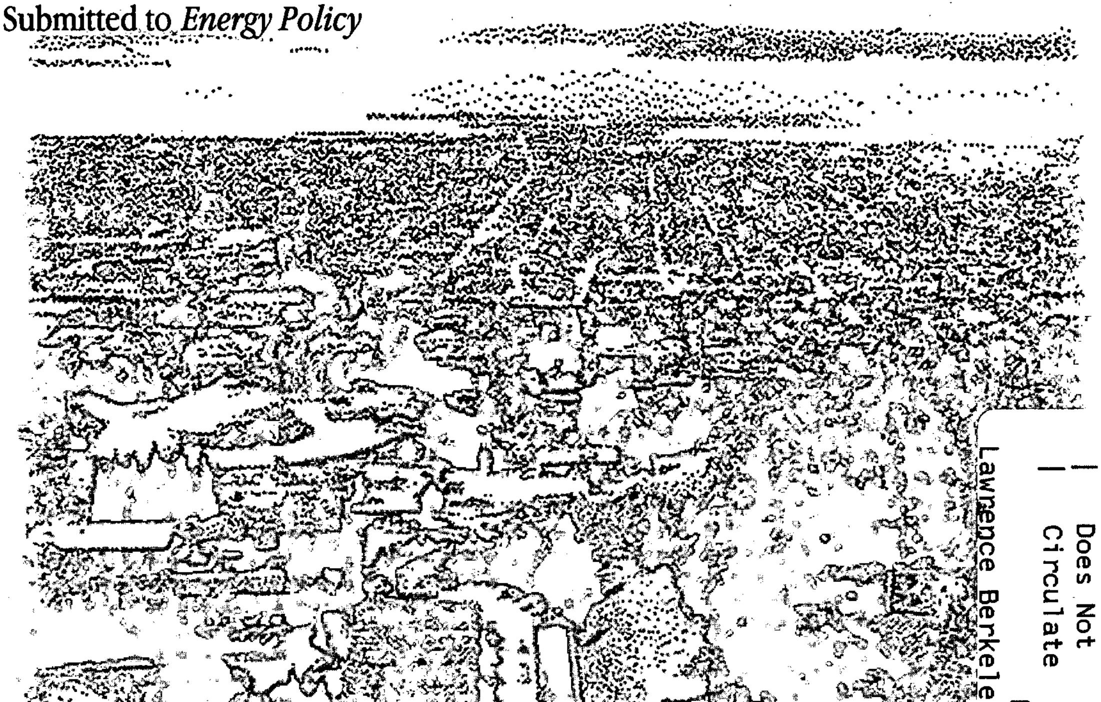

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ENERGY INTENSITY IN THE IRON AND STEEL INDUSTRY: A COMPARISON OF PHYSICAL AND ECONOMIC INDICATORS

Ernst Worrell, Lynn Price, Nathan Martin, Jacco Farla, and Roberto Schaeffer

Energy consumption of the iron and steel industry is examined in seven countries (Brazil, China, France, Germany, Japan, Poland, and the United States) for the period 1980-1991. Using a decomposition analysis based on physical indicators for process type and product mix, we decompose intra-sectoral structural changes and efficiency improvements. Specific energy consumption decreased in all countries except Poland. Efficiency improvement played a key role in Brazil, China, Germany and the U.S., while structural changes were the main driver for energy savings in France and Japan. We also compare the use of various economic indicators to physical indicators and find that they do not track physical developments well in Poland or the developing countries we studied. In the industrialized countries, value added based energy intensity indicators generally reflect the specific energy consumption better than other economic indicators, although large differences occur in individual years. We found a smaller correlation between other economic indicators (gross output and value of shipments) and specific energy consumption. We conclude that use of physical energy intensity indicators improves comparability between countries, provides greater information for policymakers regarding intra-sectoral structural changes, and provides detailed explanations for observed changes in energy intensity.

In 1992, participants of the United Nations Framework Convention on Climate Change (UNFCCC) committed to develop national policies and measures to reduce emissions of greenhouse gases. For industrialized countries (including Eastern European countries and the former Soviet Union) — these are the Annex 1 countries as defined by the UNFCCC — this commitment involved setting voluntary national emission reduction targets. Industrialized countries further agreed to provide assistance, in the form of financial resources and technology transfer, to assist developing countries in meeting their goals (UNEP, 1992). A Ministerial Declaration signed in July 1996 by 134 countries calls for the establishment of legally binding targets for overall greenhouse gas emissions reductions to be established at the third Conference of the Parties in 1997. Establishing effective greenhouse gas mitigation policies requires detailed knowledge regarding past emissions trends, opportunities and potentials for mitigation, and the effectiveness of policies and measures designed to reduce these emissions. Over 45% of global greenhouse gas emissions are the result of production and use of energy to provide power for the world's industrial, buildings, and transport sectors (NAS, 1992). In 1992, industry used 43% of global primary energy (WEC, 1995).

In this paper, we focus on measuring energy consumption in iron and steelmaking, one of the largest energy-using and most energy-intensive industrial subsectors, in seven countries: Brazil, China, France, Germany,* Japan, Poland, and the United States (U.S.). About half of the world's steel production occurs in these countries (IISI, 1992). 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 make international comparisons of the energy intensity of steelmaking on a physical basis (e.g. per tonne of product).

Using physical intensity indicators, we perform a decomposition analysis to distinguish changes in activity, structure, and energy intensity in iron and steelmaking. One example of intra-sectoral structural change — increased use of scrap in steelmaking — is also examined using a structure/efficiency analysis. We show that using physical activity indicators improves comparability between countries, provides greater information for policymakers regarding intra-sectoral structural changes, and provides detailed explanations for observed changes in energy intensity.

Depending upon the industrial subsector and the country, physical data are not always available for analysis. In such cases, economic indicators (e.g. energy use per $ value added or per $ of gross output) have been used to track energy use and efficiency trends (Howarth et al., 1991). However, because changes in product mix or process mix are generally not captured in many economic decomposition analyses, it is difficult to analyze changes in the production

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* Data are for the former Federal Republic of Germany only.

structure of an industry using economic indicators. It is unclear whether such economic indicators are appropriate proxies for physical energy use. A review of decomposition studies (Ang, 1995) found large variations between the different output measures, while other studies showed small variations in the results. To determine if the economic indicators accurately track the actual physical trends in the iron and steel industry, we also compare physical production indicators with economic indicators for the same countries.

We begin with a short description of iron and steelmaking technologies. Next we provide a description of the data sources and the methodologies used for our comparisons. The results of our analysis are presented along with a discussion of country-specific trends. We end with conclusions on the applicability of the various indicators as well as recommendations for future analysis.

THE IRON AND STEEL INDUSTRY

Currently there are two main routes for the production of steel: production of primary steel using iron ores and scraps and production of secondary steel using scraps 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. Figure 1 presents a simplified scheme of the production routes. Crude steel production volumes and shares of the different production processes in 1990 for the countries analyzed in this paper are given in Table 1 (IISI, 1992).

Pig iron is produced in a blast furnace, using coke in combination with injected coal or oil, to reduce sintered or pelletized iron ore to pig iron. Limestone is added as a fluxing agent. Coke is produced in coke ovens. Reduction of the iron ore is the largest energy-consuming process in the production of primary steel. Modern blast furnaces are operated at various scales, ranging from mini blast furnaces (capacity of 75 Ktonnes/year) to the largest with a capacity of 4 Mtonnes/year. Reduction of the coke demand by injection of fuels reduces the energy consumption for coke making and the capital demand for the coke ovens. Besides iron, the blast furnace also produces blast furnace gas (used for heating purposes), electricity (if top gas pressure recovery turbines are installed) and slags (used as building materials).

Table 1

Crude steel production volumes and shares of the main iron and steel production processes in selected countries in 1990 (IISI, 1992)

		Furnace			
	Crude steel (Mtonnes)	Basic Oxygen (%)	Open Hearth (%)	Electric Arc (%)	Continuous Casting (%)
Brazil	20.57	74%	2%	24%	58%
China	66.26	59%	20%	21%	22%
France	19.02	72%	0%	28%	94%
Germany	38.42	82%	0%	19%	91%
Japan	110.34	69%	0%	31%	94%
Poland	13.63	53%	29%	18%	8%
U.S.	89.72	59%	4%	37%	67%

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

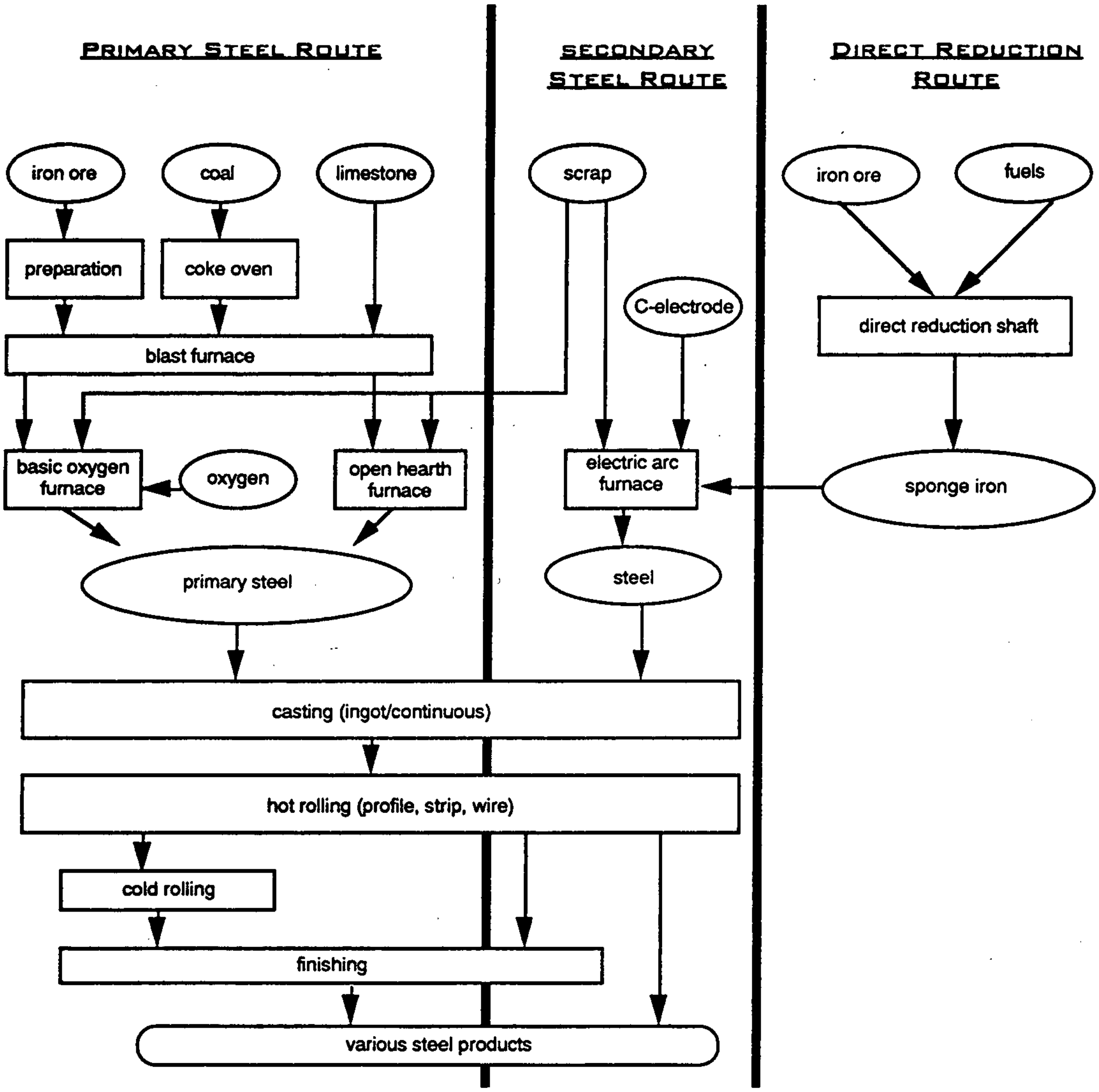
Direct reduced iron (DRI) is produced by reduction of the ores below the melting point in small scale plants (<1 Mtonnes/year) and has different properties than pig iron. DRI production is growing and nearly 4% of the iron in the world is produced by direct reduction, of which over 90% uses natural gas as a fuel (Midrex, 1996). DRI serves as a high-quality alternative for scrap in secondary steelmaking (see below).

Primary steel is produced by two processes: open hearth furnace (OHF) and basic oxygen furnace (BOF). The OHF is still used in different configurations, mainly in Eastern Europe, China, India and other developing countries; of the countries examined in this paper, the OHF process share is high in Poland (29%) and China (20%) (IISI, 1992). While OHF uses more energy, this process can also use more scrap than the BOF process. However, BOF process is rapidly replacing OHF worldwide because of its greater productivity and lower capital costs. 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.

Secondary steel is produced in an electric arc furnace (EAF) using scrap. Scrap is melted and refined, using a strong electric current. DRI can be used to enhance product quality. Several process variations exist, using either AC or DC currents, and fuels can be injected to reduce electricity use. Among the countries we analyzed, high shares of EAF are found in the U.S. (37%), Japan (31%), and France (28%).

Casting and shaping are the next steps in steel production. 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 1990 nearly 60% of global crude steel production was cast continuously (IISI, 1992). The ratio of CCM varies among the countries analyzed in this study, between a low of 8% in Poland and a high of 94% in France and Japan (IISI, 1992). The casted material can be sold as ingots or slabs to steel manufacturing industries. However, most of the steel is rolled by the steel industry to

Figure 1
Steel Production Routes



sheets, plates, tubes, profiles or wire. Generally the steel is first treated in a hot rolling mill. The steel is heated and passed through heavy roller sections reducing the thickness of the steel. Hot rolling produces profiles, sheets, or wire. After hot rolling the sheets may be reduced in thickness by cold rolling. Finishing is the final production step, and may include different processes such as annealing, pickling, and surface treatment. A more advanced technology, near net shape casting, reduces the need for hot rolling because products are cast closer to their final shape.

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 product mix (slabs, hot rolled steel, cold rolled steel) and process type (OHF, BOF, EAF). Energy intensity is analyzed on the basis of both economic energy intensity indicators (e.g. MJ/constant US$) and physical indicators or so-called specific energy consumption (SEC) (e.g., MJ/tonne).

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 (IEA, 1993). Cokemaking has not been taken into account in the analysis as coke production is a separate sector in many statistics. Trade in coke makes it difficult to assess the efficiency of cokemaking and account to a specific country or steel plant. Energy consumption of cokemaking may vary, as well as the coke input rates in the blast furnaces (IISI, 1990).

Steel production data for France, Germany, Japan, and the U.S. are from IISI (1992). Production data for Brazil are from Instituto Brasileiro de Siderurgia (1995), for China, from Iron and Steel Industry of China (1994) and Ministry of Metallurgical Industry (1993), and for Poland, from IISI (1992) and Berent-Kowalska (1996). Lawrence Berkeley National Laboratory complied energy consumption and economic data for France (Ministère de l'Industrie, 1980-1992; Institut National de la Statistique et des Etudes Economique, 1993), Germany (Arbeitsgemeinschaft Energiebilanzen, 1980-1991; Statistishes Bundesamt, 1980-1991), Japan (Japanese Institute for Energy Economics, 1980-1991; Japanese Bureau of Statistics, 1980-1991), and the U.S. (U.S. Department of Commerce, 1980-1985; U.S. Energy Information Administration, 1988, 1991, 1994; U.S. Department of Commerce, Bureau of Economic Analysis, 1992-1993). Energy consumption data for Brazil are from Ministerio de Minas e Energia (1995) and economic data were provided by Schaeffer (1996). Energy consumption and economic data for China are from Sinton et al. (1996), Iron and Steel Industry of China (1994), and Ministry of Metallurgical Industry (1993). Energy consumption and economic data for Poland were provided by Berent-Kowalska (1996).

Primary values for electricity generation were calculated by multiplying electricity consumption by the world average efficiency (33% in 1990) (Faaij et al., 1995), 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 (combined heat and power, CHP) are also obscured with a standard electricity conversion efficiency, although CHP generally plays only a minor role in the iron and steel industry due to the large amounts of energy used in high-temperature processes. We do, however, discuss the effect of changing the assumed electricity generation efficiency on the results of our analysis.

ECONOMIC INTENSITY INDICATOR: ENERGY INTENSITY

Energy intensity as an economic intensity indicator is defined in this study as the amount of energy (in enthalpy) needed to execute a certain economic activity expressed in monetary terms. Generally value added or gross output are used as the denominator (Ang, 1995). Value of shipments has also been proposed as an indicator for economic activity (U.S. Dept. of Energy, EIA, 1995). In our analysis, value added is defined as a measure of activity derived by subtracting the cost of materials, supplies, containers, purchased fuel and electricity, and contract work in US$ (1980) from the value of shipments. In essence, it is the value of an establishment's output minus the value of the inputs (U.S. Dept. of Energy, EIA, 1995). Gross output (US$ 1980) is the most comprehensive measure of manufacturing production and includes sales of receipts and other operating income plus inventory change (U.S. Dept. of Energy, EIA, 1995). Gross output is reported as national accounts compatible production in current prices in the STAN database (OECD, 1995). Value of shipments (expressed in US$ 1980) includes the receipts for products manufactured, services rendered, and resales of products bought and resold without further manufacture (U.S. Dept. of Energy, EIA, 1995). For international comparisons the monetary values have been converted to 1980 constant-US$, using GDP-deflators and purchasing power parity (PPP) corrections (OECD, 1994; OECD, 1995, Summers and Heston, 1991). Value added data for all countries were converted to US$ 1980 using PPP exchange rates.

PHYSICAL INTENSITY INDICATOR: SPECIFIC ENERGY CONSUMPTION

Specific energy consumption (SEC) is used as a physical intensity indicator and is defined as the amount of energy (in enthalpy) 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 SEC is influenced by three main factors: production process (including feedstock), efficiency of the production process, and the type of products produced. 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 (IISI, 1992). 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 might 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. We recommend further detailed study of this effect from the perspective of steel quality, economics, and energy intensity.

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 (IISI, 1992). Due to differences in national statistical systems, the various countries may report different ranges of steel products (IISI, 1992).

Finishing (e.g. galvanizing, annealing) has not been accounted for in the analysis. This introduces an uncertainty in the calculations, dependent on the share of finished product and the SEC of annealing or galvanizing (roughly equal to 0.4 GJ/tonne finished steel (Novem, 1991)). For the selected countries (even for the countries with relative high production shares of finished products like France, Japan, and the U.S.) the uncertainty in the SEC due to finishing is less than 1%. However, finishing may be more important in economic terms.

DECOMPOSITION ANALYSIS METHODOLOGY

We have followed the simple average parametric Divisia decomposition methodology* proposed by Farla et al. (1996, this issue) to understand the factors that contribute to the SEC. Because time series are available for the analysis, we use a rolling base-year which results in smaller residual terms. The aggregated SEC is calculated by dividing total primary energy consumption in the iron and steel industry by total production. 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 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 2. 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.

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

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

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:

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

STRUCTURE/EFFICIENCY ANALYSIS METHODOLOGY

In addition to the decomposition analysis, we examine changes in the SEC over time using a structure/efficiency analysis methodology. The SEC is a function of changes in product mix (production structure) and energy efficiency (Phylipsen et al., 1997). If more than one factor influences the production structure it is difficult to illustrate the relationship. For example, in the steel industry both process mix (primary steel vs. secondary steel) and product

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[*] According to the classification of Ang (1995) we have used the simple average parametric Divisia method 2 (AVE-PDM2). This method assumes weak separability, i.e. that there is an interaction between factors that may not be identified. These interactions are therefore captured in several of our index terms.

mix (slabs, hot rolled, and cold rolled steel) influence the SEC. We use a structure/efficiency analysis to show the SEC as a function of an important structural factor, i.e. share of scrap in the product mix (Worrell et al., 1994). 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 (Worrell et al., 1994). 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.

Table 2

"Best Practice" weighting factors for various steel products used in the physical decomposition analysis

Product	Fuel (GJ/tonne)	Electricity (GJ/tonne)	Primary energy (GJ/tonne)
Basic Oxygen Furnace - Slab[1]	14.24	0.36	15.3
Electric Arc Furnace - Slab[2]	0.79	1.52	5.4
Hot Rolling[3]	1.82	0.37	2.9
Cold Rolling[4]	1.10	0.53	2.7

Notes: 1. Equivalent to the 1988 Specific Energy Consumption (SEC) of an integrated steel plant in The Netherlands, assuming 10% scrap addition in the BOF (Worrell et al., 1993)

2. Equivalent to the SEC of an EAF plant in Germany (Teoh, 1989) and the SEC for continuous casting equivalent to the integrated steel plant (Worrell et al., 1993)

3. Equivalent to the 1988 SEC of a hot strip mill at an integrated steel plant in The Netherlands (Worrell et al., 1993). The SEC of wire rod production is comparable to the given SEC (IISI, 1982).

4. Equivalent to the 1988 SEC of a cold rolling mill at an integrated steel plant (Worrell et al., 1993)

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

ANALYSIS RESULTS

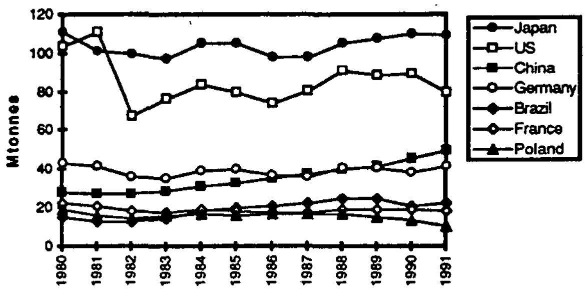
In this section we discuss the results of the analysis, focusing first on specific energy consumption trends and then on the results of the physical decomposition analysis and the structure/efficiency analysis. We end with a discussion of the comparison of economic and physical energy intensity indicators for the seven countries.

Steel production, as shown in Figure 2, varied in the selected countries over the study period, remaining nearly constant in Germany and Japan, increasing in China (on average 6%/yr) and Brazil (4%/yr), and decreasing in France (-2%/yr), Poland (-5%/yr), and the U.S. (-2%/yr). The decrease in Poland was due to the economic restructuring process that began in the last years of the analyzed period and the resulting decrease in capacity utilization and energy efficiency.

SPECIFIC ENERGY CONSUMPTION TRENDS

The SEC for iron and steel production in the seven countries is calculated by dividing primary energy consumption in the iron and steel industry by total crude steel production. These SECs are plotted in Figure 3 and show a general trend towards a reduction in SECs in most countries over the study period.*** Iron and steel production is least energy-intensive in Germany and Japan and most energy-intensive in China. 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

Figure 2
Steel production in seven analyzed countries
1980 to 1991



** 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 (IISI, 1990), 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% (IISI, 1990). This constitutes an important contribution to the negative development of the energy efficiency as shown in Figure 4.

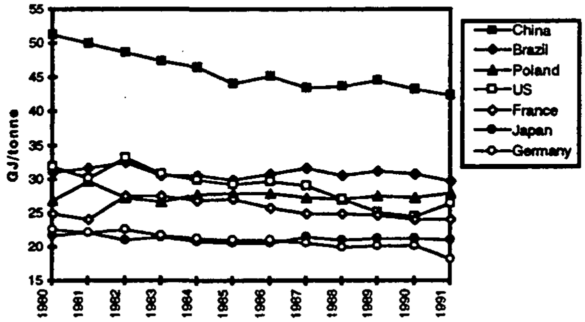
***We also calculated structure-adjusted SECs for these countries which account for differences in structure (process and produce mix) between countries and over time as measured by the PPI and which make it possible to more closely compare the energy intensities without the disturbance of differences and changes in product mix. Because the SECs and the structure-adjusted SECs were essentially the same for all countries except the U.S. and France (where structural schange towards increasing production of secondary steel had a major influence on the SEC), we do not show a separate figure.

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 (Ross and Feng, 1991). Correcting for the latter two factors may lead to 5-6% lower energy consumption in the Chinese iron and steel industry (Ross and Feng, 1991).

DECOMPOSITION ANALYSIS

The decomposition analysis summarizes the relative influence of changes in structure and efficiency on specific energy consumption in iron and steelmaking. Figure 4 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 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.

Figure 3
Specific energy consumption for iron and steel production in seven countries, 1980-1991



We have analyzed the effects of changing the electricity generation efficiency on the results of the decomposition analysis. 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.

STRUCTURE/EFFICIENCY ANALYSIS

The share of secondary (EAF) steelmaking is used as an indication of the changes in the structure (process mix) in the structure/efficiency analysis. Figures 5-11 depict the actual SEC and the "best practice" SEC for 1980 and 1991 relative to the share of secondary (EAF) steelmaking for the studied countries. The differences in process mix between the countries are depicted clearly, as well as the changes over time. The U.S. has a relative high share of EAF steelmaking (between 27% and 38%), while Germany and Poland have relative low shares (around 20% in 1991). Because the product mix is also influenced by the shares of the various products this is taken into account in the estimated SEC_{BP} of each country and year. The differences between the SEC and SEC_{BP} reflects the potential energy savings, relative to the "best practice" technologies. For most countries the two points for each year are converging, i.e. increased efficiency and reduced potential savings (e.g. China, Germany, and the U.S.). For Japan the efficiency has remained nearly constant, while for France and Poland the efficiency seems to have decreased, although modestly.

Table 3
Changes in SEC (1980 and 1991) and the influence of structure and efficiency in seven countries (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 (-5.1%)	29.7 (-4.8%)
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.

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.

Figure 4
Relative changes in specific energy consumption between 1980 and 1991 and the contribution of structure and efficiency changes

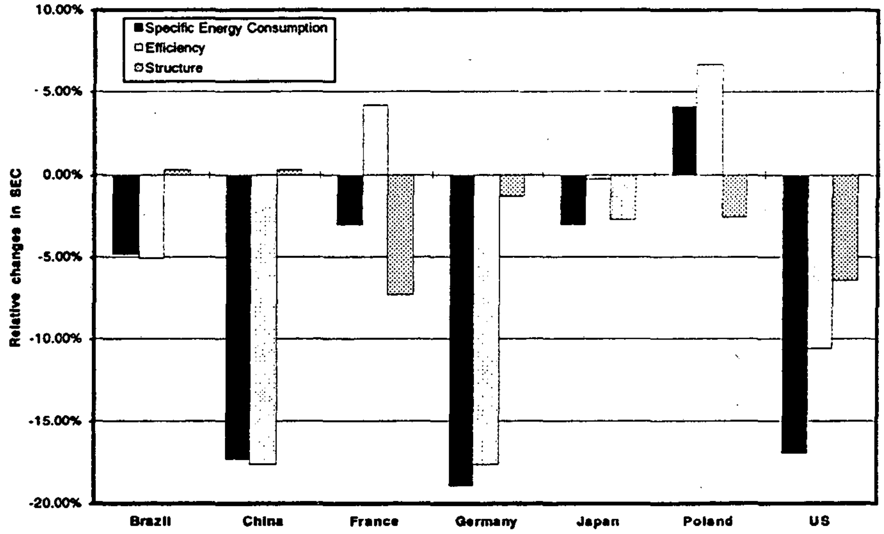


Figure 5
Actual and "best practice" specific energy consumption for 1980 and 1991 relative to the share of secondary (EAF) steelmaking for Brazil

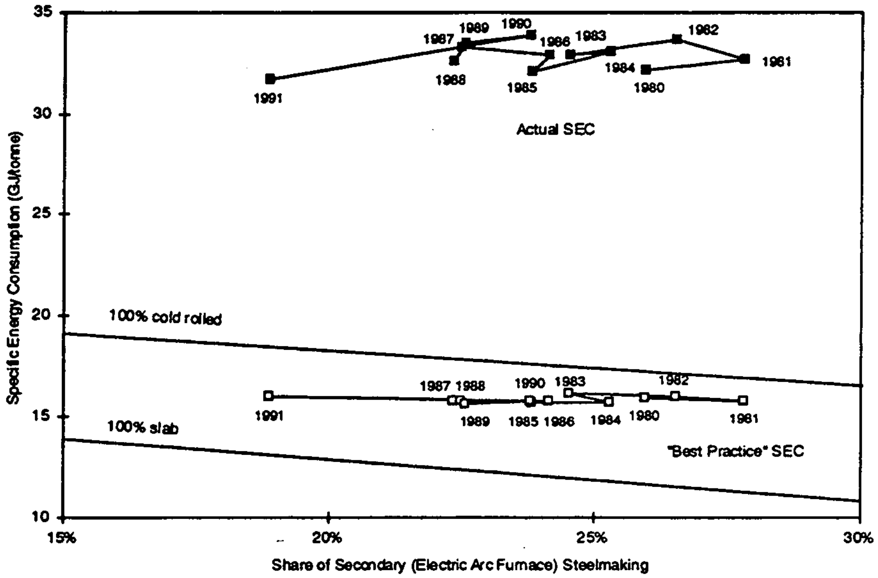


Figure 6
Actual and "best practice" specific energy consumption for 1980 and 1991 relative to the share of secondary (EAF) steelmaking for China

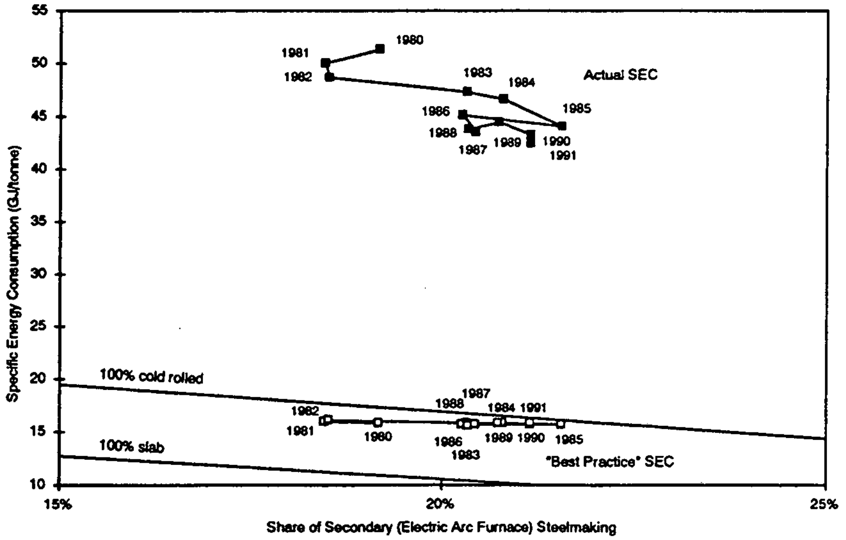


Figure 7
Actual and "best practice" specific energy consumption for 1980 and 1991 relative to the share of secondary (EAF) steelmaking for France

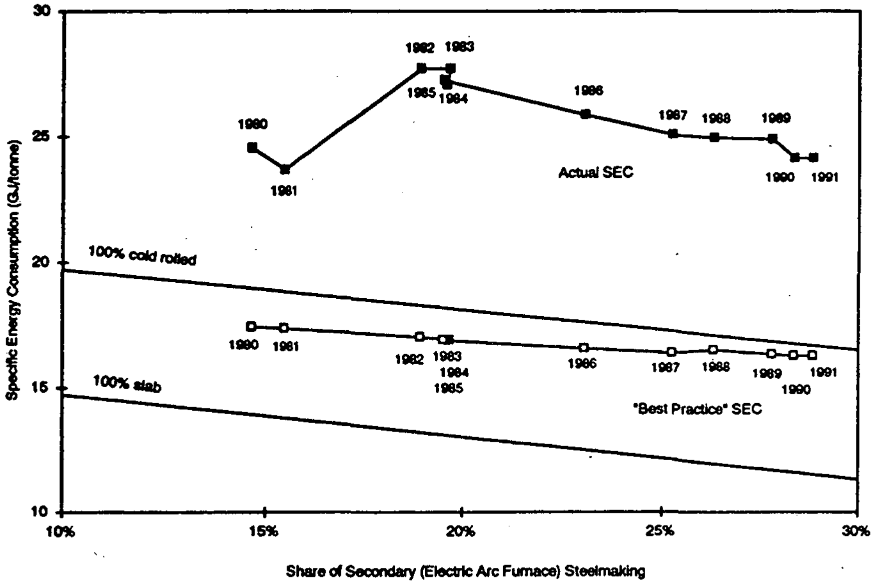


Figure 8
Actual and "best practice" specific energy consumption for 1980 and 1991 relative to the share of secondary (EAF) steelmaking for Germany

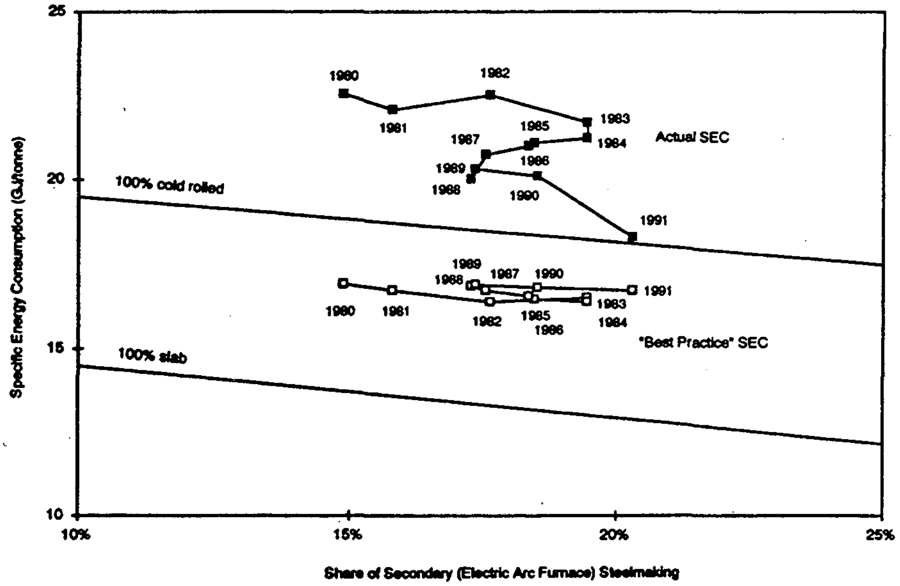


Figure 9
Actual and "best practice" specific energy consumption for 1980 and 1991 relative to the share of secondary (EAF) steelmaking for Japan

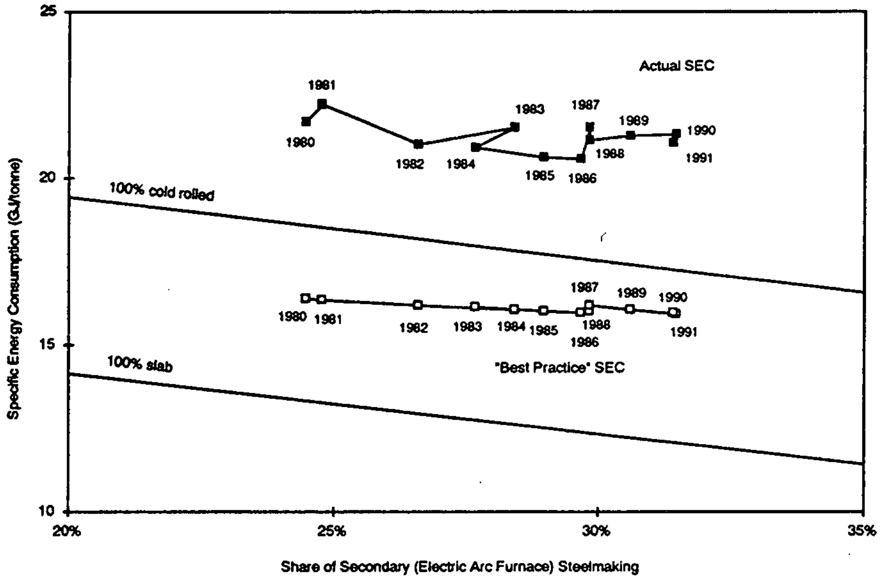


Figure 10
Actual and "best practice" specific energy consumption for 1980 and 1991 relative to the share of secondary (EAF) steelmaking for Poland

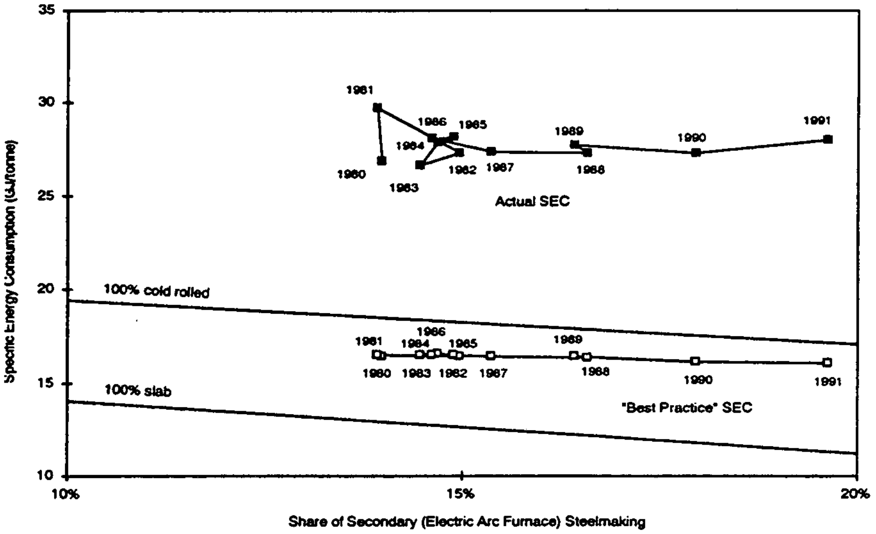
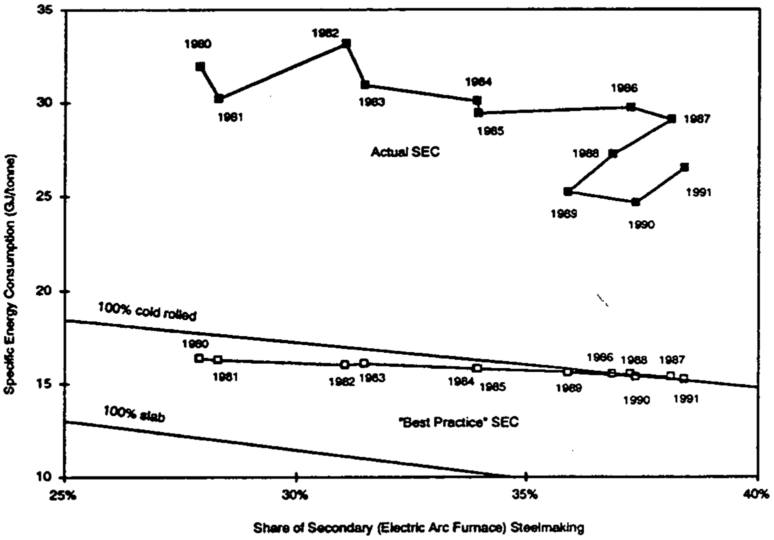


Figure 11

Actual and "best practice" specific energy consumption for 1980 and 1991 relative to the share of secondary (EAF) steelmaking for the U.S.



COMPARISON OF PHYSICAL AND ECONOMIC ENERGY INTENSITY INDICATORS

We compare trends between physical energy intensity indicators (SEC and structure-adjusted SEC) and economic energy intensity indicators (value added and gross output or value of shipments, as available) for the seven countries over the study period. Value added data are available for all countries but are only available for three years for Brazil (1980, 1985, 1990), for 1985 to 1991 for China, and for 1987 to 1991 for Poland. Gross output data are available for all countries except Brazil and Poland. Value of shipments data are only available for Brazil and the U.S. The indicators are normalized to 1980, except for China (1985) and Poland (1987). It should be noted that observing trends over a longer time series might lead to more robust conclusions on the applicability of the various indicators. Table 5 presents a summary of the observed changes in the various indicators and the SEC. The results of the comparisons are shown in Figures 12-18.

Value added based energy intensity indicators track the SEC reasonably well over the study period for the industrialized countries. The correlation between value added and the SEC is strongest for Japan, but weaker for France, Germany, and the U.S., especially in the later years. Value added seems to bear no connection to the SECs for China and Poland, and hence does not seem to be a reliable indicator for both countries. The two value added data points available for Brazil lie close to the SEC values, but it is difficult to draw any conclusions regarding trends. The lack of correlation with value added in China and Poland might be due to the pricing of commodities in these countries, which are less dependent on market developments and costs of raw materials.

Energy intensities on the basis of gross output correlate surprisingly well to SECs for China and follow trends (but not actual values) relatively closely for

Table 5

Summary of the results of the development of energy use over the period 1980-1991 using various indicators for the activity

	Observed SEC (%)	Value Added (%)	Gross Output (%)	Value of Shipments (%)
Brazil	-4.8%	+2.3%	n.a.	+43.8%
China ('85-'91)	-3.7%	+45.4%	+3.4%	n.a.
France	-3.1%	+3.2%	+17.8%	n.a.
Germany	-19.0%	-18.1%	-12.0%	n.a.
Japan	-3.0%	-13.3%	+20.4%	n.a.
Poland ('87-'91)	+2.3%	+28.6%	n.a.	n.a.
U.S.	-17.0%	-21.6%	+10.5%	-17.9%

Note: The Specific Energy Consumption (SEC) is calculated as primary energy use per tonne of crude steel. Energy intensities are calculated as energy use per unit of economic activity (in US$-1980) using various activity indicators (i.e. value added, gross output and value of shipments). Economic data for China and Poland are only for the periods 1985-1991 and 1987-1991, respectively. Value added data for Brazil are for 1980-1990. Primary energy for electricity generation is calculated using an efficiency of 33%.

Japan and the U.S. (except for 1982 and 1983). Gross output does not track SEC developments well in France or Germany, where it is often moving in the opposite direction of the SEC trend. Based on these limited observations, we find that energy intensities based on gross output seem less useful as an indicator than value added. Also the correlation with energy intensities based on value added are different, which could lead to different results, as was found in other studies (Ang, 1995).

Value of shipments data were only available for the U.S. and Brazil, and therefore conclusions should be drawn carefully. In both cases, value of shipments data show large fluctuations from year to year which do not follow the SEC trends. As with gross output, value of shipments trends are sometimes even moving in the opposite direction of the SECs, especially for the U.S. Also, because value of shipments data is not readably available for most countries, the usefulness of this economic indicator is questionable.

Figure 12
Comparison of physical and economic energy intensity indicators for Brazil, 1980-1991

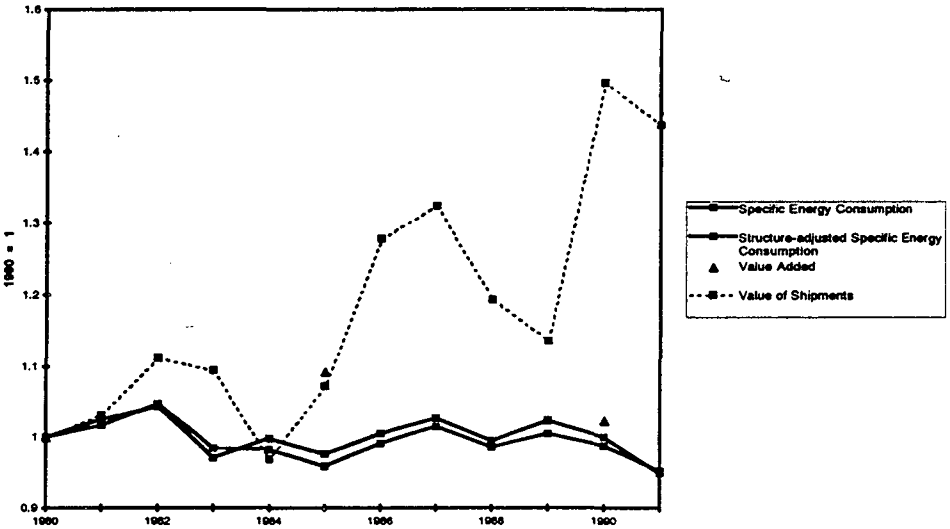


Figure 13
Comparison of physical and economic energy intensity indicators for China, 1985-1991

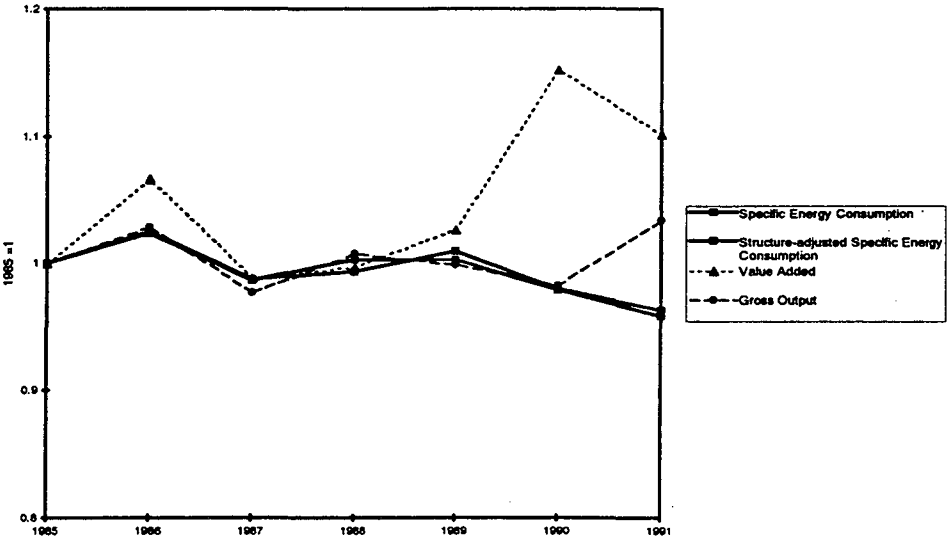


Figure 14
Comparison of physical and economic energy intensity indicators for France, 1980-1991

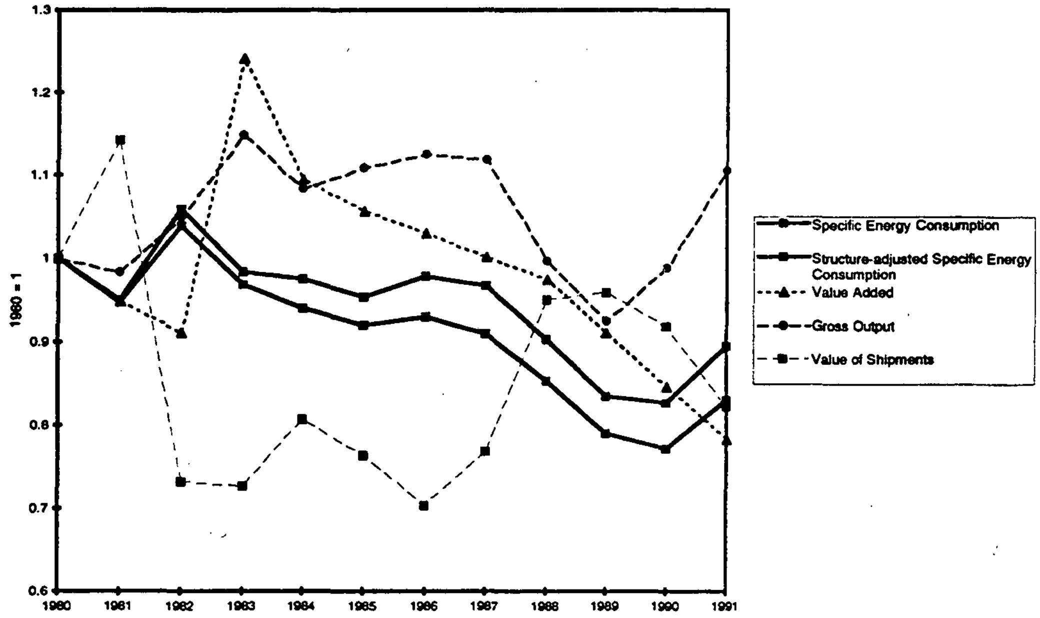


Figure 15
Comparison of physical and economic energy intensity indicators for Germany, 1980-1991

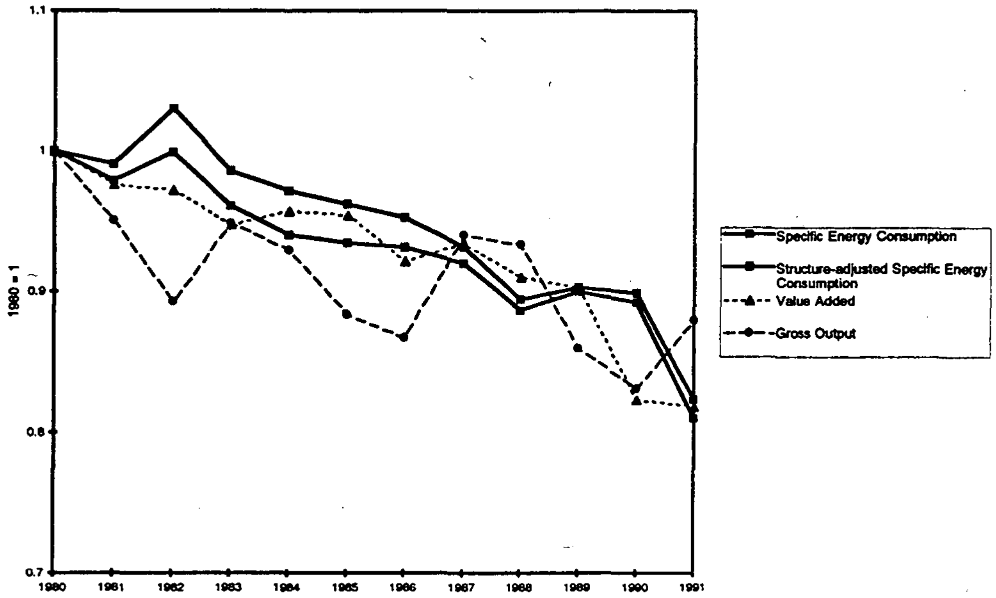


Figure 16
Comparison of physical and economic energy intensity indicators for Japan, 1980-1991

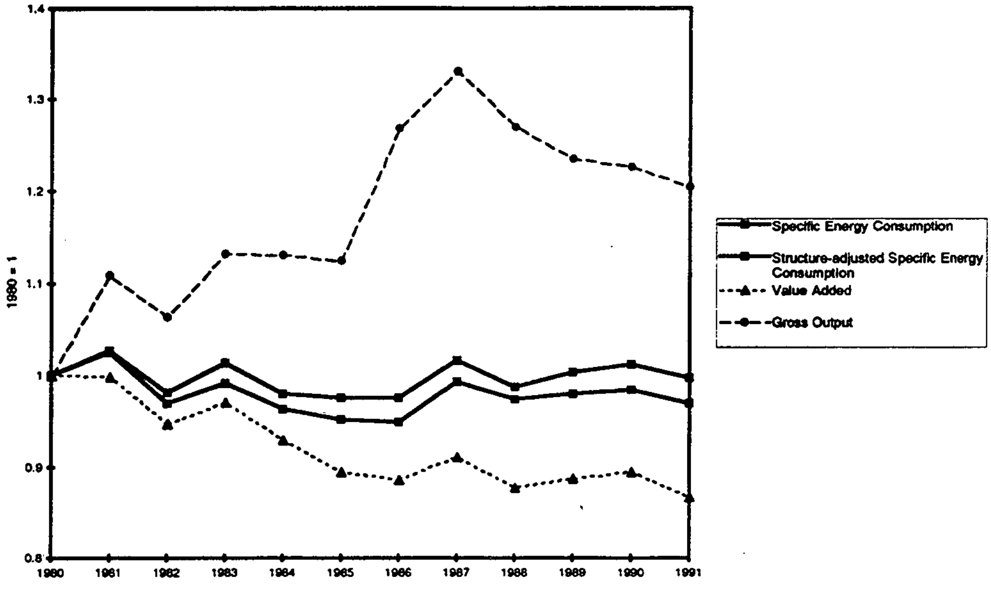


Figure 17
Comparison of physical and economic energy intensity indicators for Poland, 1987-1991

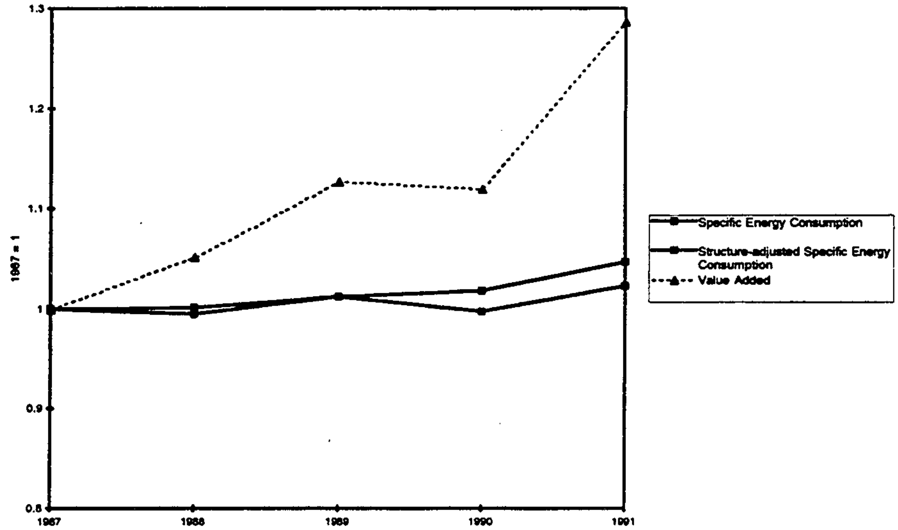
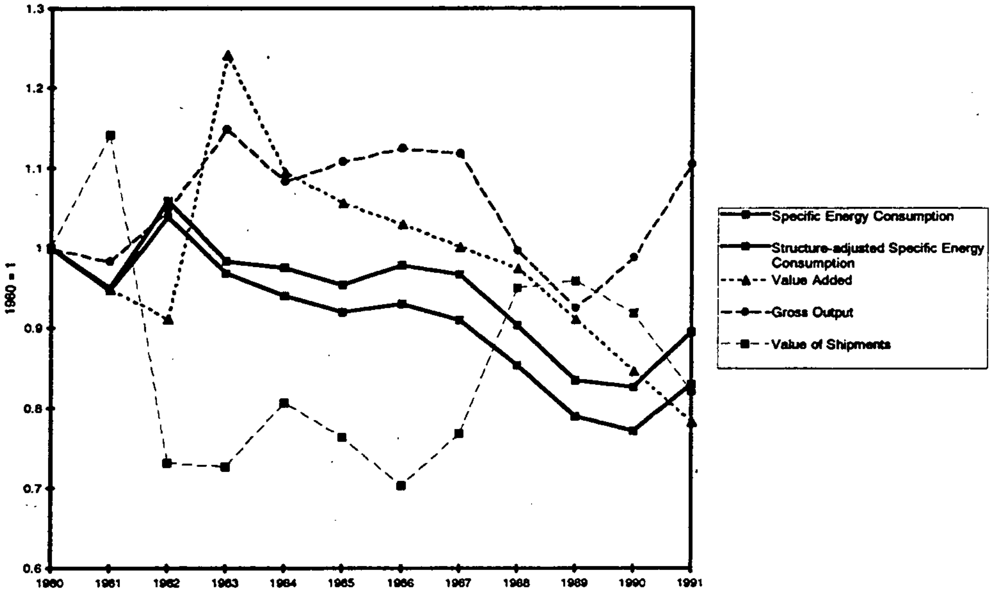


Figure 18
Comparison of physical and economic energy intensity indicators for the U.S., 1980-1991



DISCUSSION OF COUNTRY-SPECIFIC TRENDS

Crude steel production in Brazil grew at an average annual rate of 3.6% between 1980 and 1991. Even though the structure of the Brazilian steel industry became slightly more energy-intensive due to an increasing share of BOF, the SEC dropped from 31.2 GJ/tonne to 29.7 GJ/tonne, due to increases in efficiency. These gains, however, were unevenly distributed among plants of different process types, product mixes, sizes, share of different fuels used, levels of automation, levels of integration, etc. (Henriques, 1995). Investments in energy efficiency were low in Brazil during the first half of the 1980s due to economic uncertainties in the country. Substantial long term investments in modernization of plants (including new investments in energy efficiency) began in the late 1980s with the beginning of the privatization of the steel industry to prepare companies to better compete in the international market of steel products (Costa, 1996). The extension of the time series and analysis of SEC to more recent years might reflect the effect of this new investment.

In China steel production increased at an average rate of over 6% per year, leading to a growth in capacity utilization and construction of new capacity. Steel is produced in small, inefficient plants as well as in large state-owned integrated steel plants (Worrell, 1995). Currently about 70% of crude steel is produced in these so-called "key-plants". Between 1981 and 1990 China had several energy efficiency programs for the heavy industry (Sinton and Levine, 1994). Our analysis showed strong reductions in the SEC of 17%, from 51 GJ/tonne to 42 GJ/tonne, due almost entirely to improvements in efficiency. Under these programs investments were made in increased waste heat recovery, continuous casting, fuel gas recovery, industrial boilers and furnaces, and scrap processing (Liu et al., 1994). The continuous casting ratio increased in this period from 6% to 27% of the total crude steel production (IISI, 1992). The change towards more rolled products did not yet occur in the analyzed period.

In France, energy intensity increased in the early years of the study period, especially between 1981 and 1982. However, over the entire period, the SEC decreased slightly from 25 GJ/tonne to 24 GJ/tonne as a result of structural change towards more secondary steel (from 16% to 29%). The continuous casting ratio increased from 42% to 95% in the analyzed period (IISI, 1992). As Figure 4 shows, there was a reduction in energy efficiency between 1980 and 1991 which may be explained by decreasing scrap consumption in BOF steelmaking from 21% in 1980 to 14% in 1991, leading to a higher input of pig iron (IISI, 1990) and possibly reduced capacity utilization.

In Germany a small shift to a less energy-intensive product can be observed, through a slight increase in secondary steelmaking (from 16% to 20%)

partly offset by increased production of cold rolled steel. The SEC decreased 1.7%/yr on average, dropping from 23 GJ/tonne to 18 GJ/tonne, partly due to a doubling of the continuously cast steel ratio from 46% in 1980 to 90% in 1991. The use of scrap in BOF steelmaking was nearly constant at 16-18% (IISI, 1990). Important energy efficiency measures implemented during the study period were increased recovery of BOF converter gases, closing of last OHF-capacity, increased use of pellets as blast furnace feed, increased electricity production through top gas power recovery turbines at the blast furnaces, and heat recovery at the EAF, sinter plant and furnaces (Aichinger, 1993).

In Japan the observed SEC decreased approximately 3% over the 11 year period, falling to 21 GJ/tonne. Changing product mix contributed to the majority (90%) of this change, while the real efficiency increase was only modest (see Table 3). The most important contribution to the energy savings seems to be the increase in continuous casting from 59% in 1980 to 94% in 1991. The scrap use in the BOF-steelmaking decreased slightly from 8% to 5% while imports of pig iron quadrupled to 3.8 Mtonnes in 1991 (equivalent to 5% of the domestic pig iron production) (IISI, 1992). If the pig iron had been produced in Japan, the actual energy consumption of the Japanese iron and steel industry would have increased approximately 0.5% to 2.5% in 1980 to 1991, respectively.

In Poland steel production collapsed, decreasing by 46% over the period 1980-1991, due to the economic restructuring processes in Eastern Europe which has lead to a considerable decreased capacity utilization, especially in primary steelmaking. In Poland the continuous casting ratio is very small, equivalent to 4% of total steel production in 1980 and increased to 9% in 1991 (IISI, 1992). The SEC increased slightly during the study period from 27 GJ/tonne to 28 GJ/tonne. The most important structural developments in steelmaking were the decreasing importance of OHF steelmaking (from 47% to 25% of steel produced in the studied period), and the increased importance of EAF steelmaking (from 14% to 21%). The latter change has led to a less energy intensive product mix.

In the U.S., both structural change and efficiency improvement contributed considerably to the decreasing SEC, which dropped from 32 GJ/tonne to 26.5 GJ/tonne over the study period. The most important change in product mix is the growing share of secondary steelmaking from 27% to 38% of total steel production. Crude steel production in the U.S. decreased dramatically in the beginning of the 1980s, and remained constant at around 80 Mtonnes, with an upswing between 1988 and 1990 to around 90 Mtonnes. Efficiency improvement can be explained mainly by the increasing continuous casting ratio (from 20% in 1980 to 75% in 1991), and the closing of inefficient OHF steelmaking (the production share decreased from 12% to 2% in the period 1980-1991). Also the increased use of pellets as blast furnace feed (IISI, 1992) has contributed to the energy savings. The use of scrap in the BOF decreased slightly from 27 to 25% (IISI, 1990). In a cross-country comparison it should be noted that the U.S. iron and steel industry produces only a minor part of the pellets used in the blast furnace and all of the sinter (Kuck and Cvetic, 1991). It is not clear what part of the pellet manufacturing is included in the energy consumption of the U.S. iron and steel industry and what portion is considered to be part of the mining sector.

CONCLUSIONS

We analyzed the energy consumption of the iron and steel industry in seven countries for the period 1980 to 1991. We examined the trends in these countries and compared the energy efficiencies of steel production over time. Using a decomposition analysis based on physical indicators for production, we decomposed the changes over time to more carefully examine intra-sectoral structural changes, including the use of secondary steelmaking and efficiency improvements. The selected countries showed varying trends, although the observed SEC decreased in almost all countries. Efficiency improvement played a key role in the observed energy savings in Brazil, China, Germany, and the U.S., while structural changes were the main driver for energy savings in France and Japan. Even though the structure became slightly less energy-intensive, energy efficiency decreased in Poland due to the economic restructuring process.

Economic indicators are often used to study trends in energy use and compare energy efficiencies across countries. We compared the use of various economic indicators (energy intensity) to that of the physical indicators (specific energy consumption). The economic indicators were generally not meaningful for developing countries, although gross output in China followed the development of the SEC remarkably well. In general a value-added based energy intensity seems to follow the SEC better than other economic indicators, although large differences do occur in individual years and in developments between subsequent years, compared to the SEC. The use of gross output and value of shipments showed a weaker correlation with the SEC, and data on value of shipments were not available for most countries.

Improvements are recommended in the decomposition analysis and efficiency comparison on basis of the SEC, e.g. changes in product quality, electricity generation efficiency, coke production and use, and hot metal charge rates in steelmaking. Despite these uncertainties, a comparison and analysis based on physical indicators makes it possible to compare efficiencies, taking intra-sectoral structure differences and developments into account, as well as explain the observed trends. Therefore, we find that physical indicators provide a basis for a more robust analysis and we recommend their use in analysis and comparison of industrial energy intensity and efficiency trends.

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