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Energy and Materials Flows in the Iron and Steel Industry

F. T. Sparrow

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ENERGY AND MATERIALS FLOWS IN
THE IRON AND STEEL INDUSTRY

by

F.T. Sparrow
Purdue University

prepared for

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PREFACE

This report is one of a series being prepared for the U.S. Department of Energy, Office of Industrial Programs, on energy and materials flows in energy-intensive industries. Each report gives an overview of the particular industry, including its products, corporate structure, and present and emerging technologies. Suppliers and customers of major energy-consuming industries will gain a better understanding of the effects of changes in the cost and availability of energy. In cases where firms can substitute one material input for another, the reports will help these firms consider the impact of changes in energy supply on possible alternatives. Government analysts responsible for expediting industrial energy conservation should profit from having a compact and ready source of background information to help place proposed projects in perspective and to serve as a point of departure for specific evaluations. The industries studied to date and the current status of the corresponding reports are listed below.

The information presented in the report series is derived from previous reports, government and industry statistics, trade and technical publications, patents, textbooks, industry interviews, and plant visits. Some of these sources provide incomplete, out-of-date, or conflicting data; therefore, ANL staff perform additional research to supplement, update, and reconcile the sources.

Energy and Materials Reports

Industry	Status (as of June 1983)
Fabrication of aluminum products	Published 1979 (ANL/CNSV-3)
Fabrication of iron and steel semifinished products	Published 1979 (ANL/CNSV-8)
Olefins and their derivatives	Published 1980 (ANL/CNSV-9)
Petroleum refining	Published 1981 (ANL/CNSV-10)
Copper	Published 1981 (ANL/CNSV-11)
Air products	Published 1981 (ANL/CNSV-15)
Pulp and paper	Published 1981 (ANL/CNSV-16)
Cement	Published 1981 (ANL/CNSV-17)
Primary aluminum	Published 1981 (ANL/CNSV-21)

ENERGY AND MATERIALS FLOWS IN THE IRON AND STEEL INDUSTRY

by

F.T. Sparrow

ABSTRACT

Past energy-consumption trends and future energy-conservation opportunities are investigated for the nation's iron and steel industry. It is estimated that, in 1980, the industry directly consumed approximately 2.46×10^{15} Btu of energy (roughly 3% of total U.S. energy consumption) to produce 111 million tons of raw steel and to ship 84 million tons of steel products. Direct plus indirect consumption is estimated to be about 3.1×10^{15} Btu. Of the set of conservation technologies identified, most are judged to be ready for commercialization if and when the industry's capital formation and profitability problems are solved and the gradual predicted increase in energy prices reduces the payback periods to acceptable levels.

1 INTRODUCTION

1.1 PROPERTIES AND USES OF IRON, STEEL, AND STEEL ALLOYS

The physical and mechanical properties of iron, steel, and steel alloys are compared with those of other selected metals in Table 1.1. Hot metal contains 3-5% carbon along with other impurities that remain from the reduction process in the blast furnace. Carbon steel contains no more than 1% carbon, while stainless steel is an alloy of steel and chromium. These compositional differences explain the wide variation in the properties given in Table 1.1. Table 1.2 gives the impact of adding various alloying materials to steel.

Because of its relatively high thermal conductivity and malleability, iron is utilized directly in gray, malleable, and ductile castings for various purposes that require these properties; for example, engine blocks and cookware require conductivity, and ornamental structures and fences require malleability. The vast majority (95% in 1980) of iron produced in blast furnaces is converted into steel in steel furnaces, where additives (such as chromium, manganese, nickel, and molybdenum) and the type of processing (hot- and/or cold-rolling, galvanizing, annealing, tempering, pickling) determine the properties of the final product and hence its use.¹ End use shipments by

Table 1.1 Typical Properties of Selected Metals

Metal	Resistivity at 20°C (cm)	Thermal Conductivity at 0°C ² °F (Btu/hr ft ² °F)	Specific Gravity	Tensile Strength (10 ³ lb/in.)	Melting Point (°C)
Aluminum	2.8	117	2.7	30	659
Brass ^a	7	56	8.6	70	900
Copper	1.7	224	8.89	30 ^b , 60 ^c	1,083
Gold	2.4	172	19.3	20	1,063
Iron, ingot	9	77	6	45	1,538
Lead	22	20	11.4	3	327
Monel ^d	42	19	8.9	160	1,300
Nickel	7.8	36	8.9	120	1,452
Phosphor bronze ^e	7.8	30-40	8.9	25	750
Platinum	10	39	21.4	50	1,755
Silver	1.6	242	10.5	42	960
Steel, carbon	10	56	7.86	65	1,515
Steel, stainless	72	19	8.02	230	1,427
Tin	11.5	36	7.3	4	232
Tungsten, drawn	5.6	116	19	500	3,400
Zinc	5.8	65	7.1	10	419

^a70% copper, 30% zinc.

^bAnnealed.

^cHard drawn.

^d65-70% zinc, 30-35% copper.

^e90-95% copper, 5-10% tin, remainder phosphorus.

Source: Ref. 2.

Table 1.2 Roles of Ferroalloys in Steel Production

Role	Chromium	Columbium	Manganese	Molybdenum	Nickel	Vanadium
Ties up or removes oxygen			x			x
Ties up or removes sulfur			x			
Increases tensile strength		x	x	x	x	x
Increases ductility			x			x
Improves low-temperature impact resistance				x	x	
Increases hardenability	x		x	x	x	x
Improves high-temperature strength	x	x		x		x
Improves resistance to corrosion and oxidation	x	x		x		
Increases toughness			x		x	
Improves resistance to abrasion	x		x	x		

market classification for 1973-1980 are given in Table 1.3. A comparison of the 1974 percentage distribution with that of 1979 (both "good" years for the steel industry) shows a fair degree of stability in market shares, although certain markets (containers, fasteners, construction, and, in particular, autos), which accounted for 20% of steel sales over the past decade, show a decline over time, while others (oil and gas) show a marked increase.

1.2 MATERIALS SUBSTITUTION

Figure 1.1 shows which automobile parts have been eliminated by the change to front-wheel drive. Downsizing has already cut into steel demand. Further downsizing along with materials substitution -- especially of fiber-reinforced plastics (FRPs) for bodies -- will reduce steel use even more. FRPs, which until recently were used primarily in marine hulls as a substitute for wood, are generally 25-35% resin and 30-75% reinforcement, depending on the strength requirements; the remainder is filler. Resins can be either thermoplastic (i.e., can be repeatedly softened and hardened) or thermosetting (irreversibly hardened). Even though thermoplastic resins (e.g., polyethylene, polyvinyl chloride, and polystyrene) account for over 75% of total plastics production, thermosetting resins -- in particular, unsaturated polyester -- account for over 90% of the FRP market because of their better mechanical properties.⁴

Common FRP-reinforcing materials include fiberglass, asbestos (now being phased out), cotton, nylon, and cellulose. The next generation will likely include carbon-graphite (now used in tennis rackets) and silicon-carbide whiskers, the latter being characterized as "the ultimate reinforcement, in that they (whiskers) have mechanical strengths equivalent to the forces between adjacent atoms."⁴ In 1979, Ford Motor Company produced an

Table 1.3 Net Shipments of Steel Products (including carbon, alloy, and stainless steel)
by Market Classification, All Grades^a (10³ net tons)

Market Classification	1980		1979		1978		1977		1976		1975		1974		1973	
	Ship-ments	%	Ship-ments	%	Ship-ments	%	Ship-ments	%	Ship-ments	%	Ship-ments	%	Ship-ments	%	Ship-ments	%
Steel for convert- ing and processing	4,117	4.9	5,058	5	4,612	4.7	3,679	4	4,036	4.5	3,255	4.1	4,486	4.1	4,714	4.2
Independent for- gers (not else- where classified)	933	1.1	1,154	1.3	1,192	1.2	998	1.1	952	1.1	1,098	1.4	1,339	1.2	1,213	1.1
Industrial fasteners	590	0.7	934	0.9	870	0.9	848	0.9	912	1	675	0.8	1,331	1.2	1,278	1.1
Steel service centers and distributors	16,172	19.3	18,246	18.2	17,333	17.7	15,346	16.8	14,615	16.5	12,700	15.9	20,400	18.6	20,383	18.3
Construction, including maintenance	8,742	10.4	9,978	10	9,612	9.8	7,553	8.3	7,508	8.4	8,119	10.2	11,360	10.4	10,731	9.6
Contractors' products	3,148	3.8	3,745	3.7	3,480	3.6	4,500	4.9	4,502	5	3,927	4.9	6,249	5.7	6,459	5.8
Subtotal	11,890	14.2	13,723	13.7	13,092	13.4	12,053	13.2	12,010	13.4	12,046	15.1	17,609	16.1	17,190	15.4
Automotive																
Vehicles, parts, etc.	11,855	14.2	18,099	18	20,651	21.1	20,882	22.9	20,667	23.1	14,750	18.4	18,256	16.7	22,468	20.2
Independent forgers	269	0.3	522	0.5	602	0.6	608	0.7	684	0.8	464	0.6	672	0.6	749	0.6
Subtotal	12,124	14.5	18,621	18.5	21,253	21.7	21,490	23.6	21,351	23.9	15,214	19	18,928	17.3	23,217	20.8
Rail transport																
Freight cars, passenger cars, and locomotives	1,884	2.3	2,445	2.4	2,188	2.2	1,709	1.9	1,469	1.6	1,836	2.3	2,132	1.9	1,997	1.8

Table 1.3 (Cont'd)

Market Classification	1980		1979		1978		1977		1976		1975		1974		1973	
	Ship- ments	%	Ship- ments	%	Ship- ments	%	Ship- ments	%	Ship- ments	%	Ship- ments	%	Ship- ments	%	Ship- ments	%
Rails and all others	1,271	1.5	1,668	1.7	1,361	1.4	1,529	1.7	1,587	1.8	1,316	1.6	1,285	1.2	1,231	1.1
Subtotal	3,155	3.8	4,111	4.1	3,549	3.6	3,238	3.6	3,056	3.4	3,152	3.9	3,417	3.1	3,228	2.9
Shipbuilding and marine equipment	1,201	1.4	924	0.9	845	0.9	869	1	969	1.1	1,413	1.8	1,339	1.2	1,019	0.9
Aircraft and aerospace	53	0.1	60	0.1	60	0.1	63	0.1	59	0.1	69	0.1	79	0.1	69	0.1
Oil and gas industry	5,371	6.1	3,739	3.7	4,140	4.3	3,650	4	2,653	3	4,171	5.2	4,210	3.9	3,405	3.1
Mining, quarrying, and lumbering	454	0.6	508	0.5	486	0.5	-	-	536	0.6	596	0.7	644	0.6	534	0.5
Agricultural																
Machinery	852	1	1,306	1.3	1,080	1.1	1,017	1.1	1,209	1.4	1,055	1.3	1,236	1.1	1,155	1
Other	388	0.5	665	0.7	725	0.7	631	0.7	575	0.6	374	0.5	623	0.6	617	0.6
Subtotal	1,240	1.5	1,971	2	1,805	1.8	1,648	1.8	1,784	2	1,429	1.8	1,859	1.7	1,772	1.6
Machinery, industrial equip- ment and tools	4,543	5.4	5,996	6	5,992	6.1	5,566	6.1	5,180	5.8	5,173	6.5	6,440	5.9	6,351	5.7
Electrical equipment	2,441	2.9	2,819	2.8	2,811	2.9	2,639	2.9	2,671	3	2,173	2.7	3,242	3	3,348	3
Appliances, uten- sils, and cutlery	1,725	2.1	2,140	2.1	2,094	2.1	2,129	2.3	1,950	2.2	1,653	2.1	2,412	2.2	2,747	2.5
Other domestic and commercial equipment	1,701	2	2,073	2.1	1,889	1.9	1,846	2	1,813	2	1,390	1.7	1,941	1.8	1,990	1.8

Table 1.3 (Cont'd)

Market Classification	1980		1979		1978		1977		1976		1975		1974		1973	
	Ship- ments	%	Ship- ments	%	Ship- ments	%	Ship- ments	%	Ship- ments	%	Ship- ments	%	Ship- ments	%	Ship- ments	%
Containers, pack- packaging, and shipping materials																
Cans, closures	4,163	5	4,994	4.9	4,950	4.9	5,173	5.7	5,301	5.9	4,855	6	6,349	5.8	6,070	5.5
Barrels, drums, shipping pails	725	0.9	939	1	809	0.9	768	0.8	859	1	601	0.8	1,026	0.9	910	0.8
Other	663	0.7	839	0.9	836	0.9	773	0.9	754	0.8	593	0.8	843	0.8	831	0.7
Subtotal	5,551	6.6	6,772	6.8	6,595	6.7	6,714	7.4	6,914	7.7	6,053	7.6	8,218	7.5	7,811	7
Ordnance and other military	177	0.2	204	0.2	207	0.2	193	0.2	219	0.2	405	0.5	654	0.6	918	0.8
Export (reporting companies only)	2,595	3.1	2,007	2	1,224	1.3	1,076	1.2	1,839	2.1	1,755	2.2	3,961	3.6	3,138	2.8
Nonclassified shipments	7,820	9.3	9,041	9	7,864	8	6,616	7.3	5,928	6.6	5,537	6.9	6,963	6.3	7,105	6.4
Total shipments	83,853	100	100,262	100	97,935	100	91,147	100	89,447	100	79,957	100	109,472	100	111,430	100

^aNet shipments eliminate tonnage duplication by deducting from the gross total those shipments from one reporting company to another for conversion, further processing, or resale.

Source: Ref. 1.

Fig. 1.1 Change to Front-Wheel Drive (Source: Ref. 5)

experimental car whose body structure weight was reduced by 48% by substituting graphite-reinforced plastic (GRP) for steel. The cost would have been prohibitively expensive, since GRP costs \$20/lb, one order of magnitude more expensive than its substitutes.

Such substitutions, along with compacted graphite for cast-iron exhaust manifolds and aluminum for cast-iron intake manifolds and blocks, are expected to decrease the amount of steel per car by 500 lb by 1987.⁶ Other studies predict even greater reductions.⁷ These reductions, when coupled with the decrease that has already occurred in steel sales to the automobile industry -- from 18 million tons in 1974 to 12 million tons in 1980 (both relatively poor years for auto sales) -- mean a major shift in the pattern of steel sales that may well be permanent, although increased use of various high-strength steels (dual-phase steels in particular) may partially offset this trend.

The life-cycle energy use implications of the competition among cold-rolled low-carbon steel, aluminum, and FRPs have been investigated in several recent studies.^{4,8} The Cummings-Saxton report⁴ calculated the impact of substituting equivalent structural amounts of FRP and aluminum for one pound

of a low-carbon steel. The change in embodied energy in the material (reduced for FRP, increased for aluminum), plus the reduction in transportation energy caused by the weight reduction (0.4 lb for FRP and 0.25 lb for aluminum), reduced lifetime energy use by 85×10^3 Btu, in the case of FRP, and 37×10^3 Btu in the case of aluminum. However, the substitution of high-strength low-alloy (HSLA) steel for low-carbon steel reduced lifetime energy consumption by 42×10^3 Btu per pound of low-carbon steel replaced.

The A.D. Little study,⁸ with one important exception, reaches a similar conclusion. This study concludes that:

- "For most cases, plastics ... show lower life cycle energy use than carbon (or HSLA) steel."
- "In many instances, sheet products made from either aluminum or carbon (or HSLA) steel show about equivalent life cycle energy use."

The only difference in the conclusions of the two reports relates to the comparison of aluminum with HSLA and the low-carbon steels. The A.D. Little report concludes that the three are about equivalent, while Cummings-Saxton concludes that both aluminum and HSLA steel have a significant advantage over the low-carbon steels presently used.

The two studies used similar 100,000-mile vehicle lifetimes, approximately the same energy savings per pound of weight reduction, and approximately the same embodied energy for aluminum and steel. Therefore, the difference in the conclusions can most likely be traced to (a) differences in the energy embodied in plastics (24.4×10^3 Btu/lb for Cummings-Saxton; a range of $27-47 \times 10^3$ Btu/lb for A.D. Little), and (b) differences in the weight replacement ratios assumed.

The possibility of substituting wood girders for steel in small structures has been investigated by the Committee on Renewable Resources for Industrial Materials of the National Research Council (NRC). The study concludes that, while manpower and capital requirements are about the same, energy requirements are cut 90% by such a substitution.⁹ These results were substantiated in a recent University of Illinois study.¹⁰ However, the substitution of steel for wooden floor joints, studding, purlins, etc., for added strength and durability may offset the use of wood in home frames.

The industrial markets for steel are also feeling a pinch. A war between adhesives and fasteners is being waged in the fastener market,¹¹ while plastic gears have been moved out of the toy market into large (8-10 ft in diameter) industrial gear applications. They are cheap since they can be formed by injection molding, are light, and need no lubrication; their major problem is low load capacity above 250°F.¹² At the high-temperature end of the market, ceramic recuperators are being substituted for the superalloys (chromium, cobalt, tungsten) to deal with temperatures in excess of 2500°F,

which are now routinely encountered in the recovery of very high temperature waste heat from melting processes. The U.S. Department of Energy (DOE) has a major research and development program in high-temperature ceramics, which should advance the introduction of these new products. Also, plastic pumps are replacing steel pumps in highly corrosive environments.¹³

Finally, graphite or boron fibers in aluminum or magnesium matrices for structures, graphite fibers in copper matrices for bearings, silicon carbide fibers in aluminum or titanium matrices for high-temperature structural applications, and graphite aluminum for light-weight applications all show signs of entering markets previously dominated by steel and its alloys.¹⁴

In almost every area, steel products are facing increasing competition from new materials; the only sectors where steel appears to have no major substitutes are agriculture and mining. With the continued increase in steel costs, the gradual reduction in steel consumption per \$1,000 of real GNP -- from 0.12 ton in 1950 to 0.08 ton in 1977 -- is expected to continue.⁶

2 THE IRON AND STEEL INDUSTRY

2.1 IRON AND STEEL STATISTICS

Figure 2.1 illustrates the major steps in making iron and steel. Iron ore containing 25-35% iron, mined principally in the upper Great Lakes region, is crushed, screened, and concentrated by gravity, flotation, or magnetic methods to yield a product containing 60-68% iron. Most of the ore now processed is either lumped and heat-hardened in a pelletizing process prior to shipment, or sent untreated to a sintering plant at the steel mill where it is agglomerated into hard masses in combination with steel-mill scale and metallics from slag and coke breeze. Then, it joins imported ores (30-35% of total shipments) for further processing.

The ore is then mixed with coke and limestone flux in a reducing environment -- the blast furnace. There, the oxygen in the ore combines with the carbon or carbon monoxide and is removed from the ore, along with various impurities taken out in the slag. Pig iron, the result of this process, contains too much carbon (4%) for most uses and is removed in the steelmaking process; it is then mixed with scrap to produce various steel alloys. Hot rolling of the ingot follows, yielding steel slabs, billets, or blooms, which are then sent to the finishing mills for further treatment and conversion into the products listed in Table 1.3. Increasingly, slabs, billets, and blooms are being continuously cast, bypassing the ingot step.

Direct reduction of iron ores, a process that bypasses the blast furnace entirely, produces sponge iron by reduction at below-melting temperatures. It is of only minor importance now, but may grow in the future.

Table 2.1 shows the pattern of world iron and steel production over the last two decades. While world production has been fitfully increasing, the U.S. share has declined from over 35% in the mid-1950s to only 14.1% in 1980, a drop paralleled by the emergence of Japan as a major steelmaking country in the free world. The trend of steel imports and exports is shown in Table 2.2, and recent steel price trends are given in Table 2.3. Estimates of total domestic investment in iron and steel plants and equipment are given in Table 2.4. The profitability of the industry, as measured by the real (i.e., deflated) rate of return on investment, was estimated to be 10% in 1949-1954, but dropped to -1% in 1975-1978, according to the Office of Technology Assessment (OTA).⁶ Figure 2.2 shows estimates of the real rates of return and inflation for 1949-1978.

According to the American Iron and Steel Institute (AISI), the total direct energy consumed in the production of iron and steel was estimated to be 2.27×10^{15} Btu in 1980 (see Table 3.2). Of this total, AISI estimates that 64% was derived from coal, 5% from fuel oil, 24% from natural gas, and 6% from electricity (see Table 3.3). Blast furnaces consumed 100% of the coke, 33% of the fuel oil, and 9% of the natural gas.

Fig. 2.1 Process Unit Interrelationships for Ironmaking, Steelmaking, and Steel Forming (Source: Ref. 15)

Table 2.1 World Raw Steel Production, 1956-1980

Year	Production (10 ⁶ tons)				U.S. Share of Total (%)
	World	Common Market	Japan	United States	
1956	283.8	77.9	12	104.5	36.8
1957	291.8	82	12.5	102.2	35
1958	270.9	78	12.1	77.4	28.5
1959	305.8	84	16.6	84.7	27.7
1960	346.1	97.9	22.1	90.1	26
1961	353.8	96.1	28.3	88.9	25.1
1962	357.4	94	27.6	89.2	24.9
1963	382.9	96.5	31.5	99.1	25.9
1964	434.5	109.9	39.8	115.3	26.5
1965	456.3	113.8	41.2	119.3	26.1
1966	470.8	110.2	47.8	121.6	25.8
1967	496.7	114.5	62.1	115.4	23.2
1968	528.3	125.3	66.8	119.3	22.6
1969	573.2	134.7	82.1	128.2	22.4
1970	593.4	137.5	93.3	119.3	20.1
1971	580.4	128.2	88.5	109.2	18.8
1972	629.9	126.2	96.9	120.8	19.2
1973	697.1	150.1	108.2	136.8	19.6
1974	710	155.5	117.1	132.1	18.6
1975	645.8	125.3	102.3	105.8	16.4
1976	683.1	134.3	107.4	116.1	17
1977	673.9	125.3	102.4	113.1	16.7
1978	711.7	133.1	102.1	124.3	17.5
1979	824	154	123	136	16.5
1980	741	140	123	111	14.1

Source: Ref. 6 for 1956-1978 data; Ref. 1 for 1979-1980 data.

There is some disagreement about the data and definitions used to calculate direct and indirect energy use. Table 3.4 in Sec. 3 calculates the amounts for 1980 in a slightly unconventional way, by focusing on total domestic energy use (e.g., assuming zero energy use for imports) and assigning only the heating value of coke (25.99×10^6 Btu/ton) to the blast furnace. The direct energy associated with the major raw materials purchased by the industry therefore amounted to 2.38×10^{15} Btu in 1980, and total energy use amounted to 2.96×10^{15} Btu. Thus, indirect energy use amounted to about 20% of direct energy use. If the full inverse input/output (I/O) treatment were applied to the industry, the percentage would be higher.

Table 2.2 U.S. Imports and Exports of
Steel Mill Products, 1956-1980

Year	Imports (10 ³ tons)	Exports (10 ³ tons)	Ratio of Imports to Apparent Consumption (%)
1956	1.2	3.9	1.7
1957	1.1	4.8	1.5
1958	1.5	2.5	2.9
1959	4	1.5	6.1
1960	3.1	2.7	4.7
1961	2.9	1.8	4.7
1962	3.7	1.8	5.6
1963	4.9	2	6.9
1964	5.8	3.1	7.3
1965	9.4	2.3	10.3
1966	9.8	1.5	10.9
1967	10.4	1.5	12.2
1968	16.3	2	16.7
1969	12.7	4.7	13.7
1970	12.2	6.4	13.8
1971	16.6	2.5	17.9
1972	16.1	2.6	16.6
1973	13.8	3.7	12.4
1974	14.5	5.3	13.4
1975	10.9	2.7	13.5
1976	13	2.4	14.1
1977	17.5	1.8	17.8
1978	19.1	2.2	18.1
1979	17.5	2.8	14.9
1980	15.5	4.1	15.5

Source: Ref. 6 for 1956-78 data (p. 118);
Ref. 1 for 1979-80 data (Tables
17, 21, and 14).

2.2 INDUSTRY STRUCTURE

In 1980, over 90% of domestic iron ore was mined in the upper Great Lakes region, with southern (3%) and western (7%) ores making up the remainder.¹⁶ The proximity of coal, cheap water, and rail transportation for the iron ores led the integrated iron and steel industry to develop along the shores of the Great Lakes. Over 80% of the integrated mills, and almost 70% of the semi-integrated and specialty steel plants, are located in states

Table 2.3 Index of Steel Industry Prices and Costs, 1965-1978
(1967 base year except as noted)

Year	Producer Price Indexes								
	Consumer Price Index	Industrial Commodities ^a	Steel Mill Products	Metal-lurgical Coal ^b	Iron Ore ^c (pellets)	Steel Scrap	Electrical Power	Fuel Oil	Wages ^d
1965	94.5	96.4	97.5	96.8	NA	112.6	103	107.7	94.05
1966	97.2	98.6	98.9	98.4	NA	106.6	99.8	105	97.37
1967	100	100	100	100	NA	100	100	100	100
1968	104.2	102.5	102.5	101.8	NA	93	100.9	95.7	105.76
1969	109.8	106	107.4	110.2	100	110.8	102.2	93.3	112.97
1970	116.3	110	114.3	150.9	105.1	138.8	106.6	125.5	119.31
1971	121.3	113.9	123	185.3	111.1	114.6	115.5	166	131.59
1972	125.3	117.9	130.4	198.4	111.1	121.8	123.9	158.8	148.7
1973	133.1	127	134.1	216.5	116.4	188	132.6	190.4	161.43
1974	147.7	153.8	170	232.8	140.3	353.2	172.3	485.4	190.79
1975	161.2	171.5	197.2	622.1	181.2	245.6	193.2	495.5	222.57
1976	170.5	182.5	209.7	657.8	201.6	259	226.9	451.7	246.82
1977	181.6	195.1	229.9	671.3	220.2	233.7	257.2	521.4	273.76
1978	195.4	209.3	254.5	704.9	230.1	278.2	279.7	496.8	300.36

^aWholesale price index.

^bHigh-volume.

^cDecember 1969 base.

^dIncluding fringe benefits.

NA = not available.

Source: Ref. 6, p. 122.

Table 2.4 Selected Financial Data for the U.S. Steel Industry, 1970-1978

Year	Profits after Taxes (\$10 ⁶)	Depreciation, Depletion, Etc. ^a (\$10 ⁶)	Gross Cash Flow (\$10 ⁶)	Cash Dividends		Net Cash Flow (\$10 ⁶)	Capital Expenditures (\$10 ⁶)
				Total (\$10 ⁶)	As % of After-Tax Credits		
1970	532	1,128	1,660	488	91.7	1,172	1,736
1971	563	1,123	1,686	390	69.3	1,296	1,425
1972	775	1,196	1,971	402	51.9	1,569	1,174
1973	1,272	1,329	2,601	443	34.8	2,158	1,400
1974	2,475	1,553	4,028	675	27.2	3,354	2,115
1975	1,595	1,591	3,186	658	41.5	2,528	3,179
1976	1,337	1,614	2,951	637	47.6	2,314	3,253
1977	22	1,888	1,910	555	b	1,355	2,850
1978	1,292	2,010	3,302	533	41.3	2,769	2,538

^aIncludes changes in reserves.

^b104%, omitting Bethlehem Steel because of its extraordinary one-time net loss of \$448.2 million. Bethlehem's dividends represented 14.6% (\$65.5 million) of that net loss.

Source: Ref. 6, p. 121.

Fig. 2.2 Annual Average Rates of Return and Inflation in the Steel Industry, 1949-1978 (Source: Ref. 6)

bordering the Great Lakes -- New York, Pennsylvania, Ohio, Indiana, Illinois, and Michigan.¹⁷ The nonintegrated mills -- those producing steel from scrap or, to a very minor extent, directly reduced iron -- are located near the large metropolitan centers that are the source of their raw material. Figure 2.3 shows the geographic distribution of iron ore mines, coke ovens, and both the integrated and nonintegrated steel producers.

In 1980, total raw steel production was approximately 111 million tons, involving 178 blast furnaces and around 700 steel furnaces.¹ Of this amount, 60% was from basic oxygen furnaces (BOFs), 12% from open hearths, and 28% from electric arcs. The BOF percentage share is leveling out after a steady rise since 1960; open hearths are being phased out, and the share of electric arcs is increasing (see Table 10.1). However, if the steel markets recover, the BOF share can be expected to again increase.

The industry's hot metal/scrap ratio (scrap defined here to mean home, prompt, and obsolete scrap) was virtually constant at 1.25 for many years. In 1977, it began to slide, reaching 1.00 in 1980 -- indicating that the source of iron was split equally between scrap and ore.¹ Further, the focus of scrap recycling has shifted from integrated mills, where electric arc and open hearth furnaces are used together to melt scrap, to electric arc furnaces in "cold," or all-scrap, mini-mills. Since some scrap is "mined" from the nation's obsolete-scrap stockpile, there are absolute limits on how small the ratio can get, depending on primary steel production growth rates, product lifetimes, and limits on the fraction of the original volume of material capable of being recycled due to rust, dispersion, etc. As explained in Sec. 9, the rising cost of collecting the increasing fraction of obsolete scrap will cause the ratio to bottom out well before it encounters any such absolute limit.

Fig. 2.3 Geographical Distribution of the U.S. Iron and Steel Industry (Source: Ref. 18)

The mini-mill industry segment is still small -- accounting for 13% of total shipments in 1978. But its output tripled in the last decade, while the market of integrated mills continued to contract. The OTA study explains some of the reasons for this shift towards the "mini-mills," as they are termed:⁶

- They use sophisticated continuous-casting, direct-rolling, electric furnace practices and advanced scrap-handling techniques.
- Construction costs and lead times are low, and small plants that are competitive for a limited range of products can be built.
- The stockpile of their raw material, scrap, is growing, while iron ore, the major raw material of the integrated mills, is getting scarcer. According to a recent report, "net additions were made to the inventory of obsolete ferrous scrap during 19 of the 20 years between 1956 and 1975."¹⁹ (Others disagree and predict a scrap shortage in the 1980s.²⁰)
- Their product markets, primarily simple products such as reinforcing bars and merchant steel, have maintained their volume while other segments -- in particular, flat products -- have slipped.

These trends are expected to continue in the 1980s, when the mini-mills will likely provide more than 25% of the market.⁶

Table 2.5 summarizes various statistics for the industry in 1977, while Table 2.6 gives historical statistics for earlier years. Table 2.7 gives the tonnages shipped and returns on investment for the top 27 companies in 1977 and 1978. Total steel shipments in 1978 were 98 million tons.¹ The top four firms accounted for over 45% of total shipments, while the top 10 accounted for almost 70%. These market shares are nearly the same as in 1973.

Table 2.5 Summary Statistics for Blast Furnaces and Steel Mills (SIC 3312), 1977

Item	Partially Integrated			Nonintegrated (SIC 3312-14)	Total
	Fully Integrated (SIC 3312-11)	With Blast Furnaces (SIC 3312-12)	Without Blast Furnaces (SIC 3312-13)		
Number of establishments					
1-19 employees	-	-	-	254	254
20-99 employees	-	-	1	44	45
100 employees or more	35	17	81	72	205
Total	35	17	82	370	504
Aggregate employee data					
Total number (10 ³)	240.8	57.3	93.6	50.2	441.9
Payroll (\$10 ⁶)	4,888.3	1,100.7	1,800.9	935.8	8,725.7
Production workers only					
Total number (10 ³)	190	47.6	73	39.6	350.2
Man-hours (10 ⁶)	350.9	90.2	141.7	75.8	668.7
Wages (\$10 ⁶)	3,712.7	877.2	1,353.2	710.1	6,653
Cost of materials (\$10 ⁶)	12,919.2	4,406.4	5,049	4,340.3	26,715
Value of shipments, including resales (\$10 ⁶)	21,311.6	6,742.1	8,246.1	5,698.5	41,998.2
Value added by manufacture (\$10 ⁶)	8,334.8	2,415.6	3,252.7	1,328.9	15,331.9
Capital expenditures for plant and equipment (\$10 ⁶)	1,284.1	105	462.6	375.8	2,227.5
New capital expenditures (\$10 ⁶)					
New buildings and other structures	164.7	3.1	36.3	21.4	225.6
New machinery and equipment	1,091.6	100.9	419.5	305.5	1,917.6
Total	1,256.4 ^a	104.1 ^a	455.8	326.9	2,143.1 ^a

^a Does not add up due to rounding.

Source: Adapted from Ref. 21.

Table 2.6 Historical Statistics for SIC 3312 Blast Furnaces
and Steel Mills, 1963-1977

Year	Number of Establishments ^a	Number of Companies ^a		Aggregate Employee Data		Production Workers Only			Value Added by Manufacture (\$10 ⁶)	Cost of Materials (\$10 ⁶)	Value of Shipments (\$10 ⁶)	New Capital Expenditures (\$10 ⁶)	Gross Value of Fixed Assets (\$10 ⁶)
		Total	With 20 or More Employees	Total Number (10 ³)	Payroll (\$10 ⁶)	Total Number (10 ³)	Man-Hours (10 ⁶)	Wages (\$10 ⁶)					
1977	396	504	250	441.9	8,725.7	350.2	668.7	6,653	15,331.9	26,715	41,998.2	2,143.1	NA
1976	NA	NA	NA	451.9	8,041.7	358	680.9	6,100.7	14,755.5	25,665.9	39,684.1	2,142.3	32,645.8
1975	NA	NA	NA	451.3	7,076.4	354.8	657.7	5,298.5	13,356.2	23,162.3	35,659.8	2,068	30,880.5
1974	NA	NA	NA	518	7,513.2	412.3	811.5	5,848.8	17,425.8	24,341.6	41,671.7	1,643.4	29,395.6
1973	NA	NA	NA	502.1	6,480.9	409.9	822.8	5,065.2	17,769.4	17,382.5	30,365.5	1,110.5	28,018.4
1972	241	364	251	469.1	5,537.8	379.3	739.1	4,254.3	10,304.7	14,022.6	23,946.7	961.2	27,083.3
1971	NA	NA	NA	482.2	4,968.9	385	737.9	3,743.8	9,563.1	12,263.7	21,971.3	1,005.4	26,486.7
1970	NA	NA	NA	526.5	5,060.3	424.7	822.5	3,854.6	9,350.5	12,381.3	21,501.6	1,329.9	25,850.4
1969	NA	NA	NA	537.7	5,092.9	436.4	872.5	3,925.5	9,853.2	12,686.7	22,299	1,574.5	24,707.1
1968	NA	NA	NA	533.1	4,719.7	432.9	856.7	3,628.9	9,275.8	11,679.5	21,161.1	1,794.7	22,654.5
1967	200	329	259	533.1	4,385.3	434	845.4	3,368.4	8,910.1	10,997.9	19,620.6	1,661	21,524.5
1966	NA	NA	NA	559.4	4,540.7	460.4	904.9	3,554.1	9,643.7	11,829.5	21,193.9	1,595.9	NA
1965	NA	NA	NA	565.4	4,431.6	464.5	912.9	3,498.5	9,379.9	11,387.3	20,841.7	1,364	NA
1964	NA	NA	NA	532.9	4,117.9	443.9	880.9	3,249.7	8,479.6	10,537.9	18,840.1	1,282.9	17,720.4
1963	161	288	247	500.6	3,711.6	412.3	791.4	2,892.0	7,506.4	8,953.7	16,418	908.4	16,604

^aThe relationship of establishments to companies is as follows: a company is a business organization consisting of one establishment or more under common ownership or control.

NA = not available.

Source: Adapted from Ref. 21.

Table 2.7 Steel Company Profitability by
Industry Segment, 1977-1978

Company	Steel Shipped (10 ³ net tons)		Return on Investment (%)		Pretax Profits from Steel Only (\$/ton shipped)	
	1977	1978	1977	1978	1977	1978
<u>Integrated companies</u>						
United States Steel	17,868	18,866	3.7	5.3	-5.3	-1.04
Bethlehem Steel	11,251	11,859	(11)	9.3	-10.48	28.6
LTV (Jones & Laughlin)	4,427	4,881	(0.4)	5.8	-11.68	5.26
National Steel	6,912	7,438	5.8	8.2	9.45	25.66
Inland Steel	5,067	5,661	6.4	9.7	15.38	36.24
Wheeling-Pittsburgh Steel	2,477	2,655	(2)	6.3	-13.27	8.6
Kaiser Steel	1,440	1,443	0.6	1.6	-8.4	-12.25
McLouth Steel	1,286	1,468	(3.8)	5.2	-18.73	7.36
CF&I Steel	1,009	990	8.8	6.6	20.4	11.64
Interlake	738	787	5.9	3.7	4.18	-31.64
Average	-	-	1.4	6.2	-	-
Republic Steel ^{a,b}	6,038	6,501	4.2	10.4	6.36	23.35
Armco ^{a,b}	4,973	5,457	7.2	10.4	-4.02	12.79
<u>Nonintegrated companies</u>						
Northwestern Steel & Wire	763	1,077	7.2	13.9	33.38	53.33
Nucor	563	718	16.7	25	41.69	70.04
Florida Steel	418	600	4.8	13.8	8.54	27.27
Keystone Consolidated Industries	461	497	0.2	2.3	-14.88	1.35
Laclede Steel	397	471	4.2	9.4	-0.99	16.64
Atlantic Steel	346	430	4	9.6	3	20.98
Average	-	-	6.2	12.3	-	-
<u>Alloy and specialty steel companies^a</u>						
Sharon Steel ^c	965	1,055	10.6	15.3	29.38	57.83
Cyclops	776	886	5.5	10.3	16.13	41.11
Allegheny-Ludlum Industries	344	357	5.2	8.5	47.75	63.3
Copperweld	297	351	11.1	8.4	77.41	54.13
Washington Steel	42	45	9.3	11.6	150.29	190.29
Carpenter Technology	-	-	16.8	16.9	NA	NA
Lukens Steel	-	-	10	9.6	NA	NA
Athlone Industries (Jessop Steel)	-	-	7.5	9.9	NA	NA
Eastmet (Eastern Stainless Steel)	-	-	6	9	NA	NA
Average	-	-	9.1	11.1	-	-

^aAlloys and specialty steels are over 10% of company steel shipments.

^bBecause of the substantial alloy and specialty steel business, the investment returns are not averaged together with those of the other integrated companies listed.

^cAlthough Sharon Steel is integrated, most of its business is in alloy and specialty steels.

Source: Ref. 6, p. 122.

3 MATERIALS AND ENERGY FLOWS OVERVIEW

3.1 DATA SOURCES

Energy use and materials flow data for the iron and steel industry can be obtained from several sources (see Table 3.1). The Census of Manufactures' five-year censuses are the most complete source of information. The Bureau of the Census also collects and publishes yearly data (in its Annual Survey of Manufacturers) on fuels, materials flows, and electricity purchased by Standard Industrial Classification (SIC) 3312 blast furnaces and steel mills, but does not routinely do so for coal, coke, and the various by-products associated with coke, which generally amount to over one-half of the industries' true direct consumption of energy. However, a special report issued in December 1980 does include coke and coal input data.²²

DOE collects and publishes data on coke and coal chemicals, including what is consumed by the iron and steel industry. The Bureau of Mines and the Bureau of the Census both collect information on SIC 1011 iron ores. The slight difference in their iron ore values is due to differences in data collection methods, coverage, and objectives.

Four sources present statistics relating to the purchase and use of iron and steel scrap. The AISI annual statistical reports provide shipments of finished steel; imports; exports; blast furnace production (weekly); raw steel production (monthly); and scrap consumption (by grade and by furnace), stocks, production, shipments, and "scrap received," which are deliveries of both obsolete and prompt scrap. The Bureau of Mines Minerals Yearbook (Vol. I) and Mineral Industry Surveys review iron and steel scrap prices for the iron and steel industry, but otherwise depend on AISI data. The section on iron and steel scrap presents data on supply, consumption, stocks, prices, and foreign trade that are based not only on AISI data, but also on monthly census surveys of steel-casting manufacturers and iron foundries. Various Bureau of Census industrial reports cover steel inventories, scrap consumption, foundry shipments, and foundry charge metallics. The Census of Manufactures is perhaps the most complete source of information.

The two basic sources -- AISI and the Bureau of the Census -- yield few contradictions in data on steel ingot producers. However, the data on steel casting and iron foundries are marred by underreporting²⁰ and mixing of output between industries.

Finally, the trade associations connected with the industries regularly collect their own statistics. The most important are AISI, whose products roughly correspond to SIC 331 without the SIC 3313 electrometallurgical products, the Institute of Scrap Iron and Steel (ISIS), and the American Iron Ore Association (AIOA).

Table 3.1 Current Periodicals on Iron and Steel

U.S. Government Publications	Nongovernment Sources
<u>Bureau of Mines</u>	<u>American Institute of Mining, Metallurgical, and Petroleum Engineers</u>
Iron Ore Iron & Steel, reported monthly and annually in Mineral Industry Surveys Iron & Steel Scrap Chapters in Mineral Commodity Summaries Minerals Yearbook Mineral Trade Notes (monthly)	Annual proceedings of the Iron and Steel Society's Ironmaking Division, Open Hearth and Basic Oxygen Steel Division, and Electric Furnace Division Mining Engineering
<u>Bureau of the Census</u>	<u>American Iron and Steel Institute, annual reports</u>
Annual Survey of Manufacturers, SIC 3312 Blast Furnaces and Steel Mills, various regular and special reports, 33121-11 to 33121-83 (includes coke ovens) Annual Survey of Mineral Industries, SIC 1011 Iron Ores, various regular and special reports	<u>American Iron Ore Association, annual reports</u>
<u>Dept. of Energy, Energy Information Administration</u>	<u>Other Publications</u>
Energy Data Reports Coke and Coal Chemicals, annually (Bureau of Mines publication prior to 1975) Energy Research Abstracts, Metals Industry entries	33 Metal Producing, annual (McGraw- Hill) American Metal Market Engineering and Mining Journal Iron Age Iron and Steel Engineer Iron and Steel International Ironmaking and Steelmaking (quarterly) Metal Bulletin (London) Metal Statistics (Frankfurt) Metals Week Mining Congress Journal Mining Magazine/Mining Journal (London) Steel Times World Metal Statistics (World Bureau of Metal Statistics, London) World Mining

3.2 TOTAL ENERGY AND MATERIALS FLOWS

As Table 3.2 indicates, the iron and steel industry has accounted for around 4% of total domestic energy consumption for a considerable time. Table 3.3, which gives the percentage breakdown of this consumption, shows that coal accounts for about 65% of the total during 1972-1980.

Within the manufacturing sector (excluding refining), the iron and steel industry is second only to chemicals and allied products, regardless of whether feedstock energy use is counted or not. If the coal used to produce reductant coke is counted, then the industry consumed about 17% of the total feedstock and energy purchased by all industry in 1974. If only purchased energy is counted, the figure rises to 20%.

Since the purpose of this document is to describe the materials, direct and indirect energy flows, and flow interactions for the entire industry, with emphasis on which processes consume which materials, the approach of many other investigators will be followed, with the analysis carried backward to the mining or recovery of the primary raw materials. In the downstream direction, stopping at the raw steel stage allows this volume to mesh with an earlier Argonne National Laboratory (ANL) report, which covered the energy and materials flows in the steps following the production of raw steel through the final fabrication of semifinished products.²⁴

If the purpose were to obtain a complete picture of the direct and indirect energy and materials flows for the industry, the only completely correct methodology to adopt would be an energy and materials I/O analysis,²⁵ or a full process analysis, which counts not only the fuel and materials used, but also the fuel and materials used to produce the fuel and other inputs, the fuel and materials used to produce the inputs to the other inputs, etc. Two sources are available for this approach -- the Bureau of Economic Analysis I/O tables, and the work of Hannon and others at the University of Illinois.^{25,26} For reasons mentioned previously, this present analysis is limited to:

- The direct energy and materials used in each of the processes in SIC 3312 blast furnaces and steel mills;

Table 3.2 Total Energy Consumption in the United States and the Domestic Steel Industry

Year	Total (10 ¹⁵ Btu)	Steel Industry	
		10 ¹⁵ Btu	% of Total
1972	71.63	3.13	4.4
1973	74.61	3.45	4.6
1974	72.76	3.42	4.7
1975	70.71	2.94	4.2
1976	74.51	3.05	4.1
1977	76.54	2.91	3.8
1978	78.15	2.98	3.8
1979	78.97	2.84	3.6
1980	76.2	2.27	2.9

Source: Ref. 6 (p. 191) for 1972-78; Ref. 23 for 1979-80.

Table 3.3 Steel Industry Energy Consumption by Source (%)

Source	1972	1973	1974	1975	1976	1977	1978	1979	1980
Coking coal	64	64.5	62.1	66.8	65.7	62.4	56.3	54.8	57
Steaming coal	3.5	3.4	2.9	2.6	2.4	2.9	2.4	2.7	0.6
Coal purchased as coke	1.3	1.7	2.8	(1.5)	(0.9)	0.9	5.8	6.2	6.4
Subtotal	68.8	69.6	67.8	67.9	67.2	66.2	64.5	63.7	64
Natural gas	20.7	19	20	20	19.9	19.9	20.5	22.6	24
Petroleum	6.2	6.9	7.6	7.3	7.8	8.6	9.4	7.9	5
Liquid petroleum gas	-	-	-	0.1	0.1	0.1	0.1	0.1	0.1
Purchased electricity	4.3	4.5	4.6	4.7	5	5.2	5.5	5.7	6
Total	100	100	100	100	100	100	100	100	100

Source: Ref. 6 (p. 191) for 1972-78; Ref. 23 for 1979-80.

- The feedstock (reductant) energy used -- e.g., coal and coke -- by SIC 3312 facilities;
- The direct energy and materials used in iron ore mining (SIC 1110);
- The direct energy used in scrap collection;
- The direct energy used to produce a few select energy-intensive inputs to these industries, e.g., explosives, limestone, fluorspar, electricity, and oxygen. (Oxygen's contribution to indirect energy use in steelmaking is described in another ANL report.²⁷)

While this approach is neither purely direct nor indirect, it strikes a balance, retaining the simplicity of the direct approach without ignoring the major sources of indirect energy use in the industry.

There are several ways to present the energy and materials flow data so collected -- by energy and material type, or by the process which consumes or produces these flows. Within each, total energy and materials or energy and materials intensities (e.g., tons/ton, Btu/ton, gal/ton) can be calculated.

The simplest method is shown in Table 3.4. This table presents, for 1980, the direct and indirect, and direct-only, energy consumption by type for SIC 331 less 3313 facilities (i.e., the AISI industry classification), based on data in the AISI annual reports and other sources cited.

Table 3.4 1980 Domestic Energy and Materials Use
by Energy and Materials Type

Material Consumed	Amount (10 ³ tons except as noted)	Energy Intensity (direct and indirect) per Unit (10 ⁶ Btu)	Energy Use (10 ¹² Btu)	
			Direct and Indirect	Direct Only ^a
Coke				
Coal in coke ^{b,c}	58,446	26.194	1,530.9	1,530.9
Purchased coke ^b	3,444	25.99	89.51	89.51
Imported coke ^d	659	0	0	0
Steaming coal ^e	2,602	26.194	68.16	68.16
Fluorspar ^f	0.52	1.59	0.00082	0
Limestone ^f	13.34	0.24	0.00324	0
Lime ^f	6.4	5.45	0.034	0
Pellets ^g				
Domestic	59,636	1.79	107	0
Imported	12,743	0	0	0
Oré fines and concentrates in sinter plants ^h				
Domestic	3,778	0.529	2	0
Imported	11,592	0	0	0
Direct shipment iron ore charged to blast furnaces ⁱ	7,164	0.449	3.21	0
Scrap ^j				
Home	36,885	0.02	0.74	0
Obsolete	16,651	0.8 ^k	13.32	0
Prompt	13,624	0.46	6.27	0
Fuel oil ^l	700 x 10 ⁶ gal	0.15	105	105
Natural gas ^l	560,312 x 10 ⁶ ft ³	0.001	560.31	560.31
Electricity purchased ^m	43,585 x 10 ⁶ kWh	0.0105	457	148.7
Oxygen purchased ⁿ	192,264 x 10 ⁶ ft ³	0.000183	35.18	0
Domestically produced ferroalloys ^o	1,608	56	90.05	0
Total energy use			3,068.65	2,502.58
Less sales of:				
Breeze ^p	2,240	20	-44.8	-44.8
Coal chemicals ^p	496 x 10 ⁶ gal	0.15	-74.4	
Net energy use			2,949.5	2,457.8

Table 3.4 (Cont'd)

^aIncludes feedstock.

^bAmount from Ref. 1 (Table 39); coking coal conversion ratio from Ref. 22 (p. 6).

^cCoke produced is $39,276 \times 10^3$ tons.

^dRef. 28, p. 8.

^eAmount from Ref. 1 (Table 37); coking coal conversion ratio from Ref. 22 (p. 6).

^fAmount from Ref. 1 (Table 38); intensity from Ref. 29.

^gAmount from Ref. 1 (Table 41); pellet imports (assumed to be all immediately consumed) were subtracted from total material consumed to yield domestic pellet amount. Intensity from Ref. 30 (includes 0.309×10^6 Btu for transport).

^hAmount from Ref. 16; intensity from Ref. 30 (includes 0.309×10^6 Btu for transport).

ⁱAmount from Ref. 1 (Table 40), reflecting total blast furnace consumption less agglomerates; intensity from Ref. 30 (includes 0.309×10^6 Btu for transport).

^jAmounts derived from Ref. 1 (Table 42), which only covers scrap produced and scrap consumed. The difference between them is the total for prompt and obsolete scrap, $30,275 \times 10^3$ tons, of which prompt scrap accounts for 55%. Intensities from Ref. 31 (pp. 63-64, 66).

^kWeighted average of 1.28×10^6 Btu/ton for shredded auto hulks and 0.51×10^6 Btu/ton for sheared scrap.

^lAmount from Ref. 1 (Table 44); intensity from Ref. 29.

^mAmount from Ref. 1 (Table 45); intensity from Ref. 29.

ⁿAmount from Ref. 1 (Table 46); intensity from Ref. 29.

^oAmount from Ref. 1 (Table 34); intensity given is weighted average of ferroalloy intensities in Ref. 29.

^pAmounts and intensities from Ref. 32.

The table is designed to allow the analyst to modify the total to suit different purposes. For example,

- Direct energy and feedstock use in SIC 331 less 3313 (the AISI energy consumption figures) can be obtained by summing coal and coke, fuel oil, natural gas, and electricity purchased, the latter valued at 3412 Btu/kWh. This is the energy and feedstock use figure reported by AISI to DOE's voluntary energy efficiency improvement program.
- Direct energy use can be obtained by subtracting the Btu values corresponding to total domestic coke consumed, and by valuing electricity at 3412 Btu/kWh. This direct energy use figure is the one usually reported by the Census of Manufactures.

- Energy use inputs to the iron and steel industry from SIC 1011 (iron mining) can be obtained by summing the Btu values for domestic pellets, fines, and direct-shipped ore.
- Energy use in scrap can be obtained by summing the Btu values for prompt, home, and obsolete scrap.
- Domestic energy saved through imports by the iron and steel industry can be approximated by substituting the domestic energy intensities for the zero values given imports, and summing.

3.3 FLOWS BY MAJOR PROCESS

The same data can be used to present 1980 usage by each major process in the industry by a judicious use of the totals, plus additional process energy intensity data presented later in this report. Table 3.5 shows the data arrayed in that fashion. (Since the data in Tables 3.4 and 3.5 were derived using slightly different assumptions, the final totals do not match, but vary by less than 1%.) As Table 3.5 indicates, the blast furnace, consuming almost $1,100 \times 10^{12}$ Btu of coke, or 37% of total direct and indirect consumption, is the largest single consumer of energy. Heating/annealing furnaces follow with 15%, while coke ovens consume 7% of the energy. The rest of the process uses less. The heating value of the coke is a matter of some dispute; Battelle assesses it at 31.5×10^6 Btu/ton.³³ In the table, 26×10^6 Btu/ton was used. If the Battelle value had been used, the allocation of energy use between coke and iron production would have changed. Coke production would have dropped to 4%, while blast furnace use would have risen to 44%.

The data can also be presented in terms of process energy intensity per ton of output for each process, which is perhaps the most illuminating way when considering variations among years and between established and emerging technologies. These calculations require a common denominator: metal flow is the obvious choice. Frequently, mining intensities are presented using tons of iron content as the denominator. In Table 3.6, this is not done; gross tons are used instead (tons of ore mined, tons of concentrates, etc.). The only convention is that all intensities are normalized on the basis of tons of usable output, e.g., energy intensity in the concentration of ores is based on energy use per ton of concentrates, blast furnace intensity is based on energy use per ton of hot metal, etc.

Finally, the time pattern of total energy intensity in steelmaking has been calculated by AISI as part of the government's voluntary energy conservation program.²³ The trend in energy use per ton of finished steel shipped is plotted in Fig. 3.1, as well as total energy use. The figure shows almost a 10% reduction in energy use per ton since 1972, an accomplishment not

even equaled by the Japanese steel industry during the same period. If steel production were also plotted, the well-documented inverse relation between steel volume and energy consumption per ton would be apparent. This relation is caused by many factors: fixed "housekeeping" energy expenditures; nonproductive energy use, such as banking and firing of furnaces; heat-up fuel for mills; mismatched capacity utilization at lower throughput rates; etc.³⁵

Table 3.5 1980 Domestic Energy and Materials Use by Major Process

Process, Materials Consumed	Total Amount (units as specified)	Energy Use per Unit (10 ⁶ Btu/unit)	Total Energy Use (10 ¹² Btu)	% of Total
<u>Mining, Concentrating, Shipping</u>				
Domestic pellets to blast furnaces	59,636 (10 ³ tons)	1.79	107	
Domestic ore fines to sinter	3,778 (10 ³ tons)	0.529	2	
Direct shipment to blast furnaces	7,164 (10 ³ tons)	0.449	3.21	
Imported pellets	12,743 (10 ³ tons)	0	0	
Imported fines	11,592 (10 ³ tons)	0	0	
Total	94,913 (10 ³ tons)		112.21	3.7
<u>Scrap Collection and Processing (Indirect)</u>				
Obsolete	16,651 (10 ³ tons)	0.8	13.32	
Prompt	13,624 (10 ³ tons)	0.46	6.27	
Home	36,885 (10 ³ tons)	0.02	0.74	
Total	67,160 (10 ³ tons)		20.33	0.07
<u>Coke Production</u>				
Coal ^a	58,446 (10 ⁶ tons)	26.194	1,530.9	
Fuel oil ^b (underfire)	10,768 (10 ³ gal)	150	1.61	
Natural gas ^b (underfire)	30,697 (10 ⁶ ft ³)	0.001	30.7	
Electricity ^c	1,161 (10 ⁶ kWh)	0.0105	12.19	
Steam	35.17 (10 ⁶ tons)	1.15 ^d	40.45	
Blast furnace gas	727,000 (10 ⁶ ft ³)	0.000095 ^d	69	
Subtotal			1,684.85	
Less:				
Heating value of coke produced	39,276 (10 ⁶ tons) ^e	25.99	-1,021.98	
Coke oven gas				
Used elsewhere in mills	471 (10 ⁹ ft ³) ^b	0.005	-235	
Sold	0 ^f			
Tar and pitch				
Used elsewhere in mills	92.92 (10 ⁶ gal) ^b	0.15 ^f	-13.94	
Sold	329 (10 ⁶ gal) ^g		-49.4	
Light oil				
Used elsewhere in mills	59.2 (10 ⁶ gal) ^h	0.13 ^f	-7.7	
Sold	170 (10 ⁶ gal) ^h		-22.1	
Coke breeze				
Used elsewhere in mills	1.416 (10 ⁶ short tons) ⁱ	20 ^f	-28.32	
Sold	2.24 (10 ⁶ short tons) ^j	20 ^f	-44.8	
Subtotal			-1,423.24	
Net Total			261.61	7.4
<u>Blast Furnace and Stoves^b</u>				
Coke ^k	43.379 (10 ⁶ tons)	varies	1,110	
Fuel oil (includes tar and pitch)	340 (10 ⁶ gal)	0.15	51	
Natural gas	20,962 (10 ⁶ ft ³)	0.001	20.9	
Electricity ^l	1,718 (10 ⁶ kWh)	0.0105	18.04	
Coke oven gas	14,362 (10 ⁶ ft ³)	0.0005	7.1	
Oxygen	20,626 (10 ⁶ ft ³)	0.000183	3.77	
Subtotal			1,210.81	
Less: Blast furnace gas used elsewhere in mills	1,296,000 (10 ⁶ ft ³)	0.000095	-123	
Net Total			1,087.81	37

Table 3.5 (Cont'd)

Process, Materials Consumed	Total Amount (units as specified)	Energy Use per Unit (10 ⁶ Btu/unit)	Total Energy Use (10 ¹² Btu)	% of Total
<u>Steel Furnaces^b</u>				
Fuel oil (includes tar and pitch)	151 (10 ⁶ gal)	0.15	22.75	
Purchased oxygen ^m	146.7 (10 ⁶ ft ³)	0.000183	26.85	
Natural gas	32,481 (10 ⁶ ft ³)	0.001	32.5	
Coke oven gas	5,885 (10 ⁶ ft ³)	0.0005	2.3	
Electricity	n	n	218.05	
Blast furnace gas	10,051 (10 ⁶ ft ³)	0.000095	0.95	
Total			303.41	10
<u>Heating/Annealing Furnaces^b</u>				
Fuel oil	151,777 (10 ⁶ gal)	0.15	22.76	
Natural gas	317,431 (10 ⁶ ft ³)	0.001	317.43	
Liquid petroleum gas	NA	NA	0.342	
Coke oven gas	208,499 (10 ⁶ ft ³)	0.0005	104.24	
Blast furnace gas	62,506 (10 ⁶ ft ³)	0.000095	5.93	
Total			450.7	15
<u>Other Processes (sinter plant, finishing, ingot casting) or Unallocated Electricity^b</u>				
Light oil	59.2 (10 ⁶ gal)	0.13	7.7	
Fuel oil (includes tar and pitch)	138.9 (10 ⁶ gal)	0.15	20.84	
Liquid petroleum gas	NA	NA	0.25	
Natural gas	158,740 (10 ⁶ ft ³)	0.001	158.74	
Coke oven gas	227,767 (10 ⁶ ft ³)	0.0005	113.88	
Blast furnace gas	1,224,859 (10 ⁶ ft ³)	0.000095	116.36	
Electricity (purchased) ^o	19,714 (10 ⁶ kWh)	0.0105	207	
Steaming coal	2,602 (10 ³ tons)	26.194	68.16	
Coke breeze	1.416 (10 ³ tons)	20	28.32	
Oxygen (purchased) ^o			4.56	
Ferroalloys			90.05	
Subtotal			815.86	
Less: steam used elsewhere			-40.45	
Net Total			775.41	26
<u>Grand Total</u>			3,125.36	

^aRef. 1 (Table 37).^jRef. 34 (Table 18).^bRef. 1 (Table 44).^kData from various sources.^cCalculated by multiplying electricity intensities in Table 6.6 by total 1980 tonnage for each product.^lCalculated by multiplying electricity intensities in Table 7.1 by total 1980 tonnage for each product.^dRef. 29.^m90% is purchased.^eRef. 1 (Table 39).ⁿCalculated by multiplying electricity intensities in Tables 10.2, 10.3, and 10.4 by total 1980 tonnage for each product.^fRef. 33 (conversion chart).^gRef. 34 (Table 25).^oUnallocated remaining.^hRef. 34 (Table 26).

NA = not available.

ⁱRef. 1 (Table 41).

Source: Table 3.4, except as noted.

Table 3.6 Direct Energy Intensity per Ton of Product
(10^6 Btu/ton)

	Source and Base Year of Data							
Process, Material	Ref. 30, 1978	Ref. 29, 1973	Ref. 36, 1978	Ref. 37, 1970	Ref. 38, 1977	Ref. 31, 1978	Ref. 39, 1976	This Report, 1980
<u>Mining</u>								
Concentrates								
Mining	0.14	0.31			0.184			
Concentration	0.08	0.31			0.04			
Other	-	0.31			0.01			
Pellets								
Mining	0.21	0.606			0.265			0.529 ^a
Concentration	0.518	1.145			0.83			
Induration	0.885	0.5 ^b , 1 ^c			0.885			
Other	0.262				0.04			1.79 ^a
<u>Scrap</u>								
Obsolete								
Auto shredding			2.4			1.28		
Auto guillotine			-			0.65		
Baled			1.5			0.72		
Sheared			1.5			0.47		
Cut			1.5			0.34		
Home			0			0.02		0.02
Prompt			0.6			0.46		0.46
Weighted average for all scrap						0.8		
<u>Sinter</u>	1.3-1.9	2.47			-	-	2.39	-
<u>Coke</u>								
Heating value of coal consumed		37.7		37.94			39.03	38.97
Underfire plus electricity		4.83		3.42			4.32	3.91
Less: By-product credit		-11.62		-9.51			-11.11	-10.25
Total ^d		30.91		31.85			32.24	32.63
<u>Blast Furnace</u>								
Consumption		20.2 ^d		21.34 ^e				18.96 ^f
Net production		-1.85		-4.62				-1.79
Net Total		18.35		16.71				17.17
<u>Steel Furnaces</u>								
Open hearth		3.4						3.29
BOF		0.52						0.52
Electric arc		5.88						7.36

^aIncludes shipping.

^bFe₃O₄.

^cFe₂O₃.

^dIncludes heating value of coke produced.

^eCoke at 31.5×10^6 Btu/ton.

^fCoke at 25.99×10^6 Btu/ton.

Fig. 3.1 Energy Use in the Steelmaking Industry, 1972-1980
(Source: Based on Ref. 23 data)

4 OPERATIONS NEAR THE MINE

4.1 RESERVES

Table 4.1 describes the major types of deposits that contain sources of iron, their present importance, and their resource potential both in the United States and abroad. There are five principal iron ores: hematite (Fe_2O_3), magnetic taconite, nonmagnetic taconite, specular hematite, and iron laterites.⁴⁰ High-grade (60% Fe) hematite ores require no beneficiation, and are directly shipped to blast furnaces or sinter plants. The Great Lakes deposits are nearly exhausted.

Magnetic taconites are presently the primary ores of the industry. In the form of magnetite (Fe_3O_4), they average 22-35% Fe and 40-50% SiO_2 ; hence, they are fine-grained, dense, and hard. Figure 4.1 shows a typical pellet beneficiation plant for such taconites. Ninety-five percent of the magnetite is recovered, and it takes 3.2 tons of ore to produce one ton of pellets containing 63% magnetite and 8% SiO_2 .

The nonmagnetic taconites can be richer than the magnetic taconites, containing 28-40% iron in the form of hematite and limonite ($\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$), but they are more expensive to concentrate due to the absence of magnetic ores. Magnetic separation can occur either by using very high intensity (approximately 20,000 gauss field strength) separation of the hematite, or by converting the hematite to magnetite by roasting.

Specular hematite is about 50% crystalline hematite and 50% granular quartz, which can be separated after crushing by flotation, then pelletized. It is of some importance, since there are deposits being mined in Michigan and reserve deposits in Quebec. (U.S. Steel's "QCM" concentrate is specular hematite.)

The iron laterites -- goethite and limonite, in particular -- are decomposition products of the primary iron minerals, and account for major amounts of southern production.⁴¹ They usually contain valuable by-products such as nickel, chromium, and alumina, which can be recovered during concentration. The ore is usually crushed, roasted, screened to permit magnetic separation of the magnetite produced by the roasting process, and finally pelletized.

Further details on reserves are given in Table 4.2. This table combines high- and low-grade ores; therefore, regional tonnages are not directly comparable. Even if the conservative assumption is made that all reserves are low-grade, there is still enough world supply to last 100 years at current production rates. The U.S. and Canadian reserves of 45 billion tons are sufficient alone to sustain North American steel production for 125 years at 1980 crude ore production rates. Nonetheless, U.S. high-grade ores are almost

Table 4.1 Categories of Iron Ore

Category	Location of Typical Example	Principal Iron Minerals	Average Iron Content (%)	Form of Exploited Deposits	Present Importance	Size of Reserves	
						United States	World
<u>Sedimentary deposits</u>							
Banded Iron formation	Labrador	Magnetite, hematite, siderite, iron silicates	33	Beds hundreds of feet thick, strikes tens of miles long.	Major	Enormous	Enormous
Ironstone	Birmingham, Ala.	Limonite, hematite, siderite, chamosite	30	Beds tens of feet thick, strikes 0-10 miles long.	Minor	Medium	Large
Miscellaneous (bog iron, black band siderite, black sands)		Limonite, siderite, magnetite, ilmenite	-	Various forms	Negligible	Small	Small
<u>Deposits related directly to igneous activity</u>							
Magmatic segregations	Xiruna, Sweden	Magnetite	65	Tabular, hundreds of feet thick, many thousands of feet long.	Modest	Medium	Medium
Pyrometamorphic deposits	Cornwall, Penn.	Magnetite, hematite	45	Tabular to podlike, a few hundred feet thick, a few thousand feet long.	Modest	Large	Medium
<u>Deposits formed by hydrothermal solutions</u>							
Replacement deposits in nonferruginous rocks	Buena Vista, Nev.	Magnetite, hematite, siderite	30	Irregular pods, lenses, stockworks, veins	Minor	Small	Small
Enrichments of preexisting ferruginous rocks	Minas Gerais, Brazil	Specular hematite	68	Tabular, parallel or subparallel to bedding of enclosing iron formation. Up to several hundred feet thick.	Modest	Negligible	Medium
<u>Laterite deposits produced by surface or near-surface enrichment</u>	Cuba	Limonite, hematite	45	Blankets, tens of feet thick, tens or hundreds of square miles in area.	Minor	Small	Large
<u>Secondary enrichments of low-grade iron deposits</u>	Lake Superior region (for direct-shipping and wash ores)	Limonite, hematite	55	Blankets to sacklike bodies, dimensions in hundreds to thousands of feet. Most are a few hundred feet below surface, but Lake Superior deposits extend to several thousand feet.	Major	Large	Large

Source: Adapted from Ref. 42.

Fig. 4.1 Beneficiation of Magnetic Taconites
(Source: Ref. 40)

exhausted; it was estimated that, in 1968, only one-fourth of the Lake Superior high-grade (51% Fe) ore remained after a century of exploitation.³⁷

4.2 MINING

Figure 4.2 shows the materials flows for mining, agglomeration, imports, and exports of iron ore and ore agglomerates for 1980. Data are from the 1980 AISI and AIOA annual reports and Table 4.3. The data differ slightly from those reported in other sources, but not enough for concern.

Table 4.2 World Iron Ore Resources
(10⁶ metric tons)

Geographic Area	Identified Resources ^a	
	Total	Reserves ^b Only
North America		
United States	101,000	9,000
Other (mostly Canada)	126,000	36,000
South America	94,000	34,000
Europe	34,000	21,000
Africa	31,000	7,000
Australia and New Zealand	17,000 ^c	17,000
Asia	72,000	17,000
Soviet Union	304,000	111,000
Total	779,000	252,000

^aIdentified deposits whose extent and grade may or may not be evaluated, and whose contained minerals may or may not be profitably recovered with existing technology and under present economic conditions.

^bIdentified deposits from which minerals can be extracted profitably with existing technology and under present economic conditions.

^cMostly high-grade ores; vastly greater quantities of lower-grade iron formations are known but have not been assessed.

Source: Adapted from Ref. 42.

To see the trend over time of the flows, Table 4.3 gives U.S. iron ore mining and shipping data. The data reveal the impact of fluctuating U.S. iron and steel production on crude ore production and shipments of the various concentrates, as well as the continuing substitution of taconite pellets for direct shipping ores (limonite, hematite) as the latter ores become scarce. Figure 4.3 shows this substitution even more clearly; since 1967, the pellet percentage has grown from 30% to nearly 70%, while directly shipped ores have decreased from 30% to less than 10%. Table 4.4 shows U.S. consumption of iron

Fig. 4.2 Materials Flows in Mining and Beneficiation, 1980
(Source: Refs. 1 and 16, and Table 4.3)

ore from all sources. Non-Canadian ore imports as a percentage of total receipts show a ratchet-like decline during the 1970s, with Canadian ores taking up the slack. Table 4.5 indicates that the mining of iron ore is not particularly energy-intensive; open-pit operations tend to be less energy-intensive than underground mining.⁴³ Taconite's mining intensity is higher than that of natural ores due to its greater toughness; taconite requires almost five times the explosive energy to mine.

There appear to be few opportunities to radically reduce energy consumption in iron ore mining, although the trend towards larger loading and hauling equipment will marginally reduce consumption.³⁰ Increasing iron ore imports is clearly an energy conservation strategy; importing 25% of domestic requirements, as at present, saves about 0.5×10^6 Btu per ton of raw steel produced. The possibility of importing ore rather than oil and lessening dependence on OPEC nations is attractive, although it tends to concentrate the burden of oil independence on the domestic iron ore industry. If all ore had been imported in 1978, an additional 130×10^{12} Btu could have been saved. Assuming that a barrel of imported oil contains 5.8×10^6 Btu, this would have reduced oil imports by 22.4×10^6 barrels, roughly 2% of 1978 imports from OPEC nations.

Table 4.3 U.S. Iron Ore Production and Shipments, 1973-1980^a (gross tons)

Material	Year	Great Lakes	Northeastern	Southern	Western	Total
Crude ore mined	1973	183,680,322	6,806,120	8,492,991	17,795,432	216,774,865
	1974	183,599,928	6,365,115	7,029,961	17,182,571	214,177,572
	1975	185,169,748	5,150,420	7,249,961	15,049,673	212,619,802
	1976	194,626,881	5,506,730	7,638,560	15,036,322	222,808,493
	1977	130,220,726	3,659,230	7,033,315	15,558,733	156,472,004
	1978	214,784,593	379,447	4,195,756	15,418,226	234,778,022
	1979	234,984,926	858,507	4,936,868	14,928,414	255,708,715
	1980	194,810,818	666,776	3,916,632	11,712,579	211,106,805
Production						
Run of Mine	1973	227,176	--	337,418	1,540,734	2,205,328
	1974	200,476	--	133,930	1,444,288	1,778,685
	1975	111,225	--	112,602	1,088,091	1,311,918
	1976	82,518	--	91,246	1,012,354	1,186,118
	1977	61,767	b	b	1,457,735	1,545,502
	1978	b	--	b	1,622,724	1,697,884
	1979	b	--	b	1,218,777	1,327,300
	1980	b	--	b	1,003,857	1,071,340
Coarse	1973	9,708,421	b	b	1,620,888	11,745,509
	1974	9,126,313	b	b	1,310,587	10,915,482
	1975	4,825,518	b	b	1,014,451	6,254,530
	1976	3,975,308	b	b	1,173,020	5,521,092
	1977	2,557,808	b	b	927,385	3,948,255
	1978	2,881,957	b	b	647,310	3,690,117
	1979	b	b	b	680,744	2,400,673
	1980	b	b	b	638,362	1,243,538
Fines	1973	10,213,751	101,478	b	b	11,670,139
	1974	9,922,906	132,548	100,705	745,812	10,901,973
	1975	6,148,216	575,816	100,260	884,733	7,709,024
	1976	5,529,862	1,120,018	112,806	886,748	7,649,434
	1977	3,141,561	971,061	110,318	873,381	5,096,321
	1978	b	b	b	950,585	4,497,473
	1979	2,399,359	b	b	1,149,545	3,916,421
	1980	2,107,336	--	--	440,080	2,851,474
Pellets	1973	56,031,439	b	2,673,189	b	63,935,447
	1974	52,944,435	b	b	3,996,066	60,050,133
	1975	53,089,020	b	b	3,411,312	59,865,167
	1976	55,340,025	b	b	3,475,261	62,155,361
	1977	37,478,248	b	b	3,459,088	43,460,566
	1978	68,251,543	--	954,758	3,360,993	72,567,294
	1979	73,712,806	--	751,994	3,551,601	78,016,401
	1980	58,831,261	--	1,276,646	2,703,249	62,811,156
Total Shipments						
	1973	76,280,787	2,367,465	3,861,552	8,328,925	90,838,729
	1974	72,194,123	2,365,704	2,818,595	7,496,753	84,875,175
	1975	64,173,979	1,888,064	3,222,157	6,398,587	75,682,787
	1976	64,927,713	2,099,251	3,151,907	6,547,383	76,726,254
	1977	43,239,384	1,587,230	2,771,649	6,717,589	54,315,852
	1978	74,307,299	421,380	1,301,131	6,581,612	82,611,422
	1979	77,836,884	330,214	1,285,138	6,600,667	86,052,903
	1980	61,536,060	300,851	1,904,549	4,785,548	68,527,008

^aIncludes iron ore with 5% or more manganese.

^bNot shown to avoid use of individual company data.

Source: Ref. 44.

Fig. 4.3 Proportioning of Iron in Different Iron-bearing Materials in U.S. Blast Furnaces (Source: Ref. 45)

4.3 CRUSHING, CONCENTRATION, AND PELLETIZATION

Further processing of direct-shipping ores uses very little energy, since only crushing, screening, and washing are required to remove clay and sand.²⁹ Estimates range from 0.05×10^6 Btu/ton to 0.08×10^6 Btu/ton. Since ore from this source is small (10% of domestic production) and on the decline (down two-thirds in the last 10 years), no further consideration will be given to it.⁴⁴

Table 4.5 shows that pellet production, on the other hand, is very energy-intensive,* ranging from 1.5×10^6 Btu to 2.3×10^6 Btu per ton of

Table 4.4 Consumption of Iron Ore at U.S. Iron and Steel Plants, 1971-1980 (10^3 gross tons)

Year	United States Ores		Canadian Ores		Foreign Ores	Total
	Great Lakes	Other	Great Lakes	Other		
1971	59,547	13,548	3,828	14,894	17,149	108,966
1972	68,782	13,075	3,871	16,480	17,729	119,937
1973	76,603	13,773	4,251	17,992	24,454	137,073
1974	70,978	12,402	3,345	15,608	26,744	129,077
1975	60,061	10,777	2,694	12,731	19,967	106,230
1976	63,864	11,267	4,672	18,185	16,335	114,323
1977	57,663	13,217	4,457	16,985	16,140	108,462
1978	64,617	10,090	3,379	18,734	19,494	116,304
1979	66,080	9,872	2,228	20,843	15,991	115,014
1980	53,985	8,297	1,368	15,912	9,835	89,397

Source: Ref. 44.

pellets, depending primarily on the amount of magnetite in the ore. The higher the magnetite content, the lower is the energy use per ton, because of (a) the lower energy requirements for magnetic separation; and (b) the generation of heat when magnetite oxidizes to hematite. The production of pellets from taconite consumes significant amounts of energy in the form of electricity and hydrocarbons, and is the major reason why iron ore mining used almost as much energy in 1977 (78.9×10^{12} Btu)⁴⁶ as steelmaking did in the previous year (94×10^{12} Btu).⁴⁷ As Fig. 4.1 illustrates, the process has three steps: crushing, separating or concentrating, and induration.

Since taconite is a very tough material, the crushing step requires considerable electrical energy to run the equipment. Concentration is done by gravity, flotation, or magnetic separation processes. The range of estimates in Table 4.5 is due almost completely to the range of electrical energy use in the references, where the estimates were 50 kWh, 75 kWh, 105 kWh, and 150 kWh per ton of taconite. Such variation can be explained by differences in the ore silicon content, age of the equipment, type of grinding process, etc., although there is some evidence that the estimates lower than 200 kWh/ton ignored the large amount of electricity used in the magnetic separation process.⁴⁸

There is much interest in energy-conserving possibilities for industrial comminution (i.e., crushing and grinding). A recent NRC publication estimates that comminution consumed between 1% and 2% of the nation's electric power production in 1978, and is "both energy intensive and inefficient."⁴⁹

Table 4.5 Direct Energy Intensities in Iron Ore Mining and Concentration^a (10⁶ Btu/ton of end product)

Reference, Base Year for Data	Concentrates				Pellets				
	Mining	Concen- tration	Other	Total	Mining	Concen- tration	Indu- ration	Other	Total
Ref. 38, 1977 ^b	0.184	0.04	0.01	0.234 ^c	0.165	0.83	0.885	0.04	2.02 ^c
Ref. 50, 1975	0.142 ^d	d	0.032	0.174		1.317		0.189	1.51
Ref. 30, 1978	0.14 ^e	0.08	-	0.22	0.21 ^f	0.518	0.5 ^g 1 ^h	0.252	1.48 ^g 1.99 ^h
Ref. 39, 1976									1.59
Ref. 29, 1975 ^b				0.31	0.606	1.145	0.561	-	2.31
Ref. 46, 1977									2.13 ^a
Ref. 37, 1980				0.28					2.69
Ref. 51, 1981							0.556 ^f 1.15 ^g 0.335 ⁱ	0.25	
Ref. 52, 1979							0.591 ^j 0.604 ^k 0.607 ^l	0.22 0.19 0.26	
Ref. 49, 1977						1.1 ^m			

^aElectricity valued at 10,500 Btu/kWh. This necessitated recalculation of data in Ref. 29, which were based on electricity at 3,412 Btu/kWh.

^bStudy results in Refs. 29 and 38 are for direct and indirect energy intensities combined. Transportation energy intensities vary between these two studies because of different assumptions about mileage and energy intensity per mile.

^cAdjusted to reflect (a) Btu/ton of product, not of contained Fe; (b) no transportation; (c) direct energy use except for electricity. If direct and indirect energy intensities were both counted, iron ore and pellet totals would be 0.34 and 2.53, respectively.

^dMining and concentration summed together yield 0.142×10^6 Btu/ton.

^eAssumes two tons of crude ore per ton of direct shipping ore.

^fAssumes three tons of taconite per ton of pellets.

^gFe₃O₄.

^hFe₂O₃.

ⁱUnder ideal conditions, as identified in Ref. 51.

^jFor shaft induration equipment.

^kFor grate-kiln induration equipment.

^lFor traveling-grate induration equipment.

^mFor magnets.

The report points out that modifying equipment with existing technology (automatic control, improved sizing and classification, closed circuit grinding, use of additives) could reduce energy consumption by 9 billion kWh(e) in five years, while new technologies could trim an additional 15 billion kWh(e) in the longer term. Despite this interest, no specific energy-conserving technologies were identified in the report for iron ore crushing; however, new technologies are being developed that will achieve more efficient blast furnace processing of ores with high iron content. They include cationic silica removal, flocculation of iron oxide to lower Fe loss, and conversion of nonmagnetic to magnetic ore to allow magnetic beneficiation.³⁷

The mixture of moist clay, hydrocarbons, and ore produced during the concentration step is then fired and heat-hardened in ignition furnaces. Table 4.5 shows that energy use in the induration step (i.e., pelletizing at 2000°F, usually using hydrocarbons) ranges from 5×10^6 Btu/ton to 1.15×10^6 Btu/ton, depending on the amount of magnetite in the ore and, to a large extent, on the type of induration equipment -- shaft, grate kiln, or traveling grate. Since hydrocarbons -- mainly fuel oil and natural gas -- have been used in the induration process, much effort has been devoted to conservation and fuel-switching opportunities.

Several firms report great success in reducing the amount of energy used in induration. The Erie Mining Co.'s plants in Aurora, Minnesota, recently received the National Energy Watch Award from the Edison Electric Institute for reducing energy consumption per ton by 20%. Hibbing Taconite Corp. reports a 38% reduction in consumption at its plants, to 300,000 Btu/ton,⁵³ which is well below the 500,000-600,000 Btu/ton average in Table 4.5 and very close to the level under ideal conditions, as identified by Wakeman and Frans.⁵¹ Ideal conditions would include nonreactive feed, no fixed heat losses, input and output air and solids temperature at 77°F, and 10% moisture content for the mixture of raw material.⁵³ Energy consumption is higher at older plants, since they lack the heat recuperation facilities that are part of all modern plants. However, most old plants can and probably will be retrofitted to recover heat from the first cooling zone, since 1981 fuel prices make the investment cost-effective.

Turning to fuel substitution for the hydrocarbons now used, since 85% of U.S. pellet capacity shown in Table 4.6 is in Minnesota and Michigan, the use of western coal as a substitute fuel is a logical possibility. Two alternatives are direct firing of the kiln by processed coal, and conversion of coal to coal gas for use. At least four of the largest pelletizing operations, representing over 50% of U.S. capacity, have taken steps towards direct firing of coal (Inland, Hibbing, U.S. Steel) or coal gasification (Erie). Operating problems still hamper these processes, and Inland's straight-grate system is still not working. Suppliers of both the grate-kiln system (Allis-Chalmers) and the traveling-grate system (Dravo) have modified their processes to insure that ash buildup, the major impediment to switching to coal, is held within acceptable bounds.³⁰ However, the experience at some plants using coal firing indicates that ash from coal may not be a problem.

Table 4.6 U.S. Pellet Plants

Company and Plant Location	Type and Number	Startup	Annual Capacity (10 ³ tons)	Feed Material (ore)	Type of Pellet ^a	Iron Content (%)
Bethlehem Steel						
Cornwall Plant, Cornwall, Penn.	shaft kiln (3)	1962	800	magnetite	BF	64-66
Grace Mine, Morgantown, Penn.	shaft kiln (6)	1961	1,800	magnetite	BF	65-66
Erie Mining Co., Aurora, Minn.^b						
Erie I	shaft kiln (24)	1957	7,500	magnetite	EF	64
Erie II	shaft kiln (2)	1961	700	magnetite	BF	64
Erie III	shaft kiln (1)	1967	1,100	magnetite	BF	65
Eveleth Taconite Co., Virginia, Minn.						
Eveleth I	rotary kiln (1)	1966	1,600	magnetite	BF	65-66
Eveleth II	rotary kiln (1)	1976	3,600	magnetite	EF	65-66
Hanna Mining^c						
Groveland Plant, Randville, Mich.	straight grate (1)	1963	1,375	magnetite/hematite	BF	62-63
Pilot Knob Plant, Mountain Iron, Mo.	straight grate (1)	1968	2,400	magnetite	BF	64
Hibbing Taconite Corp., Hibbing, Minn.^b						
Taconite I	straight grate (2)	1976	5,400	magnetite	BF	66
Taconite II	straight grate (1)	1978	2,700	magnetite	BF	66
Inland Steel^d						
Butler Plant, Cooley, Minn.	rotary kiln (1)	1967	2,000	magnetite	BF	66
Black River Falls Plant, Black River, Wis.	straight grate ^e (1)	1969	750	magnetite	BF	62-63
Minorca Mine, Virginia, Minn.	straight grate ^c (1)	1977	2,600	magnetite	BF	-
Kaiser Steel						
Eagle Mountain Plant, Eagle Mountain, Calif.	straight grate (1)	1965	2,200	magnetite/hematite	BF	64-65
Meramec Mining Co.^b						
Pea Ridge Plant, Pea Ridge, Miss.	straight grate (1)	1964	2,000	magnetite	BF	67
National Steel, Keewatan, Minn.						
National I	rotary kiln (1)	1969	2,400	magnetite	BF	66-67
National II	rotary kiln (1)	1977	4,100	magnetite	BF	65

Table 4.6 (Cont'd)

Company and Plant Location	Type and Number	Startup	Annual Capacity (10 ³ tons)	Feed Material (ore)	Type of Pellet ^a	Iron Content (%)
Reserve Mining, Silver Bay, Minn. ^f						
Reserve I	straight grate (6)	1955	5,500	magnetite	BF	62-63
Reserve II	straight grate (2)	1963	3,000	magnetite	BF	62-63
United States Steel						
Atlantic City Plant, Lander, Wyo.	straight grate (2)	1962	1,500	magnetite	BF	63-64
Mountain Iron, Minn.						
Mintac I	rotary kiln (3)	1967	4,500	magnetite	BF	65
Mintac II	rotary kiln (2)	1972	6,000	magnetite	BF	65
Mintac III	rotary kiln (2)	1977	6,000	magnetite	BF	65
TOTAL			71,525			

^aBF = blast furnace; EF = electric furnace.^eScrubbers installed for pollution control.^bPartially owned by Bethlehem Steel.^fJointly owned by Armco, Inc., and Republic Steel.^cDivision of National Steel.

Source: Ref. 55, p. 17.

^dPartially owned by Hasca Pellet Co.

Because pre-1965 facilities with shaft furnaces will encounter difficulties with direct firing of coal, they will likely turn to on-site coal gasification, as Erie has, for alternate sources of fuel. According to one source, the process economics look quite favorable, since the cost of fuel gas per long ton of pellet to achieve an 8% return on investment is \$1.81 for the shaft furnace, with coal (western unit train) at \$20 per delivered ton.⁵² The conventional shaft furnace uses roughly 600,000 Btu of natural gas per ton (400,000-450,000 Btu with heat recuperators). With natural gas selling at \$2.68/10³ ft³, the cost of conventional fuel would be \$1.56.⁵⁵ However, another study indicates that the cost would be significantly higher (\$4.80/long ton) if a 15% return on investment is used. If natural gas increases in price, on-site gasification could soon become economical. What makes the on-site system so attractive is that the low-Btu gas is delivered to the pellet plant at 1000°F; the kiln takes full advantage of the latent heat of the coal gas. A problem is that there are few uses, outside the kiln itself, for the hot low-Btu gases produced by the process.

In summary, the prospects look bright both for energy conservation and switching to coal for the pelletizing process; substantial reductions in total Btu and natural gas use per ton of pellets are likely in the near future.

5 SINTERING PLANT

Figure 5.1 gives the materials and energy flows for the blast furnace area, including the coke ovens, sinter plant, and blast furnace (including stoves) for 1980. The amounts are based primarily on AISI data, except for the data on tars, light oils, and coke breeze, which are taken from a recent DOE Energy Data Report. This chapter discusses sinter production; coke oven and blast furnace processes are discussed in the following two chapters.

The sintering plant provides a means of recycling many of the iron-bearing fines generated by ironmaking and steelmaking. Materials such as scale, sludge, and slag are added to ore fines and agglomerated into a suitable material. Flux, in the form of dolomite or limestone, is added to the sinter burden and calcined during the process, decreasing the energy requirements of the blast furnace process. Blast furnace slag is not recycled through the sinter plant, but is sold to slag scrap processors who convert the slag into salable products. Electric arc sludge and slag are not normally included in sintering burdens because of tramp impurities.¹⁵

The sinter, usually 50-60% Fe, is easily reducible, since its high surface-to-volume ratio permits high gas/solid contact. It is blended and sized prior to feeding onto the grate. To prevent ascending gas in the blast furnace from blowing it out of the stack, the blend is adjusted until it is strong enough to resist being compressed into an impervious layer in the furnace. Fuel for the process is provided by the metal-bearing raw material itself, plus coal and coke breeze. As Fig. 5.2 illustrates, the process takes place on a traveling grate that carries the sinter, which is carefully bedded to insure consistent quality. The fuel is ignited and the flame is drawn down through the sinter by air suction windboxes; the process is complete when burn-through takes place at the sintering temperature of 2500°F. The sinter is then cooled either on- or off-strand, sized to less than one-half inch, and fed into the blast furnace.

Several U.S. plants have experimentally recycled sinter gas to conserve the sensible heat and reduce environmental problems; there is some question about the cost-effectiveness of this process. No plant is now doing this recycling, since even though it saves 3% of the energy (0.059×10^6 Btu/ton), it replaces an inexpensive energy source (coke breeze) by an expensive one (electricity to run the recirculation fans).⁵⁶

Table 5.1 shows the materials flows into sintering plants. Iron in the form of sinter fell steadily from 35% of the blast furnace charge in 1967 to about 25% in 1972, and has remained roughly constant since then.⁴⁶ Sinter plant capacity has remained near 45 million tons for some time, with nearly 25% of the plants over 35 years old.⁵⁷

One source predicts little possibility of this capacity increasing, since the high-grade fines suitable for sintering (principally hematite from

Fig. 5.1 Materials Flows in the Blast Furnace Area, 1980 (Source: Refs. 1, 28)

Fig. 5.2 Typical Sintering Machine

Quebec, Brazil, and Venezuela) are being replaced by lower-grade ores (taconite) suitable for pelletizing.⁴⁶ This development prompted renewed interest in the mid-1970s in binderless (i.e., no paste) hot (1800°F) briquetting as a substitute for agglomerating steel mill wastes in the absence of such fines.⁵⁸ The process drastically reduces energy consumption since it does not require complete combustion of the nonvolatile combustible matter as does the sinter process. The excess remains in the product, allowing the energy requirements for the blast furnace to be reduced.

The Japanese have been exploring direct reduction of blast furnace and BOF wastes;⁵⁹ significant energy savings over comparable processes have been reported. Japan is the only country currently emphasizing iron fines recycling; approximately 70% of its residues are recycled.⁶ There will likely be a resurgence of sinter plants in response to the increasing values of the carbon and iron content that would otherwise be wasted. Foreign ore fines are plentiful, and improved blending and bedding of the sinter will increase the productivity of the process. Sinter is desirable in a blast furnace, since full pellet charges increase wall temperature and reduce furnace life.

Energy intensities for sinter plants show wide variation due to the large variation in input mixes encountered in the waste recycling and recovery

Table 5.1 Sinter Production, 1973-1980 (10^3 net tons)

Materials	1980	1979	1978	1977	1976	1974	1973
Inputs							
Ore fines and concentrates	15,370	20,353	21,902	21,096	22,523	28,622	29,787
Flue dust and sludge	2,065	2,509	2,422	2,520	2,452	2,357	2,289
Scale	3,464	4,235	4,057	3,697	3,531	3,790	4,031
Coke breeze	1,416	1,892	2,014	1,992	2,054	2,247	2,503
Coal	171	130	137	126	139	367	231
Cinder and slag	2,206	2,789	2,907	1,789	2,156	1,698	1,770
Limestone and dolomite	6,109	8,210	7,530	7,773	7,422	8,710	8,941
Other	1,417	2,303	2,747	2,711	2,262	1,929	1,981
Outputs: sinter, briquettes, nodules, other							
	27,886	35,969	36,140	31,987	36,331	40,769	43,335

Source: Ref. 60, except ore fines, which are from Ref. 45.

process. Table 5.2 gives the estimates from the various sources utilized in this study. The hot briquetting energy intensity is included for comparison. At least one source thinks any substantial energy savings in the sintering process to be unlikely, although alternate technologies (hot briquetting, etc.) would save energy if substituted.³⁰ Another report indicates that injection of steam produced by partial recovery of the sensible heat of sinter waste gases into the balling drum of the sinter plant has reduced fuel consumption by 8.4%.⁶¹

According to an OTA study, current capital shortages and slack capacity make it unlikely that steel companies will show much interest in what amounts to waste recycling; most likely, slag scrap recoverers will diversify into the sinter business.⁶ Most industry sources disagree, and expect a resurgence in sintering as the value of the contained iron continues to rise.

Table 5.2 Energy Intensities in the Production of Iron Ore Sinter

Source	Inputs	Input Amount (net ton/net ton of sinter except as noted)	Energy Use (10^6 Btu)	
			Per Unit	Per Net Ton of Sinter
Ref. 29	Ore fines	0.61	0.715	0.44
	Turns	0.267	0	0
	Flue dust and fines	0.143	0	0
	Mill scale (scrap)	0.122	0	0
	Limestone	0.049	0.24	0.01
	Coke breeze	0.074	21	1.55
	Natural gas	150 ft ³	0.001	0.15
	Electrical energy	30 kWh	0.0105	0.32
	Total			2.47
Ref. 39	Coal			0.35
	Natural gas			0.07
	Coke breeze			1.39
	Coke oven gas			0.07
	Electricity			0.41
	Steam			0.1
	Total			2.39
Ref. 30	Total			1.3-1.9
Ref. 56	Total			2.16
Ref. 59	Total ^a			0.6

^aFor nonsinter process of hot briquetting.

6 COKE PRODUCTION

6.1 COKE AND ITS BY-PRODUCTS

6.1.1 Characteristics of Coke

The destructive distillation of a blend of bituminous coals in coke ovens at 1650°-2000°F produces a carbonaceous residue known as coke. Coke is the primary fuel for blast furnaces, which produce the iron for steelmaking furnaces.

In the blast furnace, a chemical agent is needed to reduce the oxides of iron; this agent is carbon, provided by coke. Coke production requires an expensive low-sulfur bituminous coking coal. The optimal blend of coals, as reported by Thermo Electron Corp., is 60% high-volatile coal and 40% low-volatile coal,³⁹ although ratios of 70/30 to 80/20 are preferred by some to limit expansion. At present the average mix is 65% high-, 13% medium-, and 22% low-volatile coal. If only high-volatile coal were used, the coke would have a porous, weak form rather than the firm, cellular form desired, which is not obtainable from all bituminous coals.

Other desirable properties of coking or metallurgical-grade coals are a low ash content (no more than 8%), low sulfur content (less than 1%), and low alkali content, particularly in western coals. Use of coal with high ash and sulfur contents results in added slag in the blast furnace, increased expenditures for coke, and decreased production. However, the integrated steel mills are facing competition from the utilities for low-sulfur coal because of the scarcity of natural gas and the environmental protection laws.

6.1.2 Production Process

Coke is made as follows. A preparation facility receives the various coals suitable for coking, grinds them, and blends the high-, medium-, and low-volatile coals in the requisite proportions. The crushed coal is transferred to the plant site and charged into by-product coke slot ovens (so named because they have facilities for recovering by-products such as light oils, tar, ammonia, and coke oven gas). Combustion air is heated in regenerators and mixed with injected and recycled fuels (40% of coke oven gas is recycled, and blast furnace gas is used for underfiring) for burning in the combustion chamber. Under normal operating conditions, the charge is heated for 16 to 20 hours (14 or less with preheated coal); then the coke is forced into waiting cars, where it is water-quenched to prevent combustion. A significant portion of the sensible heat is lost here (1.4×10^6 Btu/ton of coke) and could be partly recovered. After cooling, the coke is crushed and screened. Most of it is then transported to the blast furnace, and the remaining coke dust (either buckwheat or coke breeze) is conveyed to the reclamation plant and

either utilized as fuel in the sintering operation or sold (particularly buckwheat).

Figure 6.1 depicts a typical coke oven; the outputs are: (1) coke, (2) coke oven gas, consisting of a mixture of H_2 , CO , C_2H_4 , and CH_4 with a heating value of 500 Btu/ft^3 , (3) coke breeze, (4) tars, and (5) light oils and ammonia as sulfate. (Since raw coke oven gas usually contains ammonia, it is scrubbed with sulfuric acid, forming ammonium sulfate.)

Calculating the production and disposition of coke and coke oven by-products involves reconciling two separate sources of information: AISI data on member furnace plant consumption; and DOE production and consumption data (including merchant sales) on the U.S. coke industry, including merchant and furnace plants.

The data reported by AISI include the total coal, coke oven gas, coke breeze, and tar and pitch consumed in the blast furnace, coke ovens, and elsewhere. The DOE data include both production and consumption of these materials, as well as of light oils and other minor products. For this report, an estimate of the energy value of coke oven products sold would be

Fig. 6.1 Typical Coke Oven

useful, so as not to charge the iron and steel industry for energy it does not utilize.

The DOE data also include furnace plant sales of coke breeze, coke oven gas, tar, and light oils. A comparison of furnace plant sales of tars, as reported by DOE, and AISI furnace plant consumption of breeze, tar and pitch, and coke oven gas make it clear that consumption should not be equated with production. Consequently, this study derives total production of coke oven by-products by summing AISI consumption and DOE sales data for tar, pitch, breeze, and coke oven gas; production and sales of light oils are from DOE data only.

As Fig. 5.1 indicated, the by-products can be recycled for internal use or sold. This is not a small enterprise; in 1979, steel firms' sales of coke by-products amounted to over \$520 million, or about 13% of the value of the coal consumed in coke production.²⁸ The energy equivalent of these sales is still small; Fig. 5.1 indicates that, even though 3% of the coke oven gas, 75% of the tars and light oils, and 40% of the breeze are sold, the amount is less than 5% of the total energy available from the ovens.

Table 6.1 gives the geographic distribution of U.S. coke oven capacity, and Tables 6.2, 6.3, and 6.4 give the major materials flows for the production of coke in recent years.

6.2 PROBLEMS FACING THE INDUSTRY

A major problem facing the steel industry is the aging of U.S. coke ovens and their dwindling capacity; nearly 50% of the ovens are over 20 years old, and 25% are over 25 years old. The reason for this is that replacement costs are very high; a single by-product coke battery producing one million tons per year now costs well over \$200 million.⁶² Hogan and Koelbe indicate that in the period 1975 to 1978, the industry retired 10.9 million tons of coking capacity, almost 20% of the estimated 60-million ton capacity in 1975.⁶³ (They predict another 5.3 million tons in capacity to be lost by 1985.) During the same period, coke imports rose from 1.8 million tons to 5.7 million tons (mostly from West Germany, where coke is considered a by-product of gas production).⁶⁴ While imports are a short-term solution to shortages, they can be expensive; during the world coke shortage of 1973-1974, the price of imported coke was 66% above the cost of production.⁶³

Dwindling capacity is not the only problem; domestic supplies of low-sulfur coal, although still plentiful, have been reduced to the point where future mining and processing will take place only at higher costs. Ninety percent of the low-sulfur bituminous and sub-bituminous coal reserves are not suitable for coking. Of the reserves that are suitable, 80% are in the West Virginia/Kentucky region.⁶⁴

Table 6.1 Geographic Distribution of U.S. Coke Oven Capacity

States	Number of Plants	Number of Batteries	Number of Ovens	Annual Capacity ^a (tons)	% of Total
Alabama	7	25	1,215	5,182,338	9.02
California, Colorado, Utah	3	14	710	3,273,472	5.70
Connecticut, Maryland, Massachusetts, New Jersey, New York	4	18	1,074	4,987,013	8.68
Illinois	4	7	326	1,807,560	3.14
Indiana	6	25	1,076	9,926,684	17.27
Kentucky, Missouri, Tennessee, Texas	5	10	415	2,094,916	3.64
Michigan	3	8	508	3,338,690	5.81
Minnesota, Wisconsin	1	2	100	163,210	0.28
Ohio	12	35	1,878	8,619,017	14.99
Pennsylvania	12	46	2,962	14,679,309	25.54
West Virginia	2	9	519	3,411,191	5.93
Total	59	199	11,413	57,483,400 ^b	100.00

^aPotential maximum as of July 31, 1979.

^bOther estimates are 51.8 million tons in operation, and 47.6 million tons as actual productive capacity.

Source: Ref. 63, as reported in Ref. 6, p. 225.

Table 6.2 End Uses of Coke Fines Produced in the United States, 1975-1980 (10³ short tons)

Year	Use in Steam Plants	Use by Producers in Agglomerating Plants	Other Industrial Use	Sold
1975	257	1,202	715	1,953
1976	197	1,363	838	1,846
1977	187	1,398	590	1,690
1978	167	1,550	805	1,736
1979	200	1,453	745	2,240
1980	125	1,087	NA	2,968

Source: Ref. 28.

Table 6.3 Coke and Coking Coal Consumption in the United States, 1975-1980

Year	Coke ^a (lb/short ton of pig iron)	Coke Yield ^b (%)	Coking Coal ^c (lb/short ton of pig iron)
1975	1,221.6	68.4	1,786
1976	1,187	68.9	1,722.8
1977	1,192.8	68.9	1,731.2
1978	1,438.8 ^d	68.6	1,667.3 ^d
1979	1,150	68.4	1,681.2
1980	1,138	69.2	1,644

^aCalculated by dividing coke consumption in iron furnaces by pig iron production.

^bThe percentage by weight of coke per short ton of coal carbonized.

^cCalculated by dividing column 1 by column 2 and multiplying by 100.

^dNumber is suspect because it is inconsistent with the 1978 coke rate in Table 6.4.

Source: Ref. 28 for 1975-1979; Ref. 1 for 1980.

Table 6.4 Coal Carbonized at Coke Plants, 1975-1979 (10^3 short tons)

Year	Volatile Content ^a			Total
	High	Medium	Low	
1975	57,488	9,619	15,040	82,147
1976	56,847	9,982	16,554	83,383
1977	51,734	9,191	15,752	76,677
1978	47,664	9,928	13,486	71,078
1979	49,979	9,780	17,250	77,010

^aPercentage by weight of volatile matter in moisture-free (dry) coal: high is over 31%; medium is 22-31%; and low is 14-22%.

Source: Ref. 28.

Reduced blast furnace coke rates are possible through the use of supplemental fuels, as Table 6.5 indicates, but with the price of oil and gas rising, this is an increasingly expensive option. Since 1978, the industry has substituted coke for hydrocarbons as their relative prices have shifted.

6.3 ENERGY CONSERVATION MEASURES FOR COKE OVENS

Table 6.6 presents several estimates of energy consumption in the manufacture of coke. These estimates are very close, indicating that energy use in the manufacture of coke appears to be well understood. The efficiency of coke ovens has always been quite high; a recent study comparing the efficiencies of ironmaking and steelmaking indicates that U.S. ovens operate at an efficiency of 88% -- i.e., only 12% of the heating value of coal is lost in the process.⁶⁵

Energy conservation measures for the coke ovens are as plentiful and diverse as the opinions held about their cost-effectiveness. Table 6.7 describes nine such options. Of these nine, only coal preheating, formed coke, and dry quenching are discussed.

6.3.1 Coal Preheating

Of the various conservation alternatives, coal preheating appears to be the least controversial and most likely to penetrate coke production in the

Table 6.5 Blast Furnace Output and Coke Consumption, 1964-1980

Year	Blast Furnace Production (10 ⁶ net tons ^a)	Coke Consumed (10 ⁶ tons)	Supplemental Fuels Consumed ^b (10 ⁶ tons)	Coke Rate ^c	Total Fuel Rate (net ton/net ton of hot metal)
1964	86.2	57.1	1.743	0.663	0.683
1965	88.9	59.1	2.083	0.665	0.688
1966	92.2	59.6	2.270	0.647	0.671
1967	87.6	56.2	2.201	0.642	0.667
1968	89.3	56.2	2.376	0.629	0.656
1969	95.5	60.2	2.620	0.630	0.658
1970	91.8	58.2	2.778	0.634	0.664
1971	81.7	51.5	2.614	0.630	0.662
1972	89.4	54.6	3.401	0.611	0.649
1973	101.2	60.7	4.056	0.600	0.640
1974	95.9	58.8	4.926	0.612	0.665
1975	79.9	48.8	3.874	0.611	0.659
1976	86.9	51.6	4.232	0.594	0.643
1977	81.3	48.5	3.531	0.597	0.640
1978	87.7	51.3	4.311	0.585	0.634
1979	87.0	50.6	NA	NA	NA
1980	68.7	41.5	NA	NA	NA

^aNet throughput, excluding iron output that is recycled.

^bCoke equivalents.

^cRatio of coke consumed per ton of iron produced.

Source: Ref. 62 for 1964-1978; Ref. 32 for 1979-1980.

near term. The first commercial use of coal preheating was in 1970, and many installations, including such large facilities as Jones & Laughlin's Aliquippa works and Inland Steel's Indiana Harbor facility, have a long history of operation.³⁰ Several estimates are available for the amount of energy saved due to reduced coke oven underfiring, faster coking, and elimination of leveling. Battelle⁶⁶ estimates savings of 2×10^6 Btu/ton of coke, while A.D. Little⁸ estimates a 10% savings over conventional processes, even after allowance is made for the additional steam and electricity consumed to operate the preheater.

The major benefits of coal preheating include not only the direct energy savings achieved in coke manufacture, but also the improved quality of the coke produced, and the consequent reduction in coke charged to the blast furnace; alternatively, poorer-quality coals could be used to produce a coke

Table 6.6 Energy Consumption to Manufacture Coke

Process, Material	Amount Used Per Net Ton of Coke ^a	Energy Use per Unit of Material ^a (10 ⁶ Btu)	Energy Use per Net Ton of Coke (10 ⁶ Btu)			
			Ref. 33 ^b	Ref. 39 ^c	Ref. 37 ^d	This Report ^e
<u>Consumption</u>						
Mining of coal	1.45 net tons	0.25	0.36			
Explosives	1.02 lb	0.03	0.03			
Rail transport	300 net ton-mi	0.00067	0.2			
Heating value of coal	1.45 net tons		37.7		37.94	
Subtotal			38.29	39.03	37.94	38.98
<u>Energy consumed in coking</u>						
Electrical energy	33 kWh	0.0105	0.35	0.15		
Steam	1,000 lb	0.001	1	1.15		
Underfiring fuel						
General	6,960 ft ³	0.0005	3.48			
Fuel oil				0.03	0.04	
Blast furnace gas				0.5	0.48	
Coke oven gas				2.54	2.4	
Tar					0.32	
Natural gas					0.18	
Subtotal			4.83	4.32	3.42	3.91
Total			43.12	43.35	41.36	42.89
<u>By-product production</u>						
Coke oven gas	15,225 ft ³	0.0005	-7.61		-6.12	
Tar	13.09 gal	0.16	-2.09		-1.54	
Light oil	3.625 gal	0.125	-0.45		-0.5	
Coke breeze	0.07 net ton	21	-1.47		1.35	
Subtotal credit			-11.62	-11.11	-9.51	-10.25
<u>Total consumption minus subtotal credit</u>						
			31.5	32.24	30.85	32.64

^aRef. 33 (1975 data); ^b1975 data; ^c1976 data; ^d1974 data; ^e1980 data.

Table 6.7 Coke Oven Conservation Options

-
1. Automatic thermal control of coke batteries instead of manual control is expected to reduce fuel consumption, increase coke yield, and improve the quality and uniformity of coke pieces.
 2. Thermal stabilization of coke aims at increasing the yield of coke lumps with improved characteristics (size distribution, mechanical strength, carbon activity) for blast furnace use by optimizing coking residence time. Thermal stabilization could result by increasing oven residence time in the case of dry coke quenching.
 3. Dry coke quenching enables energy from the incandescent coke to be recovered (as steam), and could also result in: lesser pollution, elimination of water use, production of coke without residual moisture, shorter time for stabilization in ovens, and general improvement in coke quality.
 4. Charging coke ovens with preheated coking coals is expected to improve the overall energy balance, significantly increase coke oven productivity, increase uniformity in the mechanical characteristics of the coke (possibly thereby enabling the use of coals with moderate coke properties), and eliminate pollution caused by dust when the ovens are charged. The charge can could be preheated with the heat recovered from dry quenching.
 5. Briquetting noncoking coal with coke oven tar as a binder for making coke in coke ovens is an alternative to selling coke oven tar for chemical use, particularly when prices are low.
 6. Use of thin wall coke ovens and special refractories will allow a fast, programmed warm-up period and may significantly shorten coking time, enabling indirect energy savings and proportionately lower investment costs.
 7. Nontraditional coke forming processes, such as formed coke, can use more-economic fossil fuels, diversifying the sources of coal and obtaining greater supply flexibility. The gas distilled off in the first phase of manufacture of formed coke may have new chemical uses or general use as a fuel, or can be injected into the blast furnace.
 8. Reduced temperature coking (at 400-600°C rather than 1000°C), can achieve a semicoke which, though not as strong or as uniformly sized as high-temperature coke, can be used in blast furnaces at a considerable savings in the energy required to produce the coke.^a The gas yield is less than that of coke oven gas from temperature-produced coke but has about twice the heating value. Residual volatiles in low-temperature coke will be released in the blast furnace and added to the top gas produced.
 9. Partial (surface) coking is done at the typically high temperature of modern coke ovens, but at a greatly reduced residence time, which indirectly saves energy by increasing coke oven productivity. The semicoke produced has many of the poor qualities of reduced-temperature coke, such as low strength and poor size distribution.^a
-

^aThe adverse effect on blast furnace operation of using this poorer-quality coke may more than offset any energy savings in coke manufacture.

equal in quality to that made from high-grade coals. Improved resistance to abrasion, improved stability, improved homogeneity, and decreased proportions of coke less than 40 mm in size (which increases blast furnace permeability) are cited as the reasons why coke made from preheated coal outperforms coke produced by normal means.⁶⁷ No estimates of the indirect energy savings associated with this increase in quality are available.

6.3.2 Coke Dry Quenching

The most controversial conservation measure in the coke-making process, and very likely in the entire iron and steel industry, is dry quenching of coke. The first thought one has when seeing the enormous clouds of steam rising from the wet quenching bin of a conventional coke plant is to save all that energy, and reduce all that pollution. Because "waste" and pollution are so visible in the conventional process, wet quenching has been a favorite target of those in and out of the industry who wish to promote energy conservation and a clean environment.

At least three foreign processes exist for dry quenching: the German Sulzer process, dating back to 1917; the Russian Giprokoks process (used in 20 Russian coke batteries producing 16 million tons/yr of coke, and being installed in three Japanese plants); and the Waagner-Biro process.⁶⁸ In addition, DOE and U.S. Steel are constructing a pilot facility for U.S. Steel's Lorain/Cuyahoga works using a cooling chamber of the company's own design.⁶⁹ The key to the plan is that the batteries can be retrofitted one at a time, holding production disruption to a minimum, if sufficient space at the plant exists.

Energy savings estimates are all in the range of $1.1-1.3 \times 10^6$ Btu of the estimated 1.4×10^6 Btu lost through wet quenching.^{30,66,70} What is in dispute is the cost-effectiveness of the process. Two parameters dominate the economics of the operation: (a) the value of the heat saved; and (b) the capital cost of the equipment. AISI, using costs of $\$2.25/10^3$ lb of steam (generated by coal) and $\$15-20$ million for a 2000-ton/day plant, calculated a payback period of 18.29 years.⁷⁰ Increases since then in both steam and capital costs leave that conclusion unchanged. However, the vendor, American Waagner-Biro Co., used steam valued at $\$3.75/\text{million Btu}$ (twice the value assigned by AISI) and a capital cost of $\$10/\text{ton}$ (one-half that of AISI), and claimed a 3-5 year payback.³⁰ Soviet claims of a 2-4% reduction in the blast furnace coke rate due to increased coke quality (better hardness, stability, uniformity) could, if true, save up to 0.75×10^6 Btu/ton of coke, or about 12% of the 6×10^6 Btu/ton of coke lost due to process inefficiency.³⁰

6.3.3 Formcoke

Formcoking, a complete substitute for the conventional slot oven coke process, involves grinding and preforming the coal, which is then binded, pelletized, cured to a char, and completely devolitized to develop the necessary strength, a major problem in coke manufacture. Since briquettes are the final product, their uniform size and shape will improve blast furnace productivity; in addition, the process is enclosed, reducing emission problems. AISI reports two dozen formcoke processes; the early goal was to produce a smokeless coal; recently, the aim has been to produce a metallurgical-grade coke from cheaper coal blends or a single coal.⁷⁰ Two domestic technologies that have received major attention are the Food Machinery Corp. (FMC) and Consol-BNR processes, which are briefly described in Table 6.8.

The processes do not necessarily conserve energy although formcoking is a resource-saving technology.⁷¹ Indeed, Thermo Electron estimates that the FMC process will result in integrated mills using an additional 2.5×10^6 Btu/ton of coke,³⁹ since the decreased heating value of the by-product gas more than offsets any gains due to improved coal/coke and coke/iron ratios. Further, the demand for tar binder exceeds the amount of by-product tar produced from the process. Finally, there is some question regarding the coke-rate savings for the FMC process. The formcoke is of low strength and low stability, and, as such, the blast-furnace coke rate may be increased. There appears to be little question about the coking properties of the FMC formcoke as a partial replacement, but complete replacement "has not been completely proven in trials to date."⁷²

Table 6.8 Formcoke Processes in the United States

Process	Description	Blend Charged	End Product
Consol-BNR	Hot pelletizing, coking in a vertical-shaft furnace	Any type of coal, with coking coal and sometimes pitch as a binder	Metallurgical, spherical-shaped coke
FMC	Multiple fluid bed, low-temperature carbonization, briquetting, coking in a vertical-shaft furnace	High-volatile coals of any rank	Metallurgical coke

Source: Adapted from Ref. 70.

The Consol-BNR process advocated by Formcoke Associates mixes preheated crushed coal with recycled coke fines, char, and pitch. The blend is hot-pelletized, then coked in a shaft furnace. The brief history (1971-1977) of the Sparrow's Point 500-ton/day pilot plant provided evidence that serious technical problems must be solved prior to full-scale production. Unlike the FMC process, the Formcoke Associates project has the certain potential to save energy, since the offgases are of higher quality (850 Btu/ft^3) than those from conventional by-product slot ovens.

6.4 NONRECOVERY COKE MAKING

Prior to 1910, 100% of the coke needed by the steel industry was provided by nonrecovery coke processes -- i.e., those in which the by-products were combusted at the coking site, and not recovered. The advent of coal chemicals as strategic war materials in the two world wars and the Korean conflict led to the rapid replacement of these processes by vertical slot, by-product coke ovens that capture the coal chemicals in the by-product tars and light oils, while using the offgas as a heat source. With the decline in value of coal tar-based chemical products, due to the reduced costs of the same products from the oil and gas-based petrochemical industry, a return to a 100% combustion process for coke manufacture is possible.

There are now three U.S. nonrecovery coke plants, which account for less than 2% of coke production. The ovens, according to one oven promotor, cost four to five times less than by-product ovens; they are also nonpolluting and can conserve energy by generating steam.⁷³ Other industry sources say that the ovens actually require 75-100% of the investment required for by-product ovens, and hence have little opportunity to become profitable investments in the near future.

7 THE BLAST FURNACE AND EXTERNAL DESULFURIZATION

7.1 THE BLAST FURNACE

7.1.1 Pig Iron Production Process

Figure 7.1 shows the components of a typical modern blast furnace. The primary function of a blast furnace is to produce pig iron for introduction into steelmaking furnaces, although a small amount (less than 5%) is shipped each year to foundries. The manufacture of pig iron requires an input burden that may consist of agglomerated ores (pellets and/or sinter), lump ores, limestone, and coke. The coke supplies carbon monoxide, which combines with hematite and magnetite to form carbon dioxide and FeO at the upper end of the furnace at 1200°F . Flux materials are calcined, and, as the FeO descends to the hotter (3000°F) portions of the furnace, it combines with carbon or carbon monoxide to produce iron (Fe) and CO_2 , completing the reaction.

The output of a blast furnace is pig iron, slag (formed by combination of limestone with sulfur and other impurities), and an offgas with a heating value of $75\text{--}95 \text{ Btu/ft}^3$. This heating value has been dropping recently, as a result of lower coke rates and better burden preparation. During the production of pig iron (which is tapped every 3 to 5 hours in quantities of 300–600 tons), a portion of the offgas is consumed in boilers that produce compressed air via steam-powered or electric blowers. Funneling the air through three or four hot blast stoves provides the heat required in the blast, which is blown in at a temperature of 1400°F to 2000°F (when rebricked) at the tuyeres near the bottom of the blast furnace. (Temperatures of 2400°F are common in Japan.) After tapping, the pig iron is transported to the steelmaking furnaces in liquid form via torpedo cars or ladles. The blast furnace is somewhat versatile and can accept a variety of metal charges (mixes of scrap, sinter, pellets, lump ore) with little change in performance for a given Fe content, although large furnaces are less flexible.

U.S. blast furnace capacity has been slowly dropping as steel output and integrated mill shares decline, and as the older furnaces drop out of production. One source estimated that, in 1972, blast furnace capacity was 119 million tons, 72 million tons of which was in plants built prior to 1945.⁵⁷ Capacity utilization dropped from a high of 97.5% in 1973 to just under 50% in recent years. Two new blast furnace installations, Inland's 10,000 ton/day and Stelco's 5,250 ton/day Canadian plant, were added in 1980, the first significant additions since the Sparrow's Point furnace went on-line in November 1978. The total number of blast furnaces dropped to 152 in 1980, down from 178 in 1978.⁷⁴ Hot metal production has not declined as much, since the throughput efficiency (measured in tons/day per 100 ft^3 of furnace) for the remaining blast furnaces in operation has continued to increase due to better operating practices.

Legend

A. Ore bridge	J-5 Small bell	P. Downcomer
B. Ore transfer car	J-6 Large bell	Q. Hot blast line to furnace
C. Ore storage yard	J-7 Stock line	R. Gas washer
D. Stockhouse	J-8 Stack	R-1 Sludge line to thickener
D-1 Ore and limestone bins	J-9 Bosh	R-2 Spray washer
D-2 Coke bin	J-10 Tuyeres	R-3 Electrical precipitator
D-3 Scale car	J-11 Slag notch	S. Gas offtake to stove burner
E. Skip	J-12 Hearth	T. Hot blast connection from stove
F. Coke dust recovery chute	J-13 Bustle pipe	U. Stove
G. Freight car	J-14 Iron notch	U-1 Gas burner
H. Skip and bell hoist	K. Slag ladle	U-2 Combustion chamber
I. Skip bridge	L. Cast house	U-3 Checker chamber
J. Blast furnace	L-1 Iron trough	V. Exhaust gas line to stack
J-1 Bleeder valve	L-2 Slag skimmer	W. Cold blast line from blower
J-2 Gas uptake	L-3 Iron runner	X. Surplus gas line
J-3 Receiving hopper	M. Hot-metal ladle	Y. Stock—Iron ore, coke, limestone
J-4 Distributor	N. Flue dust car	Z. Jib boom crane
	O. Dust catcher	

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Fig. 7.1 Typical Modern Blast Furnace
(Source: Ref. 75)

7.1.2 Energy and Materials Use

As the largest consumer of energy and materials in the iron and steelmaking process, the blast furnace has received much attention. The primary aims in the past were to reduce the per ton use of coke or to increase productivity, rather than to decrease total energy use. Now, more attention is being paid to the latter.

Figure 7.2 shows how various factors influence blast furnace productivity. Materials flows and direct and indirect energy consumption per ton of hot metal produced are shown in Table 7.1. Direct energy use estimates are in the range of $15-18 \times 10^6$ Btu/ton, depending on a host of factors. Unit materials flows are shown in Table 7.2.

7.1.2.1 Methods of Reducing Coke Use

Various methods have been used to reduce coke use:

- Installing new blast furnaces with high top pressures;

Fig. 7.2 Factors Governing Blast Furnace Productivity
(Source: Ref. 79)

Table 7.1 Direct and Indirect Energy Consumption
in a Blast Furnace, 1980

Input	Amount per Ton of Hot Metal	Energy Use (10 ⁶ Btu)	
		Per Unit of Input	Per Ton of Hot Metal
<u>Indirect Energy Use</u>			
Iron ore	0.104 ton ^a	0.449 ^b	0.05
Pellets	1.04 ton ^a	1.79 ^b	1.86
Sinter	0.407 ton ^a	2.47	1
Mill scale	0.05 ton	0	0
Limestone	0.232 ton	0.24	0.06
Scrap	0.042 ton ^a	0.7	0.03
Refractories	5 lb	0.0125	0.06
Oxygen	333 ft ^{3a}	0.000183	0.06
Total			3.12
<u>Direct Energy Use</u>			
Coke	0.63 ton ^a	25.99 ^b	16.4
Fuel oil	4.31 gal ^a	0.15	0.64
Tar and pitch	0.59 gal ^a	0.16	0.09
Natural gas	303 ft ^{3a}	0.001	0.3
Coke oven gas	207 ft ^{3a}	0.0005	0.1
Electric energy	25 kWh	0.0105	0.26
Steam	1,200 lb	0.00199	1.2
Subtotal			18.96
Credits			
Blast furnace gas used elsewhere	18.733 ft ^{3a}	0.000095	(1.79)
Flue dust and sludge		0	0
Direct energy total			17.17
<u>Total (indirect and net direct)</u>			20.29

^aDerived from Fig. 5.1.

^bFrom Table 3.4.

Source: Ref. 33, except where noted.

Table 7.2 Materials Used in Blast Furnaces, 1973-80
(tons/ton of hot iron, except where indicated)

Material	1980	1979	1978	1976	1975	1974	1973
<u>Input</u>							
<u>Ore</u>							
Iron ore (including manganiferous and block)	0.104	0.11	0.164	0.203	0.296	0.429	0.408
Manganese ore (including ferru- ginous manganese)	0.003	0.004	0.004	0.001	0.002	0.002	0.002
Agglomerated products (sinter, pellets, etc.)	1.459	1.455	1.394	1.373	1.310	1.222	1.222
Total	1.566	1.569	1.562	1.577	1.608	1.651	1.632
Less flue dust and sludge produced	(0.026)	(0.029)	(0.03)	(0.028)	0.031	0.033	0.031
Net total	1.54	1.54	1.532	1.549	1.577	1.618	1.601
<u>Scrap</u>							
Total	0.058	0.052	0.05	0.045	0.051	0.048	0.043
Less production at blast furnaces and auxiliary units	(0.016)	(0.017)	(0.016)	(0.017)	(0.017)	(0.017)	(0.016)
Net total	0.042	0.035	0.034	0.028	0.034	0.031	0.027
Mill cinder, roll scale, etc.	0.044	0.054	0.052	0.049	0.044	0.048	0.05
Limestone, dolomite, and other flux materials	0.182	0.198	0.197	0.213	0.234	0.244	0.232
<u>Coke</u>							
Total	0.588	0.596	0.607	0.615	0.632	0.632	0.617
Less coke breeze recovered	(0.018)	(0.021)	(0.022)	(0.021)	(0.021)	(0.023)	(0.02)
Net total	0.57	0.575	0.585	0.594	0.611	0.609	0.597
<u>Output</u> (10 ⁶ tons)	68.721	87.003	87.679	81.328	86.870	79.923	95.909

Source: Ref. 59, Tables 39 and 44.

- Improving old blast furnaces by retrofitting;
- Increasing air-blast temperatures;
- Optimizing burdens;
- Using prereduced burdens; and
- Injecting hydrocarbons.

Most of the blast furnaces operating today were installed before 1950 and less than five operate above 10 psig. Coke usage can be reduced by increasing the top pressure, since higher pressures intensify the physical and chemical interactions. Thermo Electron reports that, at the optimal wind rate, savings amount to 100 lb of coke per ton of pig iron,³⁹ while Woolf indicates that larger savings are possible, as well as dramatic increases in blast furnace productivity.⁷⁶ The AISI Blast Furnace Committee estimates much lower savings; a 1-psig increase reduces the coke rate by only one pound according to its formula.⁷⁷ New blast furnaces can be designed for higher top pressures: in Japan, top pressures are as high as 32 psig. At these pressures, substituting expansion turbines for Septum valves allows 20-40% of the energy expended on blowing power to be recaptured.⁷⁸ With capital costs at 600-700/kW, AISI predicts a value of return on investment of 14-18%.⁷⁰

Relining and rebricking in existing blast furnaces and stoves allow for increased air-blast temperatures; between 1958 and 1968, the average increased from 1230°F to 1500°F. Each 100°F increase in blast temperature above 1800° decreases the coke charge by about 30 lb/ton, and temperatures around 2200°F, which would save 102 lb/ton, are considered obtainable with relining at a cost of \$5/ton of yearly capacity.³⁹ However, reducing coke rates increases the need for hydrocarbon purchases, since offgas quality declines.

Optimization of burden is most easily achieved by use of bell-less tops, which offer three distinct advantages: (a) coke usage can be reduced by 30 lb per ton of pig iron; (b) capital costs may be lower, depending on the site; and (c) the burden input mix can be distributed more uniformly, allowing better gas efficiency.

The possibility of substituting prereduced burdens for ore has received some attention. U.S. Steel has established that, as a direct result of the metallic ore (Fe) contained in the directly reduced material, for each 100 lb of that material charged per ton of hot metal produced, the production rate increases by 4% and the coke rate drops by 32 lb.⁷⁷ However, the U.S. Steel report concludes that "95% directly reduced iron can only be used economically in the blast furnace if its purchased cost is below its breakeven value."⁸⁰ This calculation is based on 1981 prices and a coal-based process; perhaps future differential fuel prices will change this, since the conclusion is mainly dependent on the cost of coke and the cost of iron oxide.

Injection of hydrocarbons involves mainly natural gas injected through "circle pipes" and oil and coal injected through lances. Since 1979, hydrocarbon fuel injection has been markedly reduced because of the economics. The total energy impact has been estimated at various amounts. Both the Bureau of Mines and Battelle have observed that total energy input increases when gas and oil are injected. This, coupled with the slight energy loss at the coke plant associated with reductions in throughput, means a decrease in thermal efficiency as hydrocarbons are substituted for coke.³⁹ However, as supplies of natural gas dwindle, more steelmaking concerns are attempting to utilize pulverized coal as the main injectant into the blast furnace, which does conserve energy -- about 0.7×10^6 Btu/ton of hot metal,⁶⁶ although this has been disputed by AISI, which concludes that "the energy input to the blast furnace will normally increase."⁷¹ Payback periods are in the 3-4 yr range, so commercialization is likely. Armco's system (the only system now in use in the United States) substitutes coal at a rate of 0.78 lb of coke per pound of coal up to 28% of the coke input.⁸¹ Retrofit capital costs for the coal-pulverizing equipment are \$6.50/ton of yearly capacity.⁷¹

Thus, some ways of lessening the per ton use of coke do not necessarily lower the energy consumption per ton of pig iron produced. Tenenbaum has described the dilemma of the steel producers trying, on the one hand, to meet federal energy conservation targets for total energy use, while on the other hand trying to follow government mandates to switch to coal.⁸² Inland's experience is to replace coal with oil and gas in order to save energy in the blast furnace, but this solution substitutes domestically scarce energy sources -- oil and gas -- with a readily available source, coal. Which policy should be followed? Tenenbaum points out that if cost minimization dictates the choice, hydrocarbon injection is preferable to increasing coal input (at 1977 prices).

7.1.2.2 Methods of Increasing Blast Furnace Efficiency

As discussed above, the rising cost of low-sulfur bituminous coking coals has led to efforts to reduce coke consumption, even at the expense of total energy use -- i.e., minimizing costs can lead to increased energy use. There are also ways of increasing the efficiency of the blast furnace, although none are dramatic, since the furnaces are very efficient to start with -- over 75%.³⁹ One method is to increase conservation and use of blast furnace offgas, which, while low in quality (75-95 Btu/ft³), is produced in large quantities; if completely utilized, it would represent about one-fourth of the total energy needed to make steel.⁶⁶ At present, most gas is recycled, but about 30% is lost due to leaks or flaring during periods of excess supply. Reasonable efforts to capture and recycle could recover an added 0.7×10^6 Btu/ton, or about 1% of the energy needed to produce steel slabs.⁶⁶ Industry sources say the 30% waste estimate is too high: a better estimate would be nearer 15%.

A second idea, put forward by Woolf, is injection of hot reducing gases into the lower stack to prereduce the iron burden, thus achieving the same effect as charging direct reduction pellets to the furnace.⁷⁶ His experiments indicate that such injection would substantially reduce the coking rate. For top gas injections in the range of 16,000-17,000 ft³/THM, coke rates were reduced by 38-41 lb/THM, and blast furnace offgases increased from 89 Btu/ft³ to 122-124 Btu/ft³.

A third idea is to increase the charging temperatures of raw materials to the furnace by capturing the latent heat of the coke (at 1000°F) and sinter (at 1000°F), and preheating the ore to 500°F with process offgases. Hall has estimated that such a practice could save 6% of the coke charge, or about 1.01×10^6 Btu per ton of iron.⁸³ Industry sources say this practice will not be adopted in the near future, since the capital costs of handling such very hot materials would be considerable.

Another approach is to use blast furnace gas, in excess supply in many plants, to preheat stove air — a practice planned for Stelco's blast furnace, but temporarily shelved until the economics improve.⁸⁴

Slag production at the blast furnace is about 1,100 lb per ton of iron and absorbs about 1.7×10^6 Btu per ton, or 9% of the heat of the furnace. If this heat could be reclaimed and used to produce steam and then electricity, it could generate 10% of the electricity purchased by the industry in a year.⁸⁵ Problems are associated with the idea. In particular, slag tapping is infrequent; how could the heat be recovered prior to slag hardening? Further, industry sources say the 1,100 lb/ton figure, and hence the potential energy savings, is overstated by a factor of nearly two.

7.2 EXTERNAL DESULFURIZATION

Sulfur is an unwanted contaminant in steel, affecting only surface quality in some instances, but in other cases, such as in steel for magnets, adversely affecting performance. Several alternatives exist to decrease the sulfur content in steel:

- Use low-sulfur coals in coke plants and low-sulfur oils in blast furnaces;
- Remove sulfur in the blast furnace by control of basic slag analysis;
- Apply soda ash in the hot ladle; or
- Remove sulfur in the steelmaking facilities.

Several trends have combined to place the main burden of increased sulfur removal on the blast furnace: the rising cost of low-sulfur coal and

oil, which has led to increased sulfur levels in metallurgical coal, the growing use of BOF steelmaking facilities with limited possibilities for sulfur removal, and the increasing demand for low-sulfur, low-alloy steels to make pipelines and sheet. The result has been to necessitate greater use of burned lime as a fluxing and desulfuring agent, with subsequent increases in the energy load on the furnace.⁶⁶

External desulfurization -- the removal of sulfur from hot metal as it is transported from the blast furnace to the steelmaking facility -- is beginning to replace blast furnace methods for removing sulfur, with consequent energy savings. Many technologies exist; the injected reagents include soda ash, calcium carbide, magnesium coke, and magnesium dolomite.⁷⁰ When external desulfurization is used to reduce the coke rate in blast furnaces by allowing high-sulfur hot metal to be produced, it saves energy. The amount depends principally on the change in the hot metal sulfur content, and can range from 0.82×10^6 Btu/ton to -0.12×10^6 Btu/ton.⁷⁰ Battelle estimates that the possible energy savings can amount to 0.9×10^6 Btu/ton,⁶⁶ while A.D. Little estimates 0.86×10^6 Btu/ton.³⁰ However, Emerson indicates that, at his site, even if energy prices doubled their 1978 levels, it would still be cheaper to remove sulfur in the blast furnace when 0.71% sulfur coke is used.⁷⁹

The economics of sulfur removal currently favor external desulfurization, and many steel companies are installing units. In 1979 and 1980 alone, U.S. Steel, Inland, Algoma, Dofasco, Stelco, Jel, Republic, CF&I, National, Crucible, and Ford all installed either hot metal or steel external desulfurization facilities.⁸⁶

8 DIRECT REDUCTION

Direct reduction (DR) processes (any reduction processes in which metallic iron is produced without melting the material) are basically of two types: gaseous and solid. The first uses a gas, either hydrogen and/or carbon monoxide, for removing oxygen from iron; the second uses solid carbon. The reactions reduce hematite to magnetite and wustite, and then to Fe. Reductants in use are carbon, hydrogen, and carbon monoxide. An ideal lump iron ore for use in a DR process would have an iron content of at least 65%.⁷⁷ Substantial amounts of this type of ore exist abroad, and if a run-of-the-mine ore cannot be used, beneficiated pellet ores can. The product, directly reduced iron (DRI), is 90-95% metallized, and hence is suitable for feed to steelmaking units (electric arcs, BOFs after melting) or ironmaking units (blast furnaces, cupolas).

DR is not a new technology; early man used a primitive version of it around 3000 B.C. to reduce iron minerals to metal. Table 8.1 summarizes data on all DR plants constructed or scheduled for completion by 1980; these plants include the first Persian Gulf integrated mill in Qatar, which utilizes gas. Many processes are available; Table 8.2, taken from a U.S. Steel report (which is the definitive work in the field), lists 20 separate processes representing five different technologies. However, 75% of installed capacity is either the Midrex or HyL process, both of which use natural gas as a reductant; coal-based reductant capacity amounts to 11.1% of the total.

Since coal-based plants are expected to be more economical in the United States as gas prices rise relative to coal, Table 8.3 lists all operating DR plants using coal, coke breeze, or coal gas as a reductant. Table 8.4 gives energy consumption estimates for both the gas and coal reductant processes; coal-based systems use about twice the energy per ton used by gas-based systems.

Major advantages of the pelletization process are:

- The pellets have a known and uniform chemical composition, which contains no tramp elements (Zn, Pb, etc.) as does the substitute for pellets in mini-mills, scrap.
- The pellets can be manufactured easily at a variety of locations, since small-scale plants are as efficient as larger ones, and many reductants can be used (coke, coal, gas, oil, CO, and even CO and H₂ produced from biomass⁸⁸).
- The pollution and coal supply problems associated with coke production are eliminated when pellets substitute for hot metal in integrated mills.

Table 8.1 Direct Reduction Plants Constructed or Scheduled
for Completion by 1980.

Process	Number of Plants	Year of First Plant	Year of Last Plant	Countries	Reductant	Annual Capacity (10 ³ tons)	Type ^a
Hoganas	3	1954	1954	Sweden	Coke breeze	63-154	-
Wiberg	4	1954	1964	Sweden, Japan	Coke breeze	9-82	-
Rotary kiln	1	1957	1957	Japan	Coal	22	RK
Hyl	14	1957	1980	Mexico ^b	Natural gas	91-1905	SB
Highveld kiln	2	1968	1977	S. Africa	Coal	272-907	RK
Midrex	17	1969	1980	United States ^b	Natural gas	272-2268	SF
Kawasaki	3	1969	1977	Japan	Coke breeze	65-227	RK
SL-RN	6	1970	1978	New Zealand ^b	Coal	54-327	RK
Purofer	4	1970	1980	W. Germany ^b	Natural gas, CO	136-726	SF
Koho	1	1971	1971	Japan	Coke breeze	44	-
Armco	1	1972	1972	United States	Natural gas	300	SF
Krupp	1	1973	1973	S. Africa	Coal	136	RK
HIB	1	1973	1973	Venezuela	Natural gas	590	FB
Sumitomo	1	1975	1975	Japan	Coal	218	-
Kubota	1	1975	1975	Japan	Coal	190	-
ACCAR	2	1975	1976	Canada	Coal, oil, gas	45-218	RK
FIOR	1	1976	1976	Venezuela	Natural gas	363	FB
NSC	2	1976	1977	Japan	Oil	136-218	-
Kinglor-Metor	1	1976	1976	Italy	Coal	36	-
Azcon ^c	1	1978	1978	United States	Coal	91	RK

^aRK = rotary kiln, SF = static bed, SF = shaft furnace, FB = fluidized bed.

^bPrincipal country; some of the plants are scattered in other countries as well.

^cNow known as Direct Reduction Corp. (DRC).

Source: Ref. 6.

Table 8.2 Direct Reduction Processes

<u>First Generation Coal-Based Processes</u>	<u>Reformed Natural Gas Processes</u>
Krupp-Codir: rotary kiln	Midrex: shaft furnace
SL/RN: rotary kiln	HyL: static bed
DRC: rotary kiln	Purofer: shaft furnace
	Armco: shaft furnace
	FIOR: fluid bed
<u>Second Generation Coal-Based Processes</u>	<u>New Technology</u>
AUCAR: rotary kiln	SKF: plasmamelt
Hot gas desulfurization (HGD) shaft reduction	ELRED
Improved SL/RN: rotary kiln	INRED
Salem Reduction: rotary kiln	Midrex Electrothermal: shaft furnace
	Foster-Wheeler: plasmamelt
<u>Coke Oven Gas/DRI from HyL and Midrex</u>	Westinghouse
	DLM-modified

Source: Adapted from Ref. 77.

- For plants below one million tons/yr in capacity, the process, coupled with electric melting, has both investment cost and operating cost advantages over the coke oven/blast furnace/BOF complex.⁶
- The productivity of electric arc furnaces can be increased substantially when the pellets are continuously charged.⁸⁹

Major disadvantages of the process are:

- It will likely use more direct energy, since the energy intensities in Table 8.4 are generally more than those reported for direct energy use in the blast furnace. Since the DR process and blast furnace both use pellets as an iron source, the relative advantage of the blast furnace would likely be maintained if direct and indirect energy use were compared.
- The pellets tend to reoxidize during shipment, with consequent spontaneous ignition if reduction temperatures are below 900°C.⁹⁰

Table 8.3 Operating Direct Reduction Plants Based on Coal or Coke Breeze

Process	Company	Location	Capacity (tons/yr)	Startup Date	Product Use ^a
<u>Plants using coal directly</u>					
SL-RN	Steel Co. of Canada	N.W. Ontario, Canada	362,800	1975	A
SL-RN	Hecla Mining	Arizona	54,420	1975	C
SL-RN	Acos Finos Pir.	Rio Grande, Brazil	58,955	1973	A
SL-RN	Nippon Kokan	Fukuyama, Japan	317,450	1974	B
SL-RN	New Zealand Steel	Glenbrook, New Zealand	108,840	1970	A
SL-RN/Krupp	Dumswart	Benoni, S. Africa	90,700	1978	A
Azcon-DRC	Azcon	Tennessee	90,700	1978	A
Kinglor-Metor	Daniell	Cremona, Italy	36,280	1976	A
Kinglor-Metor	Daniell	Monfalcone, Italy	9,070	NA	A
Sumitomo	Sumitomo	Kashima, Japan	195,912	1975	B
Highveld	Anglo-American Corp.	Witbank, S. Africa	907,000	1968	B
ACCAR	Sudbury	Ontario, Canada	226,750	1976	NA
<u>Plants using coke breeze</u>					
Hoganas	Hoganas AB	Hoganas, Sweden	136,050	1954	C
Hoganas	Granges AB	Oxelösund, Sweden	32,652	1954	C
Wiberg	Sandriks AB	Sandriks, Sweden	21,768	1954	C
Kawasaki	Kawaski	Chiba, Japan	54,420	1969	B
Sumitomo	Sumitomo	Wakayama, Japan	217,680	1975	B
Rotary kiln	Nippon	Muroran, Japan	43,536	NA	B
<u>Plants using gasified coal</u>					
NSC	Nippon	Hirohata, Japan	136,050	1977	B

^aA = steelmaking feed; B = ironmaking feed; C = specialty product.

NA = not available.

Source: Ref. 77.

Table 8.4 Energy Comparison of Direct Reduction Processes

Process	Source of Reductant	Energy Required per Net Ton of DRI ^a		
		Reductant Fuel (10 ⁶ Btu)	Power (kWh)	Total Energy (10 ⁶ Btu)
Midrex	Natural gas	10-11.7	100-115	11-12.8
HyL	Natural gas	10.2-11 ^b	0-100 ^b	11-11.2
Armco	Natural gas	11.2-11.8	30-35	11.5-12.1
Purofer	Natural gas	12	118	13.2
Fior	Natural gas	15.1	57	15.7
Krupp Codir	Coal	13.8-19.3 ^c	50	14.3-19.8
SL/RN	Coal	12-23 ^c	75	12.0-23.8
DRC	Coal	19.4-19.9 ^d	110	20.5-21
ACCAR	Coal, oil, natural gas	16-16.6 ^e	50-75	16.5-17.4
HGD shaft reducer	Coal	12.4	103	13.5
Improved SL/RN	Coal, oil, natural gas	17.5 ^f	70	18.2
Salem	Coal	18.9-26 ^c	35	19.3-26.4

^aNet of scrap.

^bBased on fuel/power combinations ranging from purchasing all power to generating all power (total plant self-sufficiency).

^cDepends on rank of coal used as solid reductant.

^dA broader range would probably result if the coal rank were varied as in the Krupp Codir and SL/RN tests.

^e80-20 ratio of coal to fluid fuel. Many other combinations and fuel rates are reported. For mixes using coal, the range would depend on the coal rank.

^fLimited data available, but a range would probably be reported if the coal rank were varied.

Source: Ref. 77.

- The more-efficient processes use natural gas, an expensive fuel. Oregon Steel shut down its Midrex plant when gas reached \$3.85/10⁶ Btu.⁸⁷
- The pellets must be melted to substitute for hot metal in integrated mills, which adds to the energy disadvantage. Also, use in integrated mills will involve different charging and solid waste handling techniques, since acid slag is produced, requiring subsequent flux addition and slag removal.⁸⁹

OTA estimates that DR plants will make major inroads into international steel markets in the next 20 years, with North American capacity growing from 2.9 million tons in 1980 to 15.3 million tons by the year 2000.⁶ Hogan predicts short-run potential demand to be in the 6-8 million ton range.⁸⁷ Such forecasts are based on future trajectories of gas, coal, and scrap prices that, while reasonable, are subject to uncertainty. In contrast, the U.S. Steel report compares the cost of alternate steelmaking processes by calculating the selling price per ton of liquid steel necessary to obtain a 15% rate of return on investment, using 1981 prices of scrap, pellets, coal, fuel, and electricity.⁷⁷ It concludes that two Swedish basic oxygen processes — SKF Plasmamelt and Inred, with full costs of \$199/ton and \$205/ton of raw steel, respectively — are already competitive with present coke oven/blast furnace/BOF practice (whose full cost is \$206/ton of raw steel). The SKF Plasmamelt is also competitive with future blast furnace practice, i.e., coal injection plus O₂ blast (with a full cost of \$195/ton of raw steel).

Leary has described the consequences of a major shift to DR in blast furnace charges.⁹¹ If DR pellets are substituted for hematite/magnetite pellets in blast furnaces, the coke rate would be cut 50%, causing shortages of coke by-products, while natural gas requirements would increase 2000%. There would be a net energy increase of 0.5 x 10⁶ Btu/ton of iron. If DR pellets are used as 40% of the electric arc charge (the rest being scrap) and if the historical 75/25 ratio is maintained between primary (iron ores) and secondary (scrap) inputs, then Leary predicts much excess blast furnace and BOF capacity, corresponding undercapacity in the electric arcs, excess capacity for blast furnace grade pellets, and a tenfold increase in the demand for electric-arc grade metallized pellets.⁹¹

At present, DRI or sponge iron is not competitive with scrap in mini-mills because of reduced scrap consumption and low scrap prices in the depressed steel industry. In the future, with the return of a healthy steel industry and further use of electric furnaces in both the integrated and nonintegrated portions of the industry, scrap supply will become strained; DR pellets may then find ready markets in the mini-mill segment, if scrap prices rise sufficiently to make the deepwater port to mini-mill movement of DR pellets profitable. Jensen says that DRI "is the only thing that will help alleviate an international critical shortage of scrap."⁹²

9 SCRAP

Besides scrap, mill scale generated from water pollution control equipment in the reduction and rolling mills and casting areas can contain over 50% iron, and is a candidate for recycling.¹⁵ So are some of the dusts and sludge generated throughout the industry. Since this scrap source has been discussed in Sec. 5 on sinter, this section focuses only on revert, prompt, and obsolete scrap. Table 9.1 gives the time pattern of scrap consumption by major type.

9.1 ENERGY USE IN THE SCRAP INDUSTRY

Steel produced from prompt and obsolete scrap uses $6-8.3 \times 10^6$ Btu of energy per ton of raw steel.^{31,93} In contrast, steel produced from iron ore uses $16-24 \times 10^6$ Btu/ton (see Sec. 10 and Ref. 94). If the calculation is made on the basis of steel shipments, the difference becomes larger — 10×10^6 Btu versus 36×10^6 Btu.⁶ The difference is mainly due to the very large amount of energy used in the blast furnace to produce hot metal (12×10^6 Btu/ton²⁴) versus the smaller amounts used to collect and ship obsolete scrap — $0.55-1.5 \times 10^6$ Btu/ton.^{31,36}

Table 9.1 Consumption of Recoverable Materials in the Iron and Steel Industry, 1973-1980 (10^6 short tons)

Recoverable Material	1973	1974	1975	1976	1977	1978	1979	1980
Scrap								
Home scrap production	50.41	47.42	40.06	43.46	47.42	44.9	45.3	36.8
Purchased scrap received ^a	32.06	33.65	22.78	24.97	33.65	35.6	37.9	34.6
Total consumption	82.47	81.07	62.84	68.43	81.07	80.5	77.1	67.1
Dust and sludge	2.29	2.36	2	2.45	2.36	2.4	2.5	2

^aIncludes prompt industrial and obsolete scrap.

Source: Adapted from Ref. 1.

Kusik and Brodrick both argue that energy use depends on scrap type and recovery method. Table 9.2 gives their estimates. If the 1980 percentages of home (56%), prompt (19%), and obsolete (24%) scrap are used as weights for the energy intensities in Table 9.2, an average of between 0.34×10^6 Btu (Kusik) and 0.7×10^6 Btu (Brodrick) is obtained for each ton of scrap melted. In terms of the type of scrap purchased, Kusik considers that low-phosphorus plates; highest-quality electric furnace bundles, turnings, bushels, clips, and borings; slag scrap; and cast iron borings are primarily prompt industrial scrap, and the rest is primarily obsolete. Additional savings arise because the electric furnaces, continuous casters, and rolling mills that melt, cast, and form steel from scrap use less energy than their counterpart processes in the integrated mills. Thus, energy savings are substantial when steel made from scrap is substituted for steel made from iron ore.

Table 9.2 Estimates of Energy Use per Ton of Scrap (10^6 Btu)

Type of Scrap	Kusik ^a	Brodrick ^b
Auto scrap		
By shredding	1.28	2.4
By guillotine	0.65	-
Ferrous scrap		
By baling	0.72	1.5
By shearing	0.47	1.5
By cutting	0.34	1.5
Home scrap	0.02	0
Prompt scrap	0.46	0.6

^aRef. 31.

^bRef. 36.

Although the thrust of their argument is correct, several caveats should be mentioned. First, an increase in the amount of scrap recycled without some decrease in the amount of hot metal produced will increase, not decrease, the nation's energy use. The goal is not simply to encourage increases in scrap recycling indiscriminately, but to encourage the substitution of either scrap for hot metal in existing furnaces, or of new scrap-based furnaces for ore-based furnaces. Without such substitution, no energy will be saved. If increases in recycling are associated with an increase in steel output as domestic firms seek to recapture markets lost to steel imports, energy use will increase.

Second, the actual energy savings when scrap steel substitutes for hot iron varies, depending on the circumstances surrounding the substitution. Three issues affect the estimates:

- How much energy is used to collect, sort, process, and deliver old and new obsolete scrap? Since most prompt industrial scrap is quickly recycled (except during poor market periods, when some is not recycled at all), the substantially lower amount of energy used to recycle it is irrelevant, since additional scrap for recycling will come

from obsolete scrap. Further, collection of old obsolete scrap may be fairly energy-intensive, since it involves some transportation from remote areas.^{31,36}

- How much energy is saved by the simpler steel-forming activities associated with products made from scrap steel? Such savings should not be attributed to the substitution of scrap for hot metal, since these products could also be made in integrated mills.
- How much energy is consumed by hot metal production? As Sec. 7 on blast furnaces indicated, by-product gas credits from coke ovens and blast furnaces considerably reduce the large amount of energy apparently consumed in this process. This study estimates 19.31×10^6 Btu/ton; other estimates range higher (e.g., Battelle's 23×10^6 Btu/ton³³) or lower.

Brodrick and Kusik both also give recent data on the amount of energy used to recycle obsolete scrap. Brodrick calculates the average to be around 1.8×10^6 Btu/ton, with the mix of auto hulks to other obsolete scrap being the major determining factor.³⁶ If the scrap were from auto hulks alone, the energy use would be 2.4×10^6 Btu/ton; if it came from other scrap, the amount would be 1.8×10^6 Btu/ton. This figure includes both the direct and indirect energy necessary to produce the scrap; Brodrick did not distinguish between them in his analysis. Since the indirect requirements are a substantial fraction of total use, care must be taken to uniformly compare both the direct and indirect energy requirements between the scrap recycle and integrated mill steel routes. Kusik cites a range of 0.34×10^6 Btu/ton to 1.28×10^6 Btu/ton, with an average of 64×10^6 Btu/ton;³¹ again, the range is due to variance in the source of scrap.

The energy saved as a result of the simpler post-melting processes associated with 100% scrap steel products can be substantial. Substitution of continuous casters associated with scrap remelting for the ingot formation and remelting process found in most integrated mills saves an estimated 5×10^6 Btu/ton.²⁴ The simpler hot- and cold-rolling and heat treating processes for mini-mills saves a small additional amount per ton. These savings are frequently incorrectly attributed to scrap substitution, when in fact they are due to differences between the downstream processes and final products made in mini-mills and integrated mills.

Energy use in the process of ironmaking must also be calculated with care. Mining and transportation of the ore, coal, and limestone must be included. Energy credits associated with offgases produced at the coke ovens (500 Btu/ft^3) and blast furnaces (95 Btu/ft^3) should be deducted. Calculation in this manner yields a per ton energy use estimate of $20\text{--}24 \times 10^6$ Btu/ton of hot metal produced (see Sec. 7).

To summarize, the correct comparison to make for energy savings purposes is the direct and indirect energy used in scrap recycling versus the direct and indirect energy used in hot metal production. Taking all factors into account, the spread of savings is likely to fall in the range of $10\text{--}11 \times 10^6$ Btu/ton, considerably below the 17×10^6 Btu/ton savings claimed by supporters of scrap recycling.⁹⁴

9.2 SUPPLY AND DEMAND FOR SCRAP

Several features of the industry's supply-and-demand picture should be mentioned. For example, most integrated mills, which can obtain hot metal from blast furnaces and revert scrap from their finishing mills, are not normally major scrap purchasers, although some exceptions exist. (During the recent steel output contraction, at least one integrated mill entered the market as a seller of revert scrap.) However, in times of rapid increase in steel production, the integrated mills have temporarily turned to the purchased-scrap market for help in expanding their in-process inventory. This demand for purchased scrap is volatile, because it is linked to this output by an "accelerator" -- or stock adjustment -- mechanism. Foundries, although accounting for only 20% of total steel output, purchase almost one-third of all the scrap bought by the steel industry because scrap is their sole raw material.

9.2.1 Sources of Scrap

Revert scrap is always recycled immediately (within 10 days) or sold, since storage is a costly option for steelmakers. Mini-mills generate less revert scrap per ton of steel produced than the integrated mills because of their use of continuous casting and their concentration on steel products that require fewer steps.

Prompt industrial scrap supply is directly related to steel fabrication throughput, which is closely tied to durable goods output. This scrap is so desirable that it commands a premium price and is almost immediately recycled. Hogan calculates that 16.6% of fabricated steel returns to the mills as prompt scrap; the figure is 16.8% for foundries.²⁰

There are two types of obsolete scrap -- current and old. "Current" obsolete scrap is scrap brought into scrapyards and immediately processed and shipped. It includes auto hulks just off the street, steel from structures recently torn down, and any other scrap that does not sit in a scrapyard in an unprocessed state. It is less costly to move than "old" obsolete scrap sitting in the back boneyards of scrap collection centers. Once unprocessed scrap sits outside for any length of time, the cost of recovering and processing it increases.

The major source of additional scrap in periods of excess demand is "old" obsolete scrap. As prices rise, it pays scrap dealers to go farther and farther back into their storage areas to reclaim their old obsolete-scrap stockpiles. While some segments of the scrap-consuming industry contend that old obsolete scrap is more of a problem to use than current obsolete scrap, others conclude that scrap quality does not decrease during peak periods when more old scrap enters the market. Rather, contaminants are more a function of what went into the scrap than how long the scrap sits in a scrapyards.

Prompt and obsolete automobile scrap play a prominent role in the industry for two reasons. First, they account for almost 40% of all prompt scrap purchased and 35% of the obsolete scrap purchased.³⁶ Second, because of its high quality and uniformity, auto manufacturers and others are able to auction off their prompt scrap once a month to the highest bidder. The prices paid at the auctions are public knowledge and are a very effective barometer of the state of scrap demand.

9.2.2 Elasticity of Supply

Scrap's elasticity of supply is part of a continuous debate over scrap export controls between domestic scrap producers and consumers. Such export limits would help the users and hurt the producers. Thus, the two trade associations -- ISIS on the supply side, and the Ferrous Scrap Consumers Coalition (FSCC) on the demand side -- find themselves in continuous confrontation over fluctuations in the price and availability of scrap, and the impact of scrap exports on the fluctuations. The consumers claim that such exports reduce the obsolete scrap inventory and disproportionately increase scrap prices, and argue that those higher prices have had little impact on supply.^{95,96} The producers argue that such price increases are necessary to bring forth additional scrap, and that "the supply of obsolete scrap increases promptly and substantially as the price of scrap increases."⁹⁷ A ban on scrap exports, they say, would cause prices to drop; thus, the scrap would not be brought forth but would rust away unused. The demand side argues to the contrary. Each side can find support for its argument from a wide range of supply elasticities (0.07^{20} - 0.833^{98}), which reflect supply response to price.

A portion of this wide gap is explained by the fact that Hogan's data²⁰ support a very short-run supply elasticity, while the data used by Nathan⁹⁸ are more appropriate for calculating long-run elasticities. The fact that A.D. Little's estimates done for DOE are closer to Nathan's than Hogan's tends to support the ISIS point of view, but a final determination of "who is right" will inevitably turn on the issue of whether short-run or long-run elasticities are the appropriate measures of supply response to scrap export limits.

What, then, determines the elasticity of supply for scrap? Supply elasticities are governed by the relative ease of expanding output; significant capacity expansion costs result in inelastic supply curves, unless significant excess capacity exists.

A recent study by ISIS shows that capacity limits are not a problem in the processing portion (sorting, shredding, compacting, etc.) of the industry.⁹⁹ The study indicates that present capacity could process twice the 52 million tons of scrap recycled in 1974 (out of 60 million tons purchased), the largest amount recycled on record. The problem lies in collecting and transporting scrap. Transportation is limited primarily by the shortage of railroad gondola cars to carry the scrap.¹⁰⁰

9.2.3 Elasticity of Demand

Turning to the demand side, scrap demand elasticities are governed by (a) the degree to which products made from scrap can substitute for other products, and (b) the degree to which scrap can substitute for other inputs in the production process. The single study of demand elasticity mentioned in the 1980 OTA report-- that of Rossegger -- indicated that demand is very inelastic.¹⁰¹

As to scrap product substitution possibilities, since steel made entirely from scrap (particularly old obsolete scrap) can be used to make only a fairly limited range of products, increases in scrap recycling are limited in the short run to the amounts of these products now made in the integrated mills. Since mini-mills now account for a very large percentage of such production (chiefly rebars and simple shapes), short-run substitution possibilities are quite limited. These limits can be expected to relax as time passes, since technological advances in scrap melting and impurity elimination are constantly increasing the range of products manufactured from scrap steel, even though the only practical current solution for nickel, copper, and tin impurities is to dilute them to acceptable levels.

Another possibility is to increase the ratio of scrap to hot metal (iron from blast furnaces) in the integrated mills, which produce the full range of steel products. While this option does not have the quantity restrictions found in the mini-mill route, the integrated mills are loathe to substitute a purchased raw material on which they make no profit for hot metal, an internally manufactured product in which they have a heavy investment. Thus, most substitution can be expected only as a result of the integrated mills not replacing their existing outdated hot metal capacity (blast furnaces, coke ovens, sinter plants). Such substitution is a fairly long-run process. Further, there are technical limits on the scrap. Hot metal charges achievable in the BOFs, which dominate integrated mills, limit further substitution possibilities, although a modest increase in BOF scrap charges from the "normal" 28-32% would increase scrap consumption by two million tons.

In sum, there are limits on the amount of scrap that can be substituted for hot metal. Thus, even though the energy savings per ton would be substantial, total energy savings would be limited by the tonnage restrictions. Over time, such restrictions should ease as scrap preheating equipment is installed

on BOFs, allowing higher scrap charges in integrated mills. The historical stability of the hot metal/scrap ratio, and DOE's modest (41%) target for it in 1985, both attest to the economic and technical limits of substitution, although the appropriateness of that target has been a subject of lively discussion between the scrap iron and steel industry trade associations, since it was achieved in 1980.

10 STEELMAKING

The final step in the steelmaking process is the conversion of hot metal and scrap to steel via a refining step that removes the excess carbon left over from the smelting process and various impurities such as silicon, manganese, phosphorus, and sulfur. At the same time, various additives such as nickel, chromium, and molybdenum are injected to improve the product's characteristics.

Figures 10.1, 10.2, and 10.3 show the major components of the three types of steel furnaces now in use in the United States: the open hearth furnace, BOF, and electric arc furnace. Materials and energy flows in steel production for 1980 are given in Fig. 10.4, which is based primarily on AISI data. Direct and indirect energy use per ton varies considerably among the processes. Electric arcs are the most energy-conserving, using around 10.5×10^6 Btu per ton (electricity valued at 10,500 Btu/kWh), with a 100% scrap charge valued at 0.7×10^6 Btu/ton. Open hearths follow with around 17.3×10^6 Btu/ton, and BOFs use 18×10^6 Btu/ton. Table 10.1 shows the rise of the BOF, which only now is beginning to yield to the electric arc as nonintegrated mills continue to capture a larger share of the market. Using the percentages in that table as weights for the furnace energy intensities, the average direct and indirect energy used to produce one ton of raw steel in 1980 from scratch is estimated to be 15.6×10^6 Btu.

10.1 OPEN HEARTH FURNACES

Before 1970, the mainstay of the iron and steel industry was the open-hearth furnace, but because of economic considerations and the energy crisis, a new workhorse, the BOF, has emerged. As Table 10.1 indicates, in 1980, 60% of the capacity was in BOFs, 11% in open hearths, and 28% in electric arc furnaces. Direct and indirect energy intensities per ton of steel produced in the open-hearth furnace are shown in Table 10.2.

The open hearth furnace, which consists of a rectangular refractory hearth enclosed by refractory-lined walls and roof, is first charged with scrap and a small amount of limestone. After the fuel (which may be oil, natural gas, CO, tar and pitch, or all four) has been ignited and the melting of the charge has begun, the proportioned amount of molten pig iron is charged and high-purity oxygen is blown in. After various minor operations, the molten steel is tapped, with a total cycle time of 8-12 hours. The open hearth can take a wide range of hot metal/scrap charges, compared with the BOF, which has a limited range. The more modern BOFs can take up to 28% scrap, but the older ones are more limited. Thus, as the BOFs replaced the open hearths, the mill as a whole lost much of its hot metal/scrap flexibility. This in part is why the electric furnace is coming into its own in the integrated plants, serving as the "swing" facility when scrap is scarce or plentiful. The combination of

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Fig. 10.1 Typical Open Hearth Furnace (arrows show direction of flow of preheated air, flame, and waste gases) (Source: Ref. 75)

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Fig. 10.2 Typical BOF (Source: Ref. 75)

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Fig. 10.3 Typical Electric Arc Furnace (Source: Ref. 75).

the very-efficient BOF and versatile electric arc spelled the end for the open hearth as a major steel melting technology. Many expect it to go the way of the Bessemer in the mid-1980s, although during boom periods it has a tendency to take on new life.

10.2 BASIC OXYGEN FURNACES

The BOF is very different from the open-hearth furnace. It is a pear-shaped vessel which, at the beginning of its cycle, is tilted at 45° to accommodate a scrap charge (up to 30% of the charge) and then the molten pig iron charge. After the ladle is turned upright, high-purity oxygen is injected via a water-cooled lance located at the top of the vessel. The key to the BOF is the use of the heat of reaction of the injected oxygen with the charge constituents (in particular, the carbon) to fully melt the charge; in most instances, scrap acts as a coolant. Supplementary fuel is used only occasionally when the charge contains scrap in excess of 28%. With the melt maintained at $2500^\circ\text{--}2900^\circ\text{F}$, the necessary chemical reactions take place, after which the molten steel is poured into transfer cars for transportation to either an ingot-pouring platform or to a continuous-casting machine.

Fig. 10.4 Materials and Energy Flows in Steelmaking, 1980
(Source: based primarily on Ref. 1 data)

Table 10.1 Raw Steel Production by Type
of Furnace, 1960-1980

	Total Output (10 ⁶ tons)	Percentage of Total Output		
		Open Hearth	BOF	Electric Arc
1960	-	87	3	8
1965	-	71	17	11
1970	131	37	48	15
1971	133	30	53	17
1972	120	26	56	18
1973	150	26	55	18
1974	145	24	56	19
1975	116	19	62	19
1976	128	18	62	19
1977	125	16	62	22
1978	137	15	61	24
1979	136	14	61	25
1980	111	11	60	28

Source: Ref. 59.

The tremendous advantage of the BOF is its total cycle time of 45 minutes, compared with the open hearth's 4 to 8 hours; this results in total cost savings of 12-15% over the open hearth, as well as substantial energy savings for a given metal mix, despite higher material costs.³⁸ (The reason Tables 10.1 and 10.2 do not reflect these savings is because they have differing hot metal/scrap ratios.) With BOFs replacing open hearths at a rapid rate and with the limitations on the amount of scrap that can be charged into a BOF, integrated plants are relying on the electric arc furnace to process the excess scrap.

Table 10.3 gives direct and indirect energy consumption per ton. The energy intensities would be lower than for the open hearth if it were not for the fact that the BOF uses less scrap per ton than the open hearth.

The offgases generated during the BOF cycle might be utilized if the economics dictated it.¹⁰² The gases are generated in sufficient quantity (565,000 Btu/ton of steel) and quality (250-300 Btu/ft³ at 3000°F, which adds 127,000 Btu/ton) to warrant attention.⁷⁰ All BOFs have hoods of some sort to direct the escaping gases. Since the gases are at 3000°F, and since further combustion of CO takes place in the hoods (unless it is suppressed, as in Armco's Middleton plant), these hoods have to be steam- or water-cooled, dropping the temperature of the gases sufficiently to allow them to be further

Table 10.2 Direct and Indirect Energy Consumption in
Open Hearth Steel Production, 1980

Inputs	Amount per Net Ton ^a of Steel Produced	Energy Use (10 ⁶ Btu)	
		Per Unit of Input	Per Net Ton ^a of Steel Produced
Materials			
Hot metal	0.64 ton ^b	20.29 ^c	12.98
Scrap	0.56 ton ^b	0.7 ^d	0.39
Limestone	0.044 ton	0.24	0.01
Lime	0.013 ton	5.45	0.07
Fluorspar	0.003 ton	1.59	0.01
Ferromanganese	0.011 ton	50	0.55
Ferrosilicon	0.001 ton	123	0.12
Aluminum	0.0005 ton	250	0.13
Oxygen	1.6 ft ^{3b}	0.000183	0.29
Refractories	40 lb	0.0125	0.5
Subtotal			15.05
Fuels and energy			
Electrical energy	15 kWh	0.0105	0.16
Fuel oil	7.7 gal ^b	0.15	1.16
Tar and pitch	3.8 gal ^b	0.16	0.61
Natural gas	1,128 ft ³	0.001	1.13
Coke oven gas	458 ft ^{3b}	0.0005	0.23
Subtotal (direct only)			3.29
Total (direct and indirect)			18.34

^a88% yield.

^bFig. 10.4.

^cTable 7.1.

^dTable 9.3.

Source: Ref. 29, except where noted.

Table 10.3 Direct and Indirect Energy Consumption in
Basic Oxygen Steel Production, 1980

Inputs	Amount per Net Ton ^a of Steel Produced	Energy Use (10 ⁶ Btu)	
		Per Unit of Input	Per Net Ton ^a of Steel Produced
Materials			
Hot metal	0.83 ton ^b	20.29 ^c	16.84
Scrap	0.32 ton ^b	0.7 ^d	0.22
Ferromanganese	0.011 ton	50	0.55
Ferrosilicon	0.001 ton	123	0.12
Aluminum	0.0005 ton	250	0.13
Lime	0.075 ton	5.45	0.41
Limestone	0.005 ton	0.24	0.00
Fluorspar	0.008 ton	1.59	0.01
Pellets	0.003 ton	1.79 ^e	0.01
Mill scale	0.008 ton	0	0
Refractories	13 lb	0.0125	0.16
Oxygen	1.94 ft ^{3b}	0.000183	0.35
Subtotal			18.8
Fuels and energy			
Natural gas	200 ft ³	0.001	0.2
Electrical energy	30 kWh	0.0105	0.32
Subtotal (direct only)			0.52
Total (direct and indirect)			19.32

^a90% yield.

^bFig. 10.4.

^cTable 7.1.

^dTable 9.3.

^eTable 3.4.

Source: Ref. 29, except where noted.

cleaned before release to the atmosphere. When steam is generated in this way, the energy recovered is estimated to be in the 150,000-250,000 Btu/ton range.³⁰ Other possibilities include limiting the combustion of the offgas by collecting it in a closed hood system and using it elsewhere in the plant, or completely combusting the gases to fire large boilers located directly over the facility. According to Thermo Electron, all the gases so collected are currently not being recovered, since the intermittent nature of the gas availability and high capital costs (\$18-25 million, including a gas holder to hold the gas until use) make it uneconomical to utilize this source.³⁹ The potential energy savings from such a system have been estimated to be in the $0.6-1.0 \times 10^6$ Btu/ton range, along with some electricity savings.³⁰

One use of the gases so collected would be to preheat the scrap charge to the BOF, allowing a higher scrap percentage charge to such furnaces. This is particularly important, since the upper limit on BOF scrap has required that some integrated mills install electric arc furnaces (which have 100% scrap charge capabilities) to handle periods of high scrap availability as open hearths are retired. If a means could be found to increase the limit on BOF scrap charges, such "swing" facilities might not have to be constructed. The U.S. Bureau of Mines conducted a series of tests at its pilot plant BOF to check the feasibility of this idea. The results were encouraging, and showed that the scrap charge percentage could be increased from 28% to 40%.¹⁰³

Scrap preheating need not be limited to use of BOF offgases; indeed, a far simpler method is to inject oxygen and fuel into the scrap portion of the charge. However, this results in severe refractory lining wear and decreased furnace availability.⁸ Consequently, other processes, such as the OBM-S process modification, might have to be used.¹⁰⁴ A.D. Little estimates that if all BOFs were converted to gas injection or to OBM-S systems, approximately 2.48×10^6 Btu/ton of steel could be saved.¹⁵ A more realistic (but unspecified in the report) market penetration assumption would produce savings of between 0.6×10^6 Btu and 1.8×10^6 Btu/ton of steel produced.⁸

10.3 ELECTRIC ARC FURNACES

Two types of electric furnaces are used to melt steel -- the electric arc and the electric induction furnace. In the arc furnace, an arc jumping between three electrodes suspended in the charge melts the metal. The induction furnace melts the charge in a refractory crucible surrounded by a copper conduction coil.³⁷ Only the arc furnace is used for refining, since slag cannot be maintained or removed in the induction process. Its main advantages are complete flexibility of the charge composition and exact control of process.

Table 10.4 gives the direct and indirect energy intensities for electric arc furnaces. Electricity consumption per ton varies from 450 kWh/ton for modern furnaces producing carbon steel (industry estimate) to 740 kWh/ton for furnaces of the same age producing alloy or stainless steel.¹⁰⁵

Electric arc capacity was estimated to be 26 million tons in 1972,⁵⁷ of which 5.9 million tons were in nonintegrated mills.⁶ Since then, mini-mill capacity has grown to 13 million tons; mini-mills are now the only segment of the industry adding significantly to its capacity.⁶

Scrap preheating has been tried in electric arcs as well as BOFs, both to replace high-cost electric energy with lower-cost fuels and to increase productivity. In 1961, the Bureau of Mines demonstrated that 30% of the melting energy could be provided this way.¹⁰⁶ Later tests confirmed these findings. Since the substitution appears to take place on a Btu-for-Btu basis, it saves energy, since fuels production is more efficient than electricity production. In another experiment, the residual heat remaining in billets, ingots, and molds was used to preheat scrap in a Canadian electric arc furnace; energy savings of 20% were reported.¹⁰⁷ Numerous experiments and reports of ongoing operations abroad are reported by Sheridan.¹⁰⁸

Table 10.4 Direct and Indirect Energy Consumption in
Electric Furnace Steel Production, 1980

Inputs	Amount per Net Ton ^a of Steel Produced	Energy Use (10 ⁶ Btu)	
		Per Unit of Input	Per Net Ton ^a of Steel Produced
Materials			
Steel scrap	1.06 ton ^b	0.7 ^c	0.74
Scrap transportation (300 mi by rail)	139 ton-mi	0.00067	0.09
Lime	0.03 ton	5.45	0.16
Limestone	0.01 ton	0.24	0
Fluorspar	0.005 ton	1.59	0.01
Electrodes	12 tons	0.08	0.96
Refractories	26 tons	0.0125	0.33
Ferromanganese	0.011 ton	50	0.55
Ferrosilicon	0.001 ton	123	0.12
Aluminum	0.0005 ton	250	0.13
Oxygen	352 ft ^{3b}	0.000183	0.06
Subtotal			3.15
Fuels and energy			
Natural gas	100 ft ³	0.001	1.1
Electrical energy	596 kWh ^b	0.0105	6.26
Subtotal (direct only)			7.36
Total (direct and indirect)			10.51

^a90% yield.

^bFig. 10.4.

^cTable 9.3.

Source: Ref. 29, except where noted.

11 SUMMARY AND CONCLUSIONS

As Table 11.1 indicates, opportunities are plentiful for saving energy throughout the iron and steel industry over and above the roughly 10% reduction per ton achieved since 1973. Little research effort was required to achieve that 10% savings or will be required in the future. This is partly because, in the past, little attention was paid to the more exotic technologies (nuclear steelmaking, continuous steelmaking) for specific energy-saving purposes. Rather, the new generation of steelmaking technologies was expected to drastically improve all the traditional industry input mixes and performance measures, and only incidentally alter energy consumption.

Why are existing "best practice" technologies not displacing less energy-efficient technologies? AISI has concluded that many are simply not profitable enough investments for the capital-short iron and steel industry; payback periods are too long because of high capital costs and/or insufficient fuel savings.⁷¹ The latter will be remedied if fuel prices increase at the 2-3% real rate that many government and industry experts predict. Others argue that the industry, faced with a constant or shrinking market in the last few years, cannot afford to purchase new equipment except to replace old. This limits drastically the introduction of energy-saving technologies, since as a general rule the cost of retrofitting existing equipment with conservation options is higher than the incremental cost of purchasing a new piece of equipment with the option built in.

Whatever the reason, while many of the options in Table 11.1 are no more than "best practice," there is little indication that the domestic iron and steel industry could or should make these technologies "average practice," given present costs of capital and energy prices.

Several other recent studies of the industry have reached similar conclusions. In a report for DOE, A.D. Little concluded that "few programs with large energy-conserving potential will be undertaken and pursued to completion within the near term without some form of government incentives."¹⁰⁹ In a more recent document, A.D. Little indicated that, of 13 conservation technologies analyzed, none required anything but development and demonstration activities to speed commercialization: the technologies were already proven.⁸

The opinion that basic research in steelmaking is not really necessary is not supported everywhere. The OTA report concludes that "the industry could adopt new steelmaking innovations if the Federal Government supports basic research in steelmaking (which barely exists today),"¹¹⁰ The body of the report, however, does not seem to support this conclusion. When discussing changes in technology, the report by in large concentrates on speeding the introduction of existing technologies. Indeed, of the six major technologies discussed at length (direct reduction, direct steelmaking, plasma steelmaking, direct casting, formcoke, and continuous casting), only two -- direct casting and plasma steelmaking -- have much technological uncertainty

**Table 11.1 Summary of Potential Areas for Energy Conservation
in Iron and Steel Manufacture**

Production Step	Energy Conservation Opportunities	Stage of Development ^a
Mining	Few, outside of larger loading/hauling equipment, importation of ore	C
Crushing	Improve comminution with existing and new technologies	C,D
Separation	Remove cationic silica; floculate iron oxide; use more-efficient magnets	R R C
Induration	Install heat recuperation facilities on all plants; substitute coal for hydrocarbons; use grate-kiln and traveling-grate shaft furnaces for on-site coal gasification; use partial reduction of pellets	C C D D
Sinter plants	Use binderless briquetting; use direct reduction of blast furnace and BOF wastes; recover sensible heat of sinter plant gases	D D C
Coke production	Nine options given in Table 6.6	C,D,R
Blast furnace	Use higher top pressures, plus expansion turbines; increase air blast temperatures; optimize burdens; use coal injection; reduce blast furnace gas loss; prereduce iron burden in lower stack; preheat ore with latent heat of coke and sinter; use blast furnace gas to preheat stove air; use heat in slag	C C C C C R D D R
Direct reduction	Use coal-based processes	C
Scrap	Develop cheaper shredders to increase scrap recycle rate; Change scrap transport prices to better reflect costs	D D
Steelmaking	Recover BOF offgas; Use scrap preheaters for BOFs and electric arcs	C D

^aR = research stage; D = development stage; C = commercial stage.

surrounding them, and even for direct casting, none of the proposed systems represents the application of new basic principles.

As in all industries where the product is both durable and recoverable, substantial energy savings can result from increased scrap recycling. Increased recycling activity in iron and steel is currently hampered by distortions in the relationship between the price paid to collect and move scrap and the true cost of such collection and movement. Perhaps with increased deregulation of the transportation industry, true costs and prices will come into line, making secondary recovery more profitable.

There are, of course, limits on scrap recovery; scrap must be "mined" and any substantial increase in the recycle rate can be done only at a cost, which might include having to limit exports, not a happy prospect for the scrap supply industry.

In summary, this study joins others in concluding that the role of government research and development in iron and steel high-technology projects is probably small compared with that in other industries (e.g., copper/lead, where smelting technology that is energy-efficient, cost-effective, and in compliance with the Clean Air and Water Act simply doesn't exist). However, there is a need for new, innovative government policies that would make it profitable for firms to capitalize on the developed technologies that await them at the "best practice" margin.

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