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Steel Recycling and Energy Conservation

Bruce Hannon and James R. Brodrick

Summary. The potential for energy conservation through increased use of steel scrap by the U.S. steel industry is examined. It is concluded that increased use of scrap would reduce energy use, but it is not economical, due mainly to volatile scrap prices. Other energy-saving technologies exist, but it is likely that energy will be conserved through reduced use of steel as rising energy costs are passed through to consumers.

In this article we discuss the potential for energy conservation through increased recycling in the U.S. steel industry. The industry, which plays a fundamental role in the U.S. economy, is regarded as very energy intensive. As international competition for metallurgical grade coal and public concern about waste have grown, the increased use of scrap steel to save energy in the steel industry has become an important topic. To our knowledge, this subject has not previously been studied in a comprehensive way; no research results are available in the open literature that quantify the total energy impact on the economy of shifts between the various steelmaking technologies or changes in the amount of recycling.

We calculate the historic energy intensity of the U.S. steel industry and the intensity under a variety of technological mixes needed to handle significant increases in recycling. The energy intensity is the direct and indirect energy required per ton of steel produced by the industry. Direct energy is defined as all the energy used on site by the steel manufacturer per ton of finished steel produced. Indirect energy is the energy used elsewhere in the United States and the world to furnish the manufactured goods, energy, and services used by the steelmaker per ton of finished steel. The total energy intensity is the sum of the direct and indirect energy intensities. After calculating the decreases in total energy intensity that result from increased steel scrap recycling, we determine the dollar cost of saving this energy and compare this dollar cost with the marginal costs of energy from new sources.

Our results show that most investigators have greatly understated the total energy cost of finished steel, and that two different types of furnaces used in steelmaking—the basic oxygen and open hearth furnaces—require essentially the same amount of energy per ton of finished steel. We find that the principal way to reduce energy use in steelmaking is to use more scrap, but even if all the steel were made from scrap the total energy intensity of steel would be reduced by only about 6 percent, saving less than 1 percent of total annual U.S. energy use.

An economic analysis of the cost of saving this energy indicates that it is very unlikely that rising energy prices will encourage significant energy savings in the steel industry. However, there may be other reasons for the industry to increase its use of scrap, such as relative rises in labor costs in the iron and iron ore industries and relatively high ore taxes. Several energy-conserving alternatives to scrap recycling exist, as we discuss in the concluding section of this article. However, extensive new capital investment will be required in the steel industry to reduce energy use and to keep the rise in the cost of production at or below the inflation rate.

Scrap and the Steelmaking Processes

Molten iron and iron and steel scrap are mixed with special additives in the steelmaking processes, which are of three basic types: the open hearth furnace, the basic oxygen furnace, and the electric arc furnace. The steel mills of the 1960's employed a mixture of all three technologies, but in recent years the open hearth process has been largely

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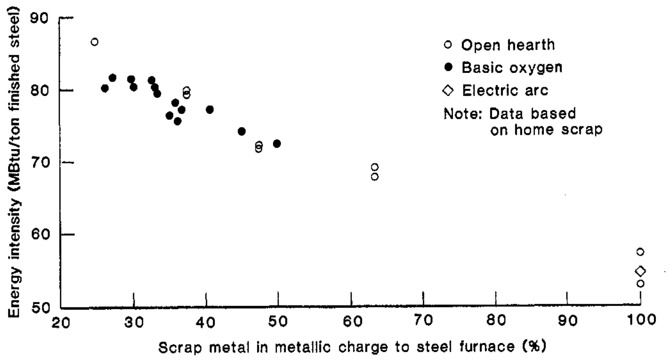


Fig. 1. Total energy intensity of finished steel for selected steelmaking processes with a varying scrap content. Because the data are based on home scrap, the material generated at the steel furnaces and rolling and finishing mills, the energy cost of scrap transportation is excluded in this figure. Also, these data do not include additional requirements for natural gas in the finishing section because of the reduced production of blast furnace gas and coke oven gas as recycling increases. These omissions apply equally to all processes. The data are presented in this form to allow the energy intensities of the three processes to be compared.

phased out because of high operating costs and environmental difficulties. In 1965 the distribution of steel production among the processes was 72 percent open hearth, 18 percent basic oxygen, and 10 percent electric arc. In 1975 the distribution was 18, 62, and 20 percent, respectively (*1*). Despite these dramatic changes in the type of furnace employed, scrap use was nearly a constant fraction of the metallic input—about 50 percent.

The basic oxygen process is sensitive to variations in the amount of scrap in the furnace charge. Higher rates of production are achieved with this process (compared to the open hearth process) by blowing large quantities of oxygen into the charge of scrap and molten iron. When the scrap fraction is greater than 25 to 30 percent of the metallic charge, the scrap is preheated before the molten iron is added. The scrap charge in the open hearth can vary from 0 to 100 percent, and the fuels used are oil, pitch, tar, and both coke oven and natural gas. The electric arc furnace normally handles an input composed completely of scrap, achieving a melt by passing a large electric current through the charge. Consequently, the electric arc process is widely distributed across the country, near the scrap supplies found in large urban areas and steel fabrication centers.

Determining Energy and Labor Costs

The comprehensive nature of our analysis depended on very large data bases. First, to account for the indirect energy pathways into steelmaking we needed a complete, detailed set of input-output transactions for the U.S. economy. When we began our study the only such data base was the 1967 input-output (I-O) matrix, which was released in 1974. Second, we had to convert the energy sales in the I-O matrix from dollars to physical units in order to accurately portray the direct energy transactions throughout the economy. We also had to derive the direct labor use [in full-time equivalent person-years (FTE)] for each industry in the economy (1 person-year = 2000 person-hours). In the third step, a mathematical one, we transformed the I-O matrix into a set of total energy and labor intensities. An intensity represents the total energy or labor used to produce a unit of a particular good or service (*2*, *3*). We then developed equally detailed descriptions (357 possible different inputs) of modern steelmaking technologies through surveys of the major steel companies. Included in this were data on the necessary inputs to scrap collecting companies.

By combining the energy and labor intensities with the descriptions of the steelmaking and scrap handling processes, we determined the energy and labor intensities for steel produced by a variety of technologies. We used this information in a linear program to find the combination of steel technologies that would minimize total energy use. The program can complete this minimization process for a specified level of recycling or recycle rate (that is, percentage of the metallic material input to a steel furnace that is scrap).

In constructing our energy and labor models we used a technique that estimates the amount of U.S. energy and labor that would have been required to produce our imports. Thus, the energy and labor used for steelmaking is an estimate of the world impact on energy and labor resources.

We used our survey data and the results of a steel-cost model to calculate the extra dollar cost of the steel produced for specified recycle rates. Only capital costs for the major portions of each process were used. We were therefore able to calculate the dollar cost of the energy saved through increased scrap recycling.

The data for our calculations are from different time periods. We believe that we have overcome most of the problems associated with the date of the I-O model by describing the steel technologies as they were in the late 1970's. Our recent comparison of the average energy intensities of the iron and steel industry in 1967 and 1974 showed them to differ by only 2.3 percent (*1*, *3*). Such a difference is probably within the error bounds of our calculation, but it might also be accounted for by a changing output mix. For example, if the amount of relatively energy-intensive stainless steel production declined while the production of less energy-intensive cold-rolled steel increased between 1967 and 1974, the average energy intensity would have declined.

Results

The total energy intensity of finished steel depends on the technology used to make it. Our results are given in Table 1, assuming that the energy intensity of scrap is zero at the point of discard.

The typical open hearth and basic oxygen processes require essentially the same amount of energy, even though the open hearth process uses considerably more scrap. The electric arc process is the lowest in total energy demand because it uses only scrap and avoids the energy cost of the blast furnace process.

A graphic view of the variation in the total energy cost of finished steel is shown in Fig. 1, which was derived from production process information supplied by steel companies. Increased use of scrap lowers the energy intensity of steel by avoiding blast furnace use. The energy use in the basic oxygen and open hearth processes seems about equally sensitive to changes in scrap use. The total energy used in the open hearth and electric arc processes is about the same at a 100 percent scrap rate.

Our results on the historic energy cost of steel are compared with those of others in Fig. 2, which shows the total energy cost, that is, the energy used from the ore mine to the finished steel shape. Our results obtained with the I-O model are 35 percent greater than the highest result achieved by the conventional means of process analysis, and almost 300 percent greater than the lowest result. The reasons for this difference are important. At least 110 separate industries deliver goods or services to steel producers, and each delivery comes with

Table 1. Energy intensities and scrap consumption of steelmaking processes (*1*).

Process	Energy intensity (Btu's per 1978 producer's dollar)*	Scrap consumption (per cent of input metal)
Open hearth	212,000	45
Basic oxygen	221,000	30
Electric arc	124,000	100

*Intensities inflated from base year to 1978 with inflators of sector 331 (*19*).

an "embodied" energy. It is too laborious to track down the energy embodied in each of these inputs by any procedure except the I-O process. Most researchers investigate what they believe to be the major inputs and neglect the many smaller ones that together constitute a major energy requirement (for instance, the energy cost of the oxygen manufactured for the basic oxygen process). Artificially low figures for the energy cost of steel might mislead policy-makers about the potential for energy conservation in the steel industry.

For a fuller examination of that potential, we needed a more detailed knowledge of the energy and employment costs of increased use of prompt scrap (that readily available from steel-using industries) and obsolete scrap (that discarded by individuals and commercial establishments). After an extensive review of the available data on scrap handling, we calculated that the collection, processing, and transport of 1 ton of scrap requires 0.6 million Btu's and 1.01 person-hours for prompt scrap; and 2.4 million Btu's and 3.7 person-hours for obsolete scrap (*1*).

By a process similar to the calculation of the energy cost, we computed the total labor cost of finished steel as about 20.6 FTE per thousand tons. The actual value depends on the steel furnace and the amount and type of scrap being used. As shown below, increased use of scrap would raise this total labor requirement (the energy cost of labor was not included in our calculation of the energy cost of steel).

Minimizing Energy Use

To determine how the United States might minimize total energy use while producing the same amount of steel, we set up a linear program involving all conceivable combinations of the three steelmaking technologies with various amounts of scrap recycling. Since the present-day processes use all of their home scrap and almost all of the immediately available prompt scrap, we made a model of the process for retrieving obsolete scrap. Such scrap comes from auto hulks, construction, railroad and packaging scrap, metal cans, and so on, or from scrapyard storage (the scrap "bank"). Our model included the increased energy (and labor) required as the distance from the steel mills to the scrapyards increases.

The average metal charge into steel furnaces in the past two decades has been about 50 percent scrap; it is composed of 60 percent home scrap and 40 percent purchased scrap. The purchased scrap is 45 percent prompt industrial and 55 percent obsolete scrap. About 35 percent of the obsolete scrap is auto hulks (*1*); the remainder comes from railroads, steel construction, farm machinery, appliances, and food and beverage containers.

In practice, two metallurgical problems inhibit the increased recycling of steel: contamination of the steel with nonmetals such as glass and other noncombustibles, and contamination with nonferrous materials such as copper, chrome, nickel, lead, molybdenum, sulfur, and tin. The nonferrous materials seriously impair the strength and ductility of steel, and the nonmetal contaminants require additional additives. As a result, such contaminated scrap materials are often sent to impurity-tolerant processes such as casting production, where they can saturate the demand.

In our linear program, 72 possible technologies were combined in ways constrained by total iron and steel furnace capacity, the scrap handling limits for each furnace type, the availability of prompt and obsolete scrap, and production levels and time. Because coke oven gas is used in the steel finishing processes, increased recycling reduces the availability of this heating fuel. Consequently, increased recycling results in increased use of natural gas in the finishing process, and this requirement becomes an additional constraint in the linear program. There are 72 possible combinations of source material and furnace type. There are 24 combinations of hot metal and scrap, which are divided among the three furnaces; the scrap in each combination can be one of three types, thus yielding 72 processes.

Availability of home scrap was not considered a variable in the program. This scrap plus a variable fraction of the prompt scrap have been used to maintain

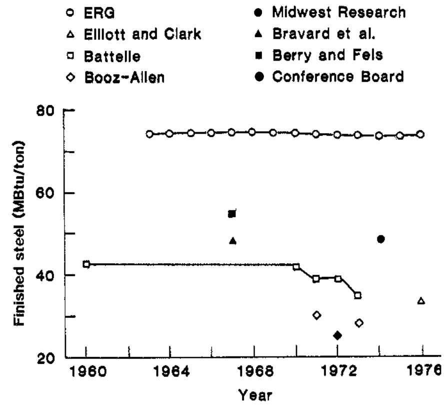


Fig. 2. Comparison of different estimates of the total energy cost of finished steel. Estimates are from the Energy Research Group (*ERG*) (*4*), Elliott and Clark (*20*), Battelle (*11*), Booz-Allen (*21*), Midwest Research Institute (*22*), Bravard *et al.* (*23*), Berry and Fels (*24*), and Conference Board (*25*).

a nearly constant 50 percent scrap charge rate (percent of metallic input to furnace) over many years of U.S. steel production (*4*). Because our program represents a variation from a 1967 economy, the linear program was constrained to produce 83.9 million tons of finished steel. The prompt scrap available was 22.2 million tons, and the obsolete scrap available was 40.8 million tons; the combined 63 million tons of available scrap was considered to be the 100 percent utilization rate.

Rates higher than 100 percent meant that withdrawals from the obsolete scrap bank have been incorporated. In the early 1970's, the bank was growing at a rate of 20 million tons per year, and it is now believed to contain about 635 million tons (*1*).

Figure 3 shows the decline in energy intensity with increased use of prompt and obsolete scrap in the three furnace types. The energy intensity calculated for the actual operation of the industry is quite close to the maximum total energy for the historic scrap recycle rate, calculated from the more recent steel process descriptions. Increasing the recycle rate to 100 percent reduces the energy cost by 4.5 million Btu's per ton of finished steel—a reduction of only 6 percent in the total energy cost of steel. (This reduction is about 0.6 percent of the total energy expended in the country.) Note that even if all the steel produced had been made from scrap, the energy cost would have been reduced by only about 7 million Btu's per ton of finished steel.

There are three reasons for these surprisingly small energy savings in the steel industry. First, even with the recycle rate raised to unprecedented levels, there is still a demand for energy-inten-

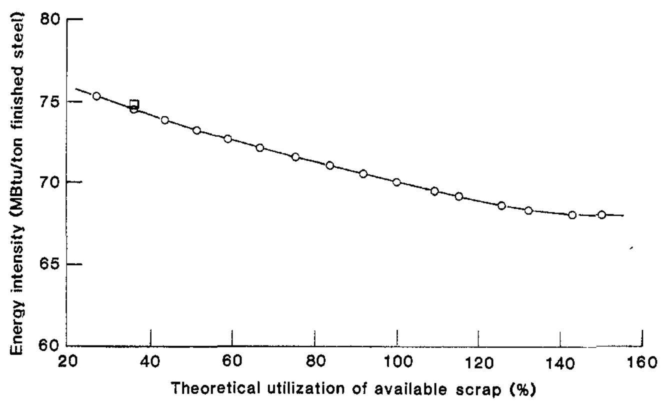


Fig. 3. Total energy intensity of finished steel for increasing recovery of available (prompt industrial and obsolete) scrap. Scrap uses greater than 100 percent mean that scrap is being used from the scrap "bank"—the collection of stored obsolete steel scrap. (□) Historic scrap recycle rate.

sive molten iron. This use of molten iron is necessary because of a production time constraint and a coincident lack of open hearth and electric arc furnace capacity. The next least energy-intensive option is to increase the proportion of scrap used in the basic oxygen furnace from its normal 30 percent to 50 percent. This change requires increasing amounts of scrap preheating. The upper scrap level is considered by the industry to be the highest attainable, principally because of furnace geometry; thus, we had reached the scrap handling capacity (as determined in the late 1970's) of the combined U.S. steel furnaces. The program could be improved by allowing for furnace capacity to be added and retired, but the industry generally operates well below capacity today.

Second, the energy cost of retrieving obsolete scrap is much larger than the cost for prompt or home scrap. As the recycle rate increases, the energy cost of obtaining the average ton of scrap increases. Although we assumed a fixed energy cost of obtaining obsolete scrap, that cost might rise even higher as the industry tries to retrieve more remote and dispersed quantities.

Third, there is an increased use of natural gas (instead of coke oven gas) in the rolling and finishing sections of the steel mills. Coke oven gas production declines as the amount of molten iron (blast furnace) production is reduced, and an external energy source is required.

As Fig. 3 indicates, the energy savings reach a minimum at a recycle rate of 140 percent, when the scrap handling capacity of the available furnaces is saturated. At this recycle rate, the use of new (pig or molten) iron is 15.7 million tons, a reduction from 68.6 million tons (base use). Home scrap use remains at 43 million tons, prompt scrap use reaches 20 million tons, and use of obsolete scrap climbs to 64 million tons. At the 140 percent recycling rate, about 3 million tons per year is being drawn from the scrap bank.

Figure 4 shows the percentages of total steel production by the three types of furnaces as recycling of available scrap increases. For lower rates of recycling (up to 60 percent), the percentages produced in open hearth and basic oxygen furnaces are constant. The predicted energy-minimum combination of production at 36 percent recycling is 30.9 percent open hearth and 69.1 percent basic oxygen. Actual production was 55.6 percent open hearth, 32.6 percent basic oxygen, and 11.9 percent electric arc (*1*). Note that production from a furnace did not include specification of the process (ratio of hot metal to scrap) used in the furnace because the production from one type of furnace can be made up of two or three processes. The energy intensity of steel decreases as the recycle rate increases to 60 percent (Fig. 3) even though the steel production of two furnaces remains the same, because the hot metal/scrap ratio to the furnaces is being changed by the linear program.

As more scrap becomes available, production by basic oxygen decreases and production by open hearth increases (open hearth is slightly more energy efficient) with the continued decline in energy intensity noted in Fig. 3. Full utilization of the open hearth capacity occurs at 115 percent recycling, and use of the electric arc furnace begins. As scrap recycling increases further, the model predicts that the basic oxygen furnace would continue to lose production—this time to the electric arc furnace, which is more (total) energy efficient. At 132 percent recycling, the three types of furnaces reach constant values of production (open hearth at 66.1 percent, basic oxygen at 21.4 percent, electric arc at 12.5 percent). In Fig. 3, the energy intensity continues to decline for recycle rates from 132 to 140 percent, although proportional output from each type of furnace remains constant.

The critical factor that limited attainment of the objective of energy minimization was the supply of prompt and obsolete scrap up to 115 percent recycling. Above that rate, the critical factor was the availability of the open hearth and electric furnaces. Therefore the furnace capacities did not constrain the objective until the 115 percent recycle rate was reached.

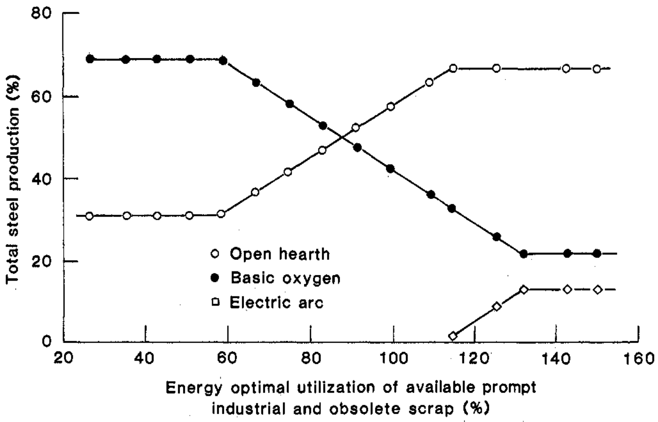
Table 2. Total (direct and indirect) labor required for various steel and scrap processes (*1*, *3*).

Process or scrap type	Labor intensity (FTE per thousand tons of finished steel)	Conditions
Open hearth	18.4	100 percent home scrap
Open hearth	20.2	52.6 percent prompt scrap
Open hearth	22.0	100 percent obsolete scrap
Basic oxygen	19.5	36.3 percent home scrap
Basic oxygen	19.9	36.3 percent obsolete scrap
Electric arc	20.4	100 percent prompt scrap
Electric arc	22.9	100 percent obsolete scrap
Home scrap		Always included in each steelmaking process
Prompt scrap	0.47	200 miles from shredder to mill
Obsolete scrap	1.71	200 miles from shredder to mill; 100 miles from consumer to shredder

Labor Demand

The optimum energy use configurations for the steel industry produce an interesting variation in the demand for employment. In Table 2 we give the total labor demand for a variety of steel processes used in the linear program. The labor demand varies from 18.4 to 22 FTE per thousand tons of finished steel. The labor required in scrap collection varies by more than a factor of 3.

Labor demand varies with recycle rate as shown in Fig. 5. For two reasons we



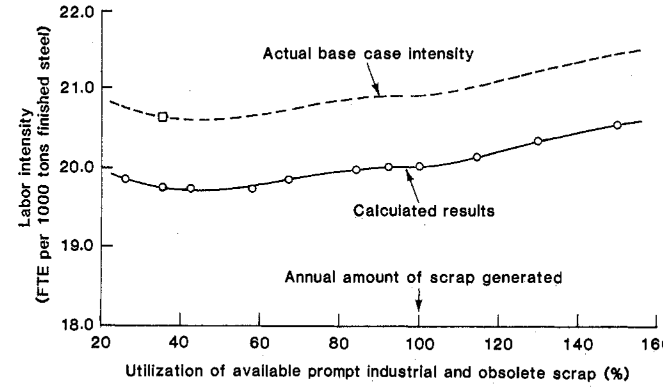


Fig. 4 (left). Energy minimizing distribution of steel production, by type of furnace, for increasing recovery of available (prompt industrial and obsolete) scrap. Alternative optimal solutions exist; that is, approximately the same value of total energy cost can be obtained with a different mix of furnace types. This occurs because some of the steelmaking processes have similar values of energy intensity. Thus if electric arc production capacity were unconstrained in the program, it could assume the position of the open hearth curve without a significant change in energy savings. The programming process selected the open hearth first because it is slightly less energy intensive than the electric arc furnace when consuming 100 percent scrap. Fig. 5 (right). Total labor intensity of finished steel for increasing recovery of available prompt industrial and obsolete scrap generated. Scrap used beyond 100 percent comes from the scrap bank. The dashed line is parallel to the unbroken line and passes through the actual base case intensity–scrap use rate point (□). It represents the best guess for actual changes in total labor intensity as the scrap content is increased. The calculated results are from the energy minimizing model.

could not match the labor intensity (open square in Fig. 5) (5 percent difference) obtained for the base case. First, the linear programming model is designed to pick out all the energy-intensive processes and may miss some of the labor-intensive ones. Second, the model did not select the actual base mix of furnace types because the base case mix was not quite the energy-minimizing one. To give an idea of the effect of increased recycling on labor intensity, we drew the rising dashed line through the base case point parallel to the program output data. This indicates that increased recycling will produce a slight increase in the demand for labor. However, the difference between the lines is about the same as the variation in labor intensity, and therefore the actual effect on labor demand cannot be stated with certainty.

Dollar Cost of Saving Energy

Having calculated the total direct and indirect energy savings for increasing levels of recycling, we wished to determine the associated dollar costs. Rather than calculate this for all levels of recycling, we estimated the change in dollar cost of steel per unit of total energy saved for the base level of the recycle fraction. This number permitted us to estimate the average and marginal costs paid for energy directly and indirectly by the steel industry. Because of the relatively rapid initial decline in energy intensity as the percentage of scrap increases (Fig. 3), we know that if the initial cost of saving a unit of energy by increased recycling is greater than the marginal and average energy cost paid by industry, it will be even greater at higher levels of recycling.

The following equation was used to determine the dollar cost of saving energy. Here the supply quantity of obsolete scrap is S_{sc} and its real unit cost is P_{sc}; the total energy intensity of finished steel (Btu's per ton) is ε_{st}, and Δ represents a small change. In these terms, the obsolete scrap supply curve would yield an elasticity e_{sc} of

$$e_{sc} = \frac{P_{sc}}{S_{sc}} \frac{\Delta S_{sc}}{\Delta P_{sc}}$$

Likewise, the finished steel energy intensity elasticity e_E is

$$e_E = \frac{S_{sc}}{\varepsilon_{st}} \frac{\Delta \varepsilon_{st}}{\Delta S_{sc}}$$

Then we define the ratio

$$\frac{1}{e_{sc} e_E} = \frac{\Delta P_{sc}/P_{sc}}{\Delta \varepsilon_{st}/\varepsilon_{st}}$$

The first elasticity, e_{sc}, was estimated by Rourk (*5*) to be 0.833 (at the mean). That is, for mean values of S_{sc} and P_{sc} for the period 1964 to 1975, a 1 percent increase in the price of obsolete scrap would have produced a 0.833 percent increase in the obsolete scrap supply. Correcting this mean value to the actual S_{sc} and P_{sc} in 1967 gives an elasticity of 0.930 (*5–8*).

The finished steel energy intensity elasticity, e_E, was obtained from our data. The appropriate data (*6*) were plotted and the base elasticity was found to be −0.017.

In a study for the Energy Research Group (*6*), A. D. Little calculated the cost of a fixed bundle of finished steel products under a series of cases representing increases in use of obsolete scrap. These cases corresponded to the scenarios generated in our energy minimizing model. Their results were striking. As long as the price of scrap did not change, the cost of the finished steel products did not change appreciably (< 3 percent), even though scrap as a fraction of metallic input varied from 50 to 90 percent. Apparently, it is safe to assume that the only cause for steel cost increases would be increases in the cost of scrap itself, induced by the rising demand for scrap (the general cost of labor, capital, and energy held constant).

If this is so, then for the level of 1967 scrap use we can say that the simplest relation between the cost of scrap and the cost of steel is

$$P_{st} = A + P_{sc}$$

where A is a constant (the unit processing cost of making finished steel) and P_{st} is the real unit cost of finished steel. Now we can show that

$$\frac{\Delta P_{st}}{\Delta \varepsilon_{st}} = \frac{P_{sc}}{\varepsilon_{st}} \frac{1}{e_{sc}\, e_E}$$

This is the form that gives us the change in the cost of finished steel relative to the change in energy cost in the base era; that is, $\Delta P_{st}/\Delta \varepsilon_{st}$ equals the dollar cost of saving a unit of energy by a marginal increase in scrap use by the steel industry. To calculate this value for the average condition in the U.S. steel industry, let ε_{st} = 74.4 million Btu's per ton (*1*) and P_{sc} = $75 (1976) per ton (*6*).

Therefore $\Delta P_{st}/\Delta\varepsilon_{st}$ = \$64 (1976) per million Btu's, and the cost of energy to the steel industry must be equal to or greater than this amount or it will not be economically feasible to increase the amount of recycling of steel.

By contrast, the industrial marginal energy costs (higher than the average energy costs) ranged from \$1.25 per million Btu's for coal to \$9.34 per million Btu's for electricity in 1979 (*9*). Even without reducing these costs for inflation, the dollar cost of saving energy through increased recycling is many times higher than the dollar cost of new energy supplies. Therefore the economic incentive does not exist to save energy through increased recycling, unless the price of scrap steel can be controlled. Government stockpiling of scrap to control the price would be economically appropriate if excess profits were being made in the scrap industry. The absence of integration of the steel companies into the scrap market gives some evidence of the lack of excess profitability in this market.

Alternatives

These results lead us to conclude that it is highly unlikely that rising energy costs will induce the steel industry to recycle more steel, even though such a move would save energy. The evidence since 1967 supports this view (*5*). Even though real energy costs have risen, the amount of recycling has not changed appreciably. The steel industry has responded to higher energy costs by internal process improvements rather than increased scrap recycling. Economic constraints are such that the scrap and energy savings link is not being utilized.

Energy can also be saved through changes in the steelmaking process. One of the major energy-saving changes is continuous steel casting, which reduces the generation of home scrap so that the percent of finished to raw steel increases from 0.69 to 0.79 (*1, 4*). At most, about 50 percent of all present finished steel could be continuously cast (*10*); therefore continuous casting would reduce home scrap generation by 5 percent. To produce the desired quantity of finished steel, prompt and obsolete scrap use would have to be increased 2.0 percent (home scrap is about 41 percent of total scrap). This means that continuous casting through the reduction of scrap generation could at most reduce the average energy cost of steel by about 400,000 Btu's per ton, about a 0.6 percent reduction.

In addition, the continuous casting process reduces the ingot reheating step, resulting in an energy saving of about 2.8 million Btu's per ton of finished steel. In 1975 only 6 percent of the raw steel made in the United States was continuously cast (*11*). By reducing ingot reheating, the energy cost of present steel production could be reduced by 1.4 million Btu's per ton. Combined with the savings due to home scrap reduction, the maximum possible energy savings is about 1.8 million Btu's per ton of finished steel. This is a 2.4 percent reduction in the energy cost of steel, roughly one-third of the maximum energy savings physically achievable by recycling.

A steel industry report (*12*) indicates that while continuous casting would reduce the energy cost of steel, it would be economically feasible to replace existing with continuous casting only in wholly new steel plants. With steady to declining levels of steel production in the United States, a significant replacement of the present casting method is unlikely to be accomplished even in the distant future. However, a study by the federal government concluded that the cost of replacing present ingot with continuous casting may be recovered in 2.5 to 5 years (*13*).

In any event, recycling and continuous casting seem to be the only energy conserving technologies available that save any appreciable amounts of energy. Other changes may appear more cost effective but have only small effects on the total energy cost. Several interesting adjunct questions can be answered with the information we gathered in this study. One of these is the controversial question of scrap exports. Restrictions on the export of steel scrap would tend to depress U.S. scrap prices and probably encourage more recycling. Such restrictions would have an interesting effect on the energy cost of U.S. steel. If we did not export the steel scrap, we could process it through an electric arc furnace. From Fig. 3, we find that, at the present recycle fraction, the energy used per ton of steel decreases about 0.15 percent for every 1 percent increase in the recycle fraction. Thus exporting scrap is equivalent to exporting energy conservation opportunity, if the scrap market is constrained by scrap supplies.

To restore economic equilibrium, something besides that quantity of scrap would have to be exported to achieve the same degree of trade balance. The energy required to produce this alternative export item (for instance, corn or soybeans) would reduce the energy savings from increased scrap use. The net energy savings would depend on the relative prices and energy costs of the scrap and the alternative traded good.

The adoption of steelmaking technology from other countries to reduce energy use may be fruitful (*14*). The Japanese steelmaking industry uses about 16 percent less direct energy per ton than U.S. processes. The difference appears to be in the coking process, more continuous casting, several novel energy recovery techniques, and the large average size of the Japanese steelmaking units.

Conclusion

The results of our study leave us in a predicament. Although rising energy prices can noticeably affect the price of steel (*15*), they will not produce significant energy conservation in the industry. In addition to the relative cost reasons given above, this conclusion is supported by the following facts. (i) Energy costs have always been a significant concern in the steel industry, and therefore some pressure has always existed to reduce them. (ii) When scrap use increases, the resulting reduction in coke oven and blast furnace gas, now used in the finishing operations, must be replaced by increased use of natural gas. (iii) Increased use of scrap produces rising dollar and energy costs of scrap.

We are left with the conclusion that the only way in which energy can be conserved in the steel industry is for steel production to shift in product mix or to decline. These are the likely results if real energy prices increase and industrial consumers find substitutes for steel. The mechanism for this conservation is the passed-through cost increases of direct and indirect energy.

Because the steel industry appears to have little room for energy conservation, some may argue that marginal costs for energy should not be charged to the industry. However, we contend that marginal cost-pricing of energy throughout industry is a desirable goal, and one that can be achieved by appropriate rate reform of gas and electricity pricing by the appropriate regulatory agencies and possibly by energy taxes on refined petroleum products. Some portions of industry and commerce will react to marginal cost-pricing by real energy conservation. Other portions, notably the steel industry, will react by raising prices. Consumer reaction to these prices will then produce conservation of steel and, consequently, of energy. Fewer cars and appliances, for example, might be purchased; existing ones might be used for longer periods. Greater reuse of metals might occur, as in the refurbishing of bus bodies (*16*), the rebuilding of auto engines (*17*), and the reclaiming of steel barrels and drums (*18*). The actual shifts in product mix and the price-induced decline in steel consumption are difficult to estimate. However, the techniques used here should aid industry and government planners in predicting demand responses due to increases in the cost of energy.

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