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SCIENCE

# Iron Ore: Energy, Labor, and Capital Changes with Technology

## Energy and labor are conserved with a shift from high-grade ore to lean-ore pelletization.

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Many people believe that mineral production will require an "increase in energy consumption as [ore] grade decreases" (*1, 2*). This is not always the case. Pelletized iron ore may be produced by mechanical concentration from finely ground taconite containing magnetite in natural concentrations averaging 25 percent iron. Use of this pelletized ore results in substantial energy (and labor) savings per ton of molten iron produced at the blast furnace when compared to the use of naturally concentrated hematite and goethite ores containing 50 percent or more iron. Thus, the technological breakthrough of pelletizing represents a step change in physical economic factors of production that temporarily offsets the persistent entropy trend associated with reliance on leaner and leaner ores.

In this article I address energy, labor, and capital changes resulting from the shift to pelletized lean iron ore during the last two decades. Changes in the substitution of factors of production, tax policies, and geographic distribution of environmental damage and employment are also discussed.

*Summary.* Resource gathering is depending on leaner crude ores. Iron ore mining typifies this trend. To make lean taconite iron ores useful required a technologic breakthrough—pelletization. The shift to iron ore pellets has the advantage that they require less energy and labor per ton of molten iron than high-grade naturally concentrated ores. Increased reliance on pellets causes a geographic shift of some jobs and environmental effects from blast furnaces to iron ore mines.

Total energy requirements were computed for two iron ore technologies: (i) that based on hematite and goethite ores naturally concentrated to approximately 50 percent iron or more, and (ii) that based on taconite ores of 20 to 30 percent crude iron mechanically concentrated to more than 60 percent iron and then pelletized. Process and input-output techniques (*3*) were used in a hybrid energy analysis (*4*) to calculate total energy requirements per ton of molten iron from 1954 through 1975. The shift in ore technology toward pelletization produced net energy savings of 17 percent. Labor savings and modest capital increases also resulted from the shift to pellets during this period.

## Iron Ore

Since the late 1800's, deposits in the Lake Superior region have supplied the majority of iron ore to U.S. blast furnaces. The vast deposits differ in grade and treatment. Soft, oxidized, naturally concentrated ore contains the iron minerals hematite and goethite. The highest grades of naturally concentrated ore, called direct-shipping or run-of-mine ores, contained 52 percent or more iron in crude form; some deposits exceeded 65 percent iron. Today, most of the hematite and goethite ores mined are of lesser grade and require some beneficiation (mechanical concentration) before ores containing 50 to 55 percent iron can be shipped. Beneficiation may include washing, screening, jigging, high-density separation, spiraling, or scrubbing. Texture grading distinguishes coarse ores from fines. Although they receive minor treatment, I refer to these ores as naturally concentrated to distinguish them from highly treated pelletized iron ores.

In contrast, the hard taconite ores contain less than 30 percent crude iron, and the primary iron mineral is magnetite. The magnetite is mechanically concentrated by crushing, grinding (commonly to $-325$ mesh), magnetically separating, balling, and indurating in mills near the mines. The resulting marble-size pellets contain 60 to 65 percent iron. Nonmagnetic taconite and naturally concentrated ores are also pelletized, but this requires different mechanical steps and usually more energy. Sinter was used before pellets and is an agglomeration of fine, naturally concentrated iron ore; flue dust; coke breeze (a screening by-product of coke); and, more recently, fluxes, which are fused in sintering plants at the blast furnace. The sinter cake is broken into clinker-like chunks and is only somewhat inferior to pellets as blast furnace burden. Because of the predominantly mechanical concentration involved in their production, I refer to pellets and sinter as agglomerate ore burdens.

In 1955, pellets were commercially introduced. Sinter at that time accounted for less than 20 percent of the iron charge

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to U.S. blast furnaces. As capital-intensive pellet mills expanded, pellets accounted for the growth of agglomerate charge and, by the early 1960's, they had begun to replace sinter. By 1975, more than 80 percent of the iron ore burden in U.S. blast furnaces was pelletized or otherwise agglomerated. Use of naturally concentrated iron ore declined commensurately.

The shift to pelletized iron ore caused physical changes in blast furnace operations as well as mining procedures. Therefore, in analyzing the effects of this shift in ore technology, changes must be traced through the production process until physical differences between naturally concentrated and pelletized ores vanish. The production of molten iron represents the point of indistinction—that is, the physical characteristics of molten iron (commonly called hot metal or, if cooled, pig iron) are the same whether pelletized or naturally concentrated ore is fed to the blast furnace. Before this point there are physical differences between ore forms, and they cause variations in physical economics—that is, the economics of molten iron production in terms of British thermal units (Btu's), man-hours, and capital investment dollars. Therefore, the boundaries of my study extend from iron ore in the ground to molten iron produced in blast furnaces.

## Demands at the Mine

*Energy.* Fuel and material consumption was inventoried for four naturally concentrated ore mines (5). Because they use different accounting procedures and in order to preserve their anonymity, I considered the case of a hypothetical standard naturally concentrated ore. The total energy required for the standard case is 1.934 million Btu's per net ton of iron delivered to blast furnaces (Table 1). Transportation is assumed to be from the Mesabi Range in Minnesota. Indirect energy accounts for more than 60 percent of total energy. Therefore, if mine operators were to view the energy required to produce and deliver naturally concentrated ore in terms of the heat value of fuels and power consumed on site, less than two-fifths of the total energy requirement would be accounted for.

Similarly, six pellet mills were inventoried and a hypothetical standard pelletized ore was developed. The total energy required in the standard pellet case is 5.153 million Btu's per net ton of iron delivered (Table 2). Magnetic taconite ore and transportation from the Mesabi Range are assumed (6). The transportation of pellets requires less energy than that of naturally concentrated ore because 10 percent less waste rock is transported with the pellets. Indirect energy accounts for 53 percent of the total energy required to produce and deliver pellets. Pellet production depends primarily on electricity and natural gas, whereas production of naturally concentrated ores depends mostly on electricity and diesel oil.

Pelletized iron ore delivered to U.S. blast furnaces requires more than 2.5 times as much total energy as naturally concentrated ore per net ton of iron. If only mine-site preparation is considered, and transportation to blast furnaces is excluded, the difference is even greater. Preparation of pelletized iron ore requires more than six times as much energy as preparation of naturally concentrated iron ore. However, neither mining, nor mining plus transportation, includes the point of indistinction (that is, molten iron) in this resource production system.

*Labor and capital.* Preparation of pelletized iron ore also requires more labor than preparation of naturally concentrated ore. I calculate that on the average the production of pellets amounts to 4380 tons of pellets per year per employee, whereas that of naturally concentrated ore is 5660 tons of comparable iron content per year per employee (7). Therefore, the average miner of naturally concentrated ore produces 29 percent more iron than the pellet plant worker.

Estimates of the expansion costs of four pellet companies in 1973 averaged approximately $50 per gross ton of annual pellet capacity (7). Engineering documents entered in the case of the State of Minnesota versus Reserve Mining Co. indicate a cost of $75 per gross ton of annual pellet capacity for 1975 (8). Discussions with pellet plant operators verified these costs.

There has been little new construction or added production capacity for natural-

Table 1. Energy requirements for naturally concentrated ore. Values are for a hypothetical standard case based on actual mine inventories. Factors used to derive the values in column 3 are given in (5, p. 62).

| Process | Energy per net ton of iron in ore: Original units | Energy per net ton of iron in ore: Btu's |
|---|---|---|
| Stripping non-ore overburden | | |
| Electricity | 1.78 kilowatt-hours | 23,000 |
| Diesel oil | 0.31 gallon | 52,500 |
| Explosives | 0.31 pound | 9,200 |
| Rubber tires | $0.15 | 6,000 |
| Subtotal (percentage of total) | | 90,700 (4.7) |
| Mining crude ore | | |
| Electricity (process) | 10.19 kilowatt-hours | 132,000 |
| Electricity (pumping) | 6.18 kilowatt-hours | 80,000 |
| Diesel oil | 0.69 gallon | 115,000 |
| Lubricants | 0.10 gallon | 17,000 |
| Gasoline | 0.03 gallon | 5,200 |
| Explosives | 0.89 gallon | 26,600 |
| Rubber tires | $0.34 | 13,800 |
| Steel wear parts | $0.52 | 25,000 |
| Subtotal (percentage of total) | | 414,600 (21.4) |
| Concentrating ore | | |
| Electricity | 8.08 kilowatt-hours | 104,600 |
| Diesel oil | 0.02 gallon | 2,900 |
| Lubricants | 0.01 gallon | 2,600 |
| Plant repairs | $0.07 | 2,200 |
| Steel wear parts | $0.11 | 5,400 |
| Subtotal (percentage of total) | | 117,700 (6.1) |
| Other (for example, office and stockpile) | | |
| Electricity | 0.01 kilowatt-hour | 150 |
| Diesel oil | 0.08 gallon | 14,000 |
| Rubber tires | $0.02 | 1,000 |
| Trade margins | $0.24 | 6,300 |
| Subtotal (percentage of total) | | 21,450 (1.1) |
| Transportation to blast furnace | | |
| Rail (100 miles) | 210 net ton-miles (iron) | 104,800 |
| Water (900 miles) | 1,881 net ton-miles (iron) | 1,185,200 |
| Subtotal (percentage of total) | | 1,290,000 (66.7) |
| Total | | 1,934,450 (100.0) |

ly concentrated ore, but it has been estimated that costs would range from $4 to $25 per gross ton of annual capacity if natural ore mining companies were to expand (*9*). A reasonable average might be $10 to $15. Pellet production is five times more capital intensive than production of naturally concentrated ore. Again, only mine-site labor and capital requirements are being compared.

### Demands at the Blast Furnace

*Energy*. Blast furnaces chemically reduce the iron oxide of the ore to molten iron. The substitution of pelletized ore for naturally concentrated iron ore causes three main energy changes in blast furnace firing: (i) the gas/solid contact ratio is increased because of improved permeability obtained with pellets, (ii) more air can be blown into the blast furnace because of the improved permeability, and (iii) waste removal (slag) is reduced because of the richer content of the pellets (*10*). Each of these changes reduces the amount of coke required per net ton of molten iron.

Furnace operators, however, have changed their firing practices in several ways since the introduction of pellets. The changes include increasing the blast temperatures, injecting supplemental fuels, and expanding the use of self-fluxing sinter (*11*). Together with the increased embodied energy of iron ore pellets as a substitute for naturally concentrated ores, these operating changes require additional energy per net ton of molten iron.

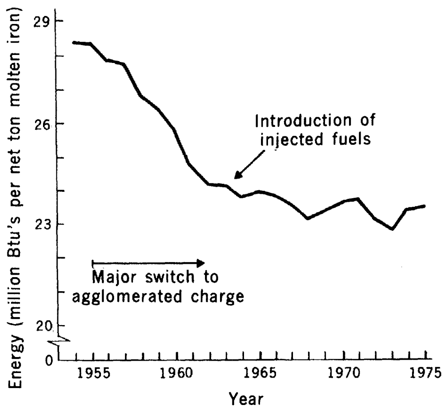
Taking into account both increases and decreases in energy use at the blast furnace, I computed the net changes in total energy requirements per net ton of molten iron for each year from 1954 through 1975. I used the observed rates for pellet charge, coking, injected fuel, flux, and other factors as recorded annually for blast furnace practices by the American Iron and Steel Institute and others (*12*) (Table 3). This analysis revealed two phases in the energy trend (Fig. 1).

The first phase, from 1954 to 1963, encompassed the major switch to agglomerate charges and resulted in a 15 percent decrease in energy required per net ton of molten iron. Thus, the decreased coke rates more than compensated for the increased embodied energy of iron ore pellets and sinter.

In the second phase, 1964 through 1975, injection of supplemental fuels into the blast furnace was widely practiced.

Table 2. Energy requirements for pelletized ore. Values are for a hypothetical standard case based on actual pellet plant inventories; the ore is assumed to be magnetic taconite mined at a northern Minnesota location. Factors used to derive the values in column 3 are given in (*5*, p. 62).

| Process | Energy per net ton of iron in ore | |
|---|---|---|
| | Original units | Btu's |
| Crude ore mining | | |
| Electricity | 3.67 kilowatt-hours | 47,600 |
| Natural gas | 10.07 cubic feet | 11,100 |
| Diesel oil | 0.66 gallon | 111,000 |
| Gasoline | 0.02 gallon | 3,590 |
| Lubricants | 0.03 gallon | 6,010 |
| Explosives | 3.93 pounds | 118,000 |
| Oxygen | 109.29 cubic feet | 20,000 |
| Rubber tires | $0.30 | 12,100 |
| Steel wear parts | $0.08 | 3,700 |
| Calcium chloride | $0.04 | 7,470 |
| Subtotal (percentage of total) | | 340,570 (6.6) |
| Coarse crushing | | |
| Electricity | 3.55 kilowatt-hours | 46,000 |
| Fuel oil plus natural gas | 0.08 gallon | 13,400 |
| Lubricants | 0.01 gallon | 1,040 |
| Steel wear parts | $0.11 | 5,120 |
| Chemicals | $0.02 | 4,230 |
| Subtotal (percentage of total) | | 69,790 (1.4) |
| Fine crushing | | |
| Electricity | 8.49 kilowatt-hours | 110,000 |
| Lubricants | 0.00 gallon | 500 |
| Steel wear parts | $0.28 | 13,300 |
| Subtotal (percentage of total) | | 123,800 (2.4) |
| Concentrating | | |
| Electricity | 94.03 kilowatt-hours | 1,218,000 |
| Natural gas | 120.69 cubic feet | 133,000 |
| Natural gas (heat) | 77.13 cubic feet | 85,000 |
| Lubricants | 0.00 gallon | 700 |
| Rod, balls, liners | 8.86 pounds | 155,000 |
| Subtotal (percentage of total) | | 1,591,700 (30.7) |
| Water handling and tailings | | |
| Electricity | 14.28 kilowatt-hours | 185,000 |
| Additives | $0.02 | 4,470 |
| Subtotal (percentage of total) | | 189,470 (3.7) |
| Agglomerating and induration | | |
| Electricity | 39.60 kilowatt-hours | 513,000 |
| Natural gas | 994.56 cubic feet | 1,096,000 |
| Gasoline | 0.00 gallon | 225 |
| Lubricants | 0.02 gallon | 4,000 |
| Bentonite | 34.00 pounds | 20,400 |
| Steel wear parts | $0.06 | 2,940 |
| Neutralizers | $0.05 | 9,200 |
| Refractories | $0.07 | 7,930 |
| Subtotal (percentage of total) | | 1,653,695 (31.9) |
| Other (office, shop, and so on) | | |
| Electricity | 1.34 kilowatt-hours | 17,300 |
| Natural gas | 11.80 cubic feet | 13,000 |
| Propane | 0.11 pound | 2,800 |
| Diesel-fuel oil | 0.24 gallon | 40,000 |
| Lubricants | 0.01 gallon | 2,500 |
| Trade margins | $0.148 | 3,900 |
| Subtotal (percentage of total) | | 79,500 (2.2) |
| Loading pellets | | |
| Electricity | 0.74 kilowatt-hour | 9,620 |
| Diesel oil | 0.02 gallon | 3,730 |
| Gasoline | 0.01 gallon | 900 |
| Lubricants | 0.00 gallon | 200 |
| Subtotal (percentage of total) | | 14,450 (0.3) |
| Transport to blast furnace | | |
| Rail (100 miles) | 177 net ton-miles (iron) | 88,400 |
| Water (900 miles) | 1,590 net ton-miles (iron) | 1,002,000 |
| Subtotal (percentage of total) | | 1,090,400 (21.0) |
| Total | | 5,153,375 (100.0) |



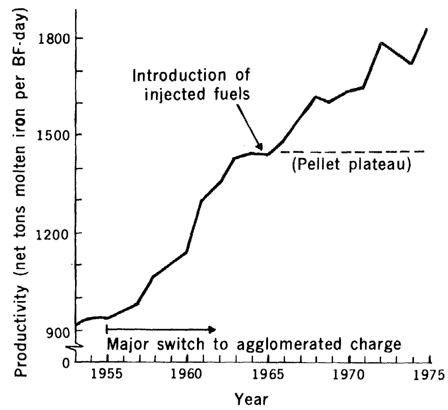




Fig. 1 (left). Total energy trend for U.S. blast furnace production of molten iron from 1954 through 1975. Fig. 2 (right). Average U.S. production of molten iron per blast furnace-day from 1953 through 1975 (*14*). Data from American Iron and Steel Institute.

Coke rates continued to decline as pellets gradually assumed a larger share of the charge, but supplemental fuel injection nullified these energy savings. Total energy requirements remained nearly constant from 1964 to 1975.

Over the complete period 1954 to 1975, there was a net reduction of 17 percent in the total energy required. This is 4.9 million Btu's per net ton of molten iron (*13, 14*). The energy conservation is attributable to the use of pellets and sinter because their improved permeability increased the chemical efficiency of blast furnaces. If supplemental fuel injection had not been practiced, the net savings could have been 23 percent of the total energy required or 6.5 million Btu's per net ton of molten iron.

*Further energy conservation.* The maximum amount of energy that could be saved through use of pellets and sinter can be calculated. A shift in the blast furnace burden from 100 percent naturally concentrated iron ore to 100 percent agglomerate, with no supplemental fuel injection, would reduce total energy consumption by 36 percent. This is more than 10 million Btu's per net ton of molten iron. An all-agglomerate charge would consume 4.1 million Btu's per net ton less than is used in current (1975) practices, or would provide an additional 18 percent savings of energy. Blast furnace production, however, would be slowed.

Could even more energy be saved by pelletizing the richer, naturally concentrated ores rather than the lean taconite ores? The answer is no, for two reasons.

First, with taconite, energy as well as iron is mined. The magnetite ($Fe_2O_3 \cdot FeO$) in magnetic taconite contains free thermodynamic energy. Induration in pellet kilns converts the magnetite to hematite ($Fe_2O_3$) and releases exothermic heat (*15, 16*). The released heat amounts to 37 percent of the total energy required for agglomeration and induration in my standard pellet production case (Table 2). Naturally concentrated ores, which are already hematite or goethite, produce no exothermic heat during induration. On the other hand, some pellets made from naturally concentrated ores require additional heat to vaporize water of crystallization during induration (*17*). Taconite has virtually no water of crystallization.

The second and more important reason involves the physical structure of the crude ore, which has a wide range of particle sizes and much clay. Crushing and grinding the very hard, metamorphic

Table 3. Total energy consumption per net ton of molten iron (NTMI) from blast furnaces in 1975, 1965, and 1955.

| Item | Million Btu's per unit | Energy per net ton of molten iron: 1975 (production = 79.9 million NTMI) | | 1965 (production = 88.9 million NTMI) | | 1955 (production = 77.8 million NTMI) | |
|---|---|---|---|---|---|---|---|
| | | Original units | Million Btu's | Original units | Million Btu's | Original units | Million Btu's |
| Naturally concentrated ore | 1.934 per net ton (iron) | 0.184 | 0.36 | 0.357 | 0.69 | 0.815 | 1.58 |
| Sinter | 6.0 per net ton (iron) | 0.275 | 1.65 | 0.387 | 2.32 | 0.172 | 1.03 |
| Pellets | 5.153 per net ton (iron) | 0.541 | 2.79 | 0.246 | 1.27 | 0.007 | 0.04 |
| Subtotal | | | 4.80 | | 4.28 | | 2.65 |
| Fuel oil | 0.168 per gallon | 4.74 | 0.80 | 0.60 | 0.10 | NR* | 0.00 |
| Tar and pitch | 0.203 per gallon | 1.44 | 0.29 | NR | 0.00 | NR | 0.00 |
| Natural gas | 1.127 per million cubic feet | 0.35 | 0.39 | 0.52 | 0.59 | NR | 0.00 |
| Blast furnace gas | 0.121 per million cubic feet | 16.73 | 2.02 | AV† | 2.03 | AV | 2.03 |
| Coke-oven gas | 0.635 per million cubic feet | 0.15 | 0.10 | 0.13 | 0.08 | NR | 0.00 |
| Oxygen | 0.183 per million cubic feet | 0.32 | 0.06 | 0.11 | 0.02 | NR | 0.00 |
| Subtotal | | | 3.66 | | 2.82 | | 2.03 |
| Coke | 31.5 per net ton | 0.611 | 19.25 | 0.656 | 20.66 | 0.873 | 27.50 |
| Limestone and other | 0.24 per net ton | 0.234 | 0.06 | 0.279 | 0.07 | | 0.09 |
| Subtotal | | | 19.31 | | 20.73 | | 27.59 |
| Mill cinder and other | 0.0 per net ton | 0.05 | 0.00 | C‡ | 0.00 | C | 0.00 |
| Scrap | 0.0 per net ton | 0.05 | 0.00 | 0.04 | 0.00 | 0.05 | 0.00 |
| Refractories | 0.013 per pound | 5.0 | 0.06 | C | 0.06 | C | 0.06 |
| Electricity | 0.013 per kilowatt-hour | 25.0 | 0.33 | C | 0.33 | C | 0.33 |
| Steam | 1 per 1000 pounds | 1.2 | 1.20 | C | 1.20 | C | 1.20 |
| Subtotal | | | 1.59 | | 1.59 | | 1.59 |
| Total | Million BTU's per NTMI | | 29.36 | | 29.42 | | 33.86 |
| By-product blast furnace gas | 0.121 per million cubic feet | 48.8 | −5.91 | AV | −5.53 | AV | −5.53 |
| Net total | Million BTU's per NTMI | | 23.45 | | 23.89 | | 28.33 |

*NR, not recorded in American Iron and Steel Institute (AISI) *Annual Statistical Reports* and assumed to be zero. †AV, the average blast furnace gas value from the AISI record for 1966 to 1975 assumed for earlier years, when it was unreported. ‡C, values held constant at Battelle (*25*) levels.

taconite ore produces more uniform and larger particles. Grinding magnetite produces particles that are about ten times larger on the average than the largest clay particles of naturally concentrated ore. There are three problems in pelletizing naturally concentrated ores: (i) difficulty in controlling moisture produces pellets of various sizes, which reduces permeability in blast furnaces; (ii) the weaker naturally concentrated ore pellets fragment and clog the blast furnace, reducing permeability; and (iii) difficulty in filtering and colloidal suspension of the particles impede the mechanical concentration of iron. Naturally concentrated hematite ore is not magnetic, and this presents a fourth problem, since magnets are used in the simplest mechanical concentration process.

*Labor and capital.* Blast furnace productivity doubled between 1954 and 1975. The increased production of molten iron reduces both labor and capital requirements per ton of product. Two phases are identified (Fig. 2).

In the first phase, from 1954 to 1963, the improved permeability of agglomerate burdens resulted in more efficient and more rapid chemical reduction of iron ore in blast furnaces. In the middle 1960's production increases began to level off, and new firing practices were developed, including greater preheating of the air blown into the furnaces and injection of supplemental fuels into the furnace base. These practices characterized the second phase of increased productivity (1964 to 1975). The resulting higher blast temperatures speeded the chemical reduction process and productivity once again began to increase, but without concomitant energy savings. Pellets and, to a lesser degree, sinter indirectly contributed to the second phase of increased production by allowing greater preheating of the blast air and injection of supplemental fuels. The direct productivity gains attributable to pellets and sinter, however, tended to reach a plateau in the middle 1960's.

To calculate labor and capital changes, I constructed a total cost schedule for molten iron production and scaled it according to the relative labor and capital intensiveness of each industrial process sector (*5*, p. 69; *18*). Absolute changes in labor and capital recorded in the *U.S. Census of Manufacturing* and by the Bureau of Labor Statistics were then weighted according to the scaling (*19*).

If labor intensities for mining are increased to reflect the observed shift in ore preparation and labor intensities for blast furnaces are decreased to reflect the productivity gains from 1954 to 1963 and half of the productivity gains after the 1963 "pellet plateau," then direct labor in mines and blast furnaces (in man-hours per net ton of molten iron) decreased by 8.2 percent. If the same conditions are applied to capital investments, it is estimated that pelletization increased capital costs (in dollars per net ton of molten iron) by 31 percent.

### Total Costs for the Mine and Furnace System

It is not possible at this point to reduce the three factors of molten iron production (total energy, direct labor, and direct capital) to common units. Thus, they cannot be added together to obtain a single evaluation of the total cost of shifting to pelletized iron ores. Energy savings are measured in Btu's per net ton of molten iron; direct labor savings are in man-hours per net ton of molten iron; and increased capital costs are for investment dollars per net ton of molten iron. Despite the lack of a factor to equate units, to ensure comprehensive coverage, and to avoid double counting, a general comparison reveals that labor is by far the largest cost component. Capital costs are generally the smallest factor in total costs; in 1967, on the average, fixed capital formation constituted only 12.3 percent of total costs in the final demand sector (*20*). Blast furnaces and iron ore pellet plants are more capital intensive than this, but 15 percent of total costs may be a generous enough estimate. Therefore, with both labor and energy conserved, the total cost of molten iron production has probably declined as a result of the introduction of pelletized iron ore.

The substitutional advantages of energy, labor, and capital in the iron and steel industry influence technological decisions. Marginal productivities for 1940 through 1977 were calculated from ratios of unit cost indexes (*21*) (Fig. 3). From 1940 to 1950, low-priced capital had a substitutional advantage over both labor and energy. After World War II, the iron and steel industry rebuilt and expanded its war-worn capital stock. Between 1950 and 1970, relatively low-priced energy held a substantial advantage over high-priced labor. The industry, however, discovered that capital investments in pellet plants could save both labor and energy until 1963; after that, capital plus energy were substituted for high-priced labor. A sharp reversal of substitutional advantage occurred in 1970, when energy became the most costly factor. Thus, capital now holds a strong substitutional ad-

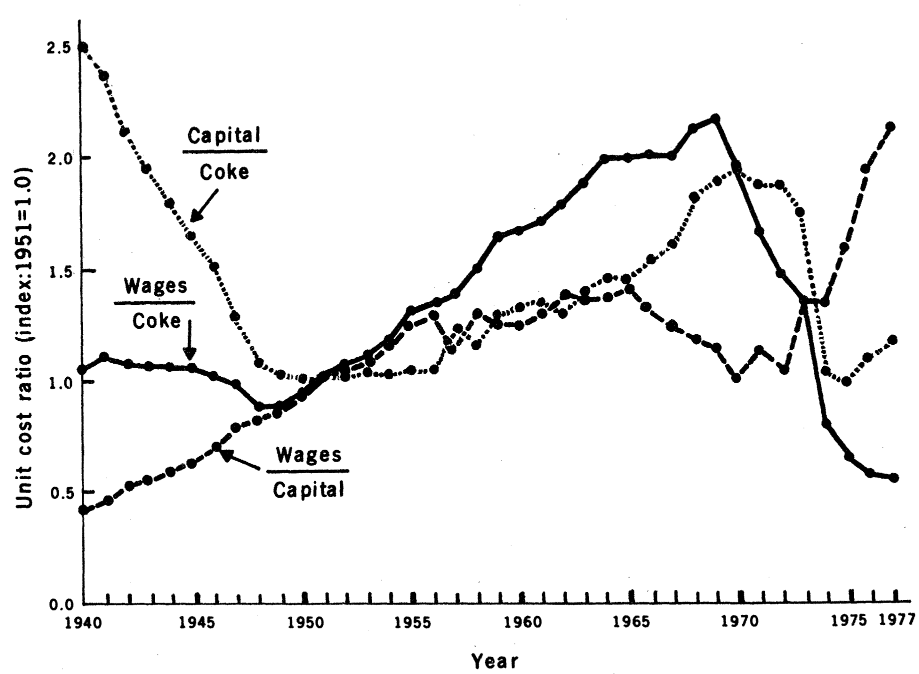



Fig. 3. Unit cost ratios for the iron and steel industry for energy, labor, and capital from 1940 through 1977. For capital, the market value of selected AA bonds for major steel companies was used. Since new capital for captive pellet plants and other mines is often raised by major steel company bonds, this measure applies to the entire molten iron production system. Wages are based on the average total payroll costs for wage employees in the iron and steel industry (*14*). Although there are discrepancies, iron ore mines belong to the same union as iron and steel workers and the patterns of wage change for both have been very similar. Coke values are based on the cost of coal per ton of coke, from the Bureau of Mines *Minerals Yearbook* for 1940 through 1975 and from *Coal Week* for 1976 and 1977. Since coke is the major fuel of the molten iron production system, its cost is a reliable indicator of energy costs for the entire system.

vantage over high-priced energy and intermediate-priced labor. The steel industry, however, chooses to substitute capital plus energy for labor when its prime savings potential is in finding capital substitutions for energy.

## Policy Implications

There are a number of policies connected with the shift to pelletized iron ore. For policies, too, the point of physical indistinction (molten iron) determines the boundaries of analysis.

As steel production shifted toward dependence on pelletized iron ore, a portion of the manufacturing process was transferred from the blast furnace to the ore mines. The pellet mill located near the mine physically manifests the relocated manufacturing activity; the increase in mine employment manifests the geographic shift of direct labor. At the steel mills, changes include fewer jobs at the blast furnace and coke ovens and fewer blast furnaces and coke ovens required per net ton of molten iron.

Transfer of some environmental damage from blast furnace locations to iron ore mines has also occurred. Pelletized ore burdens reduce blast furnace coke requirements and thus reduce associated air and water pollution. The increased energy required to produce pellets results in increased air and water pollution in the ore production region. In addition, the larger volumes of crude ore that must be processed for pelletized taconite result in more discarded waste. In some taconite deposits, trace elements in the waste rock have caused particular concern. The case of the State of Minnesota versus Reserve Mining Co. has brought public attention to emissions of amphibole and asbestiform fibers to water and air. Reserve Mining Co. is not typical of other pellet operations because of the particular taconite ores mined by Reserve. However, the expanded manufacturing activities and the larger volumes of crude ore mined for pellets do produce more waste and the potential for new pollutants. The geographic shift in environmental damage has been away from areas of dense population near blast furnaces and toward sparsely populated mining regions.

As government encourages, or regulates, energy conservation, the drafted policies should encompass the point of physical indistinction. For the iron and steel industry, pelletized taconite conserves energy even though it requires six times more energy in the mining sector than naturally concentrated iron ore.

## Taxes

Minnesota iron ore taxes illustrate some of the complexities associated with legislated mineral policies. Even before production of naturally concentrated ore began in Minnesota, low taxes were set to encourage resource exploitation. The production tax amounted to 1 cent per gross ton of iron ore mined and shipped. This lenient tax was ruled unconstitutional in 1897 and replaced by an ad valorem tax, based on 50 percent of the assessed "full and true value" of mineral properties; thus the tax rates were put in the hands of local assessors. The resulting taxes varied greatly from one mining property to another and, in general, were much higher than the earlier taxes based on production. In 1907, the State Tax Commission did much to standardize the methods of ascertaining the quantity, quality, and value of mining properties, but the iron mining industry in Minnesota continued to pay higher taxes than other businesses and industries in the state. This taxing policy for naturally concentrated iron ore was rooted in the philosophy that the state should be compensated for the removal of an irreplaceable resource (the natural heritage theory).

In 1941, the first taconite law was passed in Minnesota. Like the early legislation governing taxes on naturally concentrated ore, the first taconite law was operative before any commercialization and levied a low production tax to encourage development of pelletization. To make this law constitutional, however, a minimal ad valorem tax was applied, but only to unmined properties. As commercial taconite production began in 1955, the total tax on taconite per ton of iron in ore was only 15 percent of the taxes on naturally concentrated iron (Fig. 4).

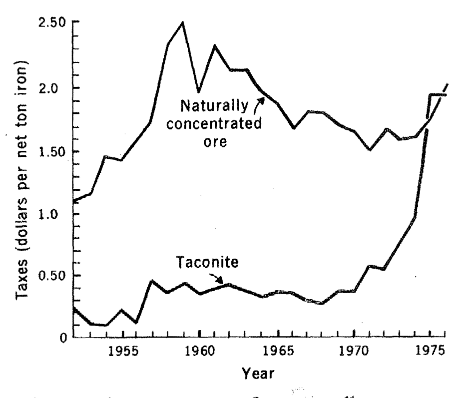



Fig. 4. Minnesota taxes for naturally concentrated iron ore and taconite pellets from 1952 through 1976. Calculations are based on taxes paid per net ton of iron in ore; the average iron content is assumed to be 63 percent for taconite pellets and 53 percent for natural ore shipped. Data are from (26).

Taconite continued to enjoy a favored tax position in Minnesota until recently. Shortly after the industry recognized the superior qualities of iron ore pellets in 1960, a successful attempt was made to hold the line on taconite taxes. Specifically, a 1964 Minnesota constitutional amendment stated that taconite-producing companies should not be singled out for inordinate tax increases for the next 25 years; taconite taxes should increase only in proportion to increases in state taxes for other manufacturing establishments. In 1971 and 1975 taconite taxes were raised significantly, and they are now on a par with taxes on naturally concentrated iron ore. However, taxes on naturally concentrated ore have been held nearly constant in current dollars for the last 20 years, so taconite still seems to enjoy a favored tax status in Minnesota.

Resource regulations have broad implications that should be understood by government and the public. The low taconite taxes have encouraged the relocation of mining and manufacturing companies in Minnesota and thus produced more jobs there; nationwide, they have encouraged energy conservation. On the other hand, Minnesota pays the cost of increased environmental damage (22), and employment is reduced slightly nationwide. Recent changes in the taconite taxes suggest that policy-makers in Minnesota are seeking a different balance point for these trade-offs.

Unfortunately, confused thinking may also motivate policy decisions, and there are two misconceptions that might support favoring taconite with low taxes: (i) that the depletion of naturally concentrated ore reserves leaves only the inferior taconite deposits to be developed; and (ii) that the high capital costs of pellet plants are a significant disadvantage to taconite compared to naturally concentrated ore. Actually, taconite pellets are the preferred form of raw iron because they improve productivity, conserve energy, and allow greater quality control of iron production from the blast furnace. In all probability, total costs per ton of molten iron are less with pellets than with naturally concentrated ore.

## Conclusions

Pelletized iron ore involves the substitution of energy to do mechanical work for energy to do chemical work. The mechanical energy required for pelletization is embodied as indirect energy for the chemical processes of the blast furnace. When the changes in all direct and indirect energy per ton of molten iron are considered, the total energy requirements decline with increased use of pellets.

This energy conservation is remarkable since the ores mined to produce pellets are leaner than high-grade naturally concentrated ores. Part of this energy saving occurs because the lean taconite ores contain both iron and energy. Pellet hardening in kilns releases exothermic heat. More importantly, however, the durability and uniform spherical shape of pellets greatly increases permeability in blast furnaces and improves the chemical efficiency of the furnaces. Improved permeability saves more than six times as much energy as the exothermic heat released in pellet kilns per ton of molten iron.

Pellets also allow significant increases in blast furnace productivity, thereby improving overall labor and capital productivity in the manufacture of iron. Net labor requirements are reduced. The labor and energy savings depend on capital investment in pelletizing plants; net capital per ton of molten iron rose with conversion to pellet technology.

Pelletization increases the efficiency of molten iron production. The technological benefits must be considered in the broader context of social policy issues involving (i) export of jobs and pollution from cities to the country, and (ii) net changes in health conditions and environmental damage.

This analysis leads to several general conclusions. First, an energy analysis confined to one industrial sector can be misleading. Changes within one sector result in changes in associated sectors that can more than compensate for them; therefore, piecemeal approaches to industrial energy conservation are inappropriate. An analysis of the direct and indirect energy required for a potential conservation adjustment must be followed to a point in the industrial process where there is no longer any physical difference in the product. Second, the example of iron ore pellets supports the view of the so-called technological optimists over that of the doomsayers. Doomsayers stress limits and finite resources; they see energy requirements increasing and effective exhaustion of resources resulting as demands continue to grow rapidly (*23*). Technological optimists view resources by analogy with a series of storerooms and consider that as man "used up what was piled in that first room, he found he could fashion a key to open a door into a much larger room" (*24*). The keys are generally formed by substitution and technological innovation. Pelletizing technology has unlocked one large storeroom of previously valueless rock, which now provides superior iron ore.

### References and Notes


1. J. Page and S. C. Creasey, *J. Res. U.S. Geol. Surv.* 3 (No. 1), 9 (1975).
2. See also B. J. Skinner, *Am. Sci.* **64**, 267 (May-June 1967); D. A. Brobst, *The System Approach to the Analysis of Resource Scarcity* (U.S. Geological Survey, Reston, Va., 1976); Committee on Mineral Resources and the Environment, *Mineral Resources and the Environment* (National Academy of Sciences, Washington, D.C., 1975); B. Harvey and J. D. Hallett, *Environment and Society: An Introductory Analysis* (MIT Press, Cambridge, Mass., 1977), p. 47.
3. R. Herendeen and C. Bullard, *Cent. Adv. Comput. (CAC) Univ. Ill. Doc. 140* (1974).
4. C. Bullard, P. Penner, D. Pilati, *Cent. Adv. Comput. (CAC) Univ. Ill. Doc. 214* (1976).
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6. Variations among plants in total energy required were due primarily to (i) the age of the plant, and (ii) the nature of the ore body mined. Newer plants and larger plants generally require less total energy per ton of pelletized iron. Nonmagnetic ores require substantially more energy to beneficiate than magnetic taconites. Comparing individual mines, I calculated that the total energy at the mine for nonmagnetic pellet plants was 45 percent greater than that for the average—and 57 percent greater than that for the most efficient—magnetic taconite pellet plants. Harder ores also require slightly more energy for crushing and grinding.
7. Calculated from the raw data base for *Energy Requirements in Minnesota Iron Ore and Taconite Mining, 1953-2000* [Minnesota Energy Agency, St. Paul, undated (about 1975-1976)]. The data were provided by W. Maki.
8. *Draft Environmental Impact Statement—Reserve Mining Company Proposed On-Land Tailings Disposal Plan* (State of Minnesota, Department of Natural Resources and Pollution Control Agency, St. Paul, 1975).
9. This was estimated by a vice president for operations of a natural ore mining company; $4 per annual long ton of capacity includes new mining fleet and equipment, shop, drills, and miscellaneous equipment, but does not include access roads or extensive power lines; $25 per ton includes roads, power lines, railroad access, and new towns in remote locations being mined for the first time.
10. Extensive discussions with blast furnace operators; T. M. Rohan, *Iron Age* (15 Sept. 1960), pp. 159-161; W. E. Marshall, *J. Metals* **13**, 308 (April 1961); K. R. Haley, in *AIME Proceedings of the Blast Furnace, Coke Oven, and Raw Materials Committee* [American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME), New York, 1961], vol. 20, pp. 15-31; P. H. Mutschler, *U.S. Bur. Mines Inf. Circ. 8677* (1976); J. E. Ludberg, W. H. Becker, R. C. Stanlake, *33 Magazine* (March 1976), pp. 505-507; American Iron and Steel Institute, *ibid.* (October 1967), pp. 44-47; H. F. Nyberg, in *Proceedings of the 50th Annual Meeting, Minnesota Section, AIME* (AIME, New York, 1977), pp. 7-1 to 7-5.
11. This is based on discussions with blast furnace operators and on *Annual Statistical Reports* (American Iron and Steel Institute, Washington, D.C., 1954-1975).
12. The rate of iron ore feed to blast furnaces averages 0.975 ton of iron in ore per ton of molten iron. Minor losses of iron ore occur in transport and in peripheral blast furnace handling. Therefore, I used a ratio of 1:1 for iron in ore produced at the mine to iron in molten iron.
13. Based on observed blast furnace feed rates for natural iron ores (81.5 percent in 1955 and 18.4 percent in 1975) and agglomerates (pellet plus sinter; 18.5 percent in 1955 and 81.6 percent in 1975), supplemental fuel injection after 1963, and other actual changes in blast furnace operation (*14*).
14. *Annual Statistical Reports* (American Iron and Steel Institute, Washington, D.C., 1953-1976).
15. I calculated the exothermic heat released as 605,672 Btu's per ton of iron, using enthalpy values for magnetite and hematite from (*16*, p. 42). An iron ore pellet induration engineer for Dravo Corporation, Pittsburgh, verified the calculation and said that current induration systems are designed to utilize most of this exothermic heat in practice.
16. D. D. Wagman *et al.*, *Natl. Bur. Stand. (U.S.) Tech. Note 270-4* (1969).
17. Caland Ore Co. (Atikokan, Ontario) pelletize natural ores; their mix of hematite, laminite, and goethite results in an average of 9 percent water of crystallization that must be lost on ignition. The energy required for this loss on ignition is 2000 Btu's per pound of water of crystallization (Dravo Corporation, Pittsburgh), and I used the National Bureau of Standards formula weight for goethite [see tables in (*16*)] to calculate 643,000 Btu's per net ton of iron required to remove the 9 percent water of crystallization for Caland's ores.
18. A. Walderhaug, *Surv. Curr. Bus.* (April 1973), p. 36.
19. The *Census of Manufacturing* shows a 54 percent increase in net tons of pig iron per blast furnace and steel mill employee from the 1954 census to the 1972 census. The Bureau of Labor Statistics shows a 51 percent increase in output per production worker and a 40 percent increase in output for all employees for steel mills from 1955 to 1974. Therefore, 50 percent increase in output per employee is used as an approximate average and converts to a 33 percent reduction of man-hours per net ton of molten iron at the blast furnace. Other reductions or increases that occurred in coal mining, flux mining, and transportation have not been considered in the labor (or capital) change analysis. Therefore, only direct labor (and direct capital) changes in ore preparation and blast furnace operations are considered. Other influences affect changes in labor productivity besides such technologies as pelletization and supplemental fuel injection; influences not analyzed here include capital investment per worker, business trend, skill of the work force, managerial skill, labor-management relations, and efficiency of materials handling.
20. R. Herendeen, B. Segal, D. Amado, *Cent. Adv. Comput. (CAC) Univ. Ill. Tech. Memo. 62* (1975), p. 8.
21. B. Hannon, *Science* **189**, 95 (1975). Factor prices for energy are derived from the cost of coal per ton of coke, for labor from the cost of wages, and for capital from the cost of current interest on selected steel company bonds. Because most iron ore mines are owned by iron and steel companies, fluctuations in unit costs for the iron and steel industry tend to be either directly related or very similar to fluctuations in unit costs for iron ore production. Thus, trends apply to the entire molten iron production system.
22. The policy decision on a favored tax status also depends on one's view of the inevitableness of environmental damage. Treatment of tailings ponds, stack emissions, and mill tailings piles can reduce environmental damage, but cost more.
23. For example, see D. H. Meadows, D. L. Meadows, J. Randers, W. W. Behrens, III, *The Limits to Growth* (Universe, New York, 1972).
24. E. Holman, *Atlantic Monthly* **189**, 29 (June 1952).
25. Battelle-Columbus Laboratory, *Phase 4, High-Priority Commodities: Energy Use Patterns in Metallurgical and Nonmetallic Mineral Processing* (for the U.S. Bureau of Mines by Battelle-Columbus Laboratories, Columbus, Ohio, 1975), table A-5, p. A-5.
26. *Mining Tax Structure in Minnesota* (Research Office, Minnesota Department of Revenue, St. Paul, April 1977).


27. I thank B. Hannon, B. Segal, and P. Penner of the Energy Research Group, Center for Advanced Computation, University of Illinois, for many helpful comments and questions; the Rockefeller Foundation for a fellowship that directly supported the research; and the Energy Research and Development Administration, Office of Energy Conservation, for indirect support. Michigan Agricultural Experiment Station Journal Article 8455.