Improving the Efficiency of Electricity Use in Manufacturing

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Largely in response to the energy shocks of the 1970s, U.S. manufacturers reduced their real fossil fuel intensity (the weighted-average ratio of energy use to production in each subsector) by 50% and achieved zero growth in real electricity intensity. In the future, adoption of new technologies for increasing the efficiency of electricity use is likely to continue to be as important as new modes of electrification, implying that the real electricity intensity will be stable; but the outcome depends on electricity pricing and other policies, public and private.

ENERGY USED BY MANUFACTURERS IN THE UNITED STATES constitutes 27% of all energy use (*1*). It is responsible for a substantial part of the air pollution burden. Changing energy costs have had a major impact on manufacturing. Many plants experienced curtailments of natural gas (associated with price controls) in the early 1970s. Energy-intensive manufacturing has been affected by energy price increases much higher than the average, and many large plants (such as aluminum smelters) have been closed as a result. Another issue is the strain caused by the high capital cost of supply. Energy supply, and especially electricity supply, is the most capital-intensive of all major activities in the economy. During the late 1970s and early 1980s, new plants and equipment to supply energy to manufacturers constituted about 10% of business investment for all purposes. This article analyzes the recent history of energy use by manufacturers and discusses future energy use, especially in terms of technical change in electricity use.

U.S. manufacturers accounted for 5.0 trillion kilowatt-hours (kWh) (17.2 quadrillion Btu or 17.2 quads) of fuel consumption for heat and power purposes in 1985 (*1*). In addition, they used 0.9 trillion kWh (3.0 quads) of oil and gas for nonenergy purposes, that is, as materials in petrochemicals, solvents, lubes, and waxes. The major energy form used was electricity (43% of all fuel use for heat and power was for generation of purchased electricity), with direct use of natural gas also heavy (27%). Direct use of petroleum products and coal for heat and power was 15% each.

The aggregate energy intensity, that is, the ratio of the energy used by all manufacturers to their production (*2*), was steady in the period from 1958 to 1972 and then fell by more than one-third from 1972 to 1985 (Fig. 1).

The different sources of energy had quite different histories, however. From 1958 to 1985, the aggregate coal and oil intensities fell 70 and 60%, respectively (*3, 4*). During this period, coal was being eliminated, except at large facilities and in very heavy industries. Petroleum was gradually losing share to natural gas, and then, with the second oil shock, its use was drastically curtailed. Between 1958 and 1971, the aggregate natural gas intensity rose 30%, and then by 1985 dropped by more than 50% (Fig. 2). Natural gas was favored by its low price and convenience until shortages began to be felt in 1971, shortly before the first oil shock.

The combined result of these developments was that the aggregate fossil fuel intensity fell 15% from 1958 to 1971 because there was fuel-efficiency improvement in energy-intensive sectors, even though real (that is, inflation corrected) fuel prices were low and falling. Beginning in 1971 the decline quickened, and by 1985 the aggregate fossil fuel intensity declined by another 50%. Part of the reason for this accelerated decline was a relative shift away from energy-intensive production.

The pattern for electricity consumption is similar, except that continuing electrification (new uses of electricity) confounds the other developments. Thus, the aggregate electricity intensity grew rapidly between 1958 and 1970 (Fig. 3), even though the efficiency of electricity-intensive processes, such as electrolysis of brine to produce chlorine and smelting of aluminum, was being substantially improved. This was a period of falling real electricity prices. Since 1970 electricity prices have mostly been rising and the aggregate electricity intensity has gradually declined. The two forces for decline, efficiency improvement and the relative decline in electricity-intensive production, have slightly outweighed ongoing electrification.

In 1958 more than 20% of total electricity used was generated and used on site by manufacturers (*3*). On-site generation was falling, however, dropping to less than 8% of the total by 1981. With the Public Utilities Regulatory Policy Act of 1978, on-site generation has begun a comeback, rising to 10% of the manufacturing total in 1986. This means that, up to 1981, utility sales of electricity to manufacturers were growing about 0.7% per year faster than total electricity use. Utility sales growth is now slower than the growth of total electricity use.

Effect of the Shifting Composition of Production on Energy Use

A critical element in understanding trends in energy use is that the manufacturing of bulk materials, including pulp and paper, industrial chemicals, petroleum refinery products, glass, cement and clay products, and metals (not including fabrication), is roughly ten times as energy-intensive as the rest of manufacturing (Table 1). Moreover, the production and use of these materials in the United States have been declining, relative to all manufacturing, since 1974.

Materials have a life cycle as industrial economies mature. Steel consumption in tons per real dollar of gross national product (GNP) peaked during World War I and has been in decline for the past

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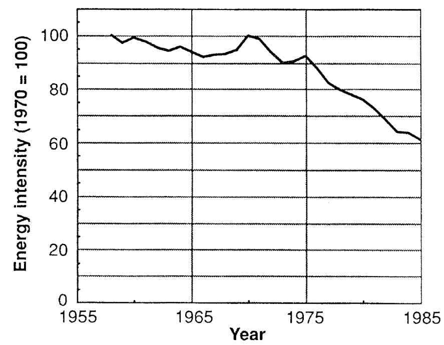

Fig. 1. The aggregate energy intensity of U.S. manufacturing, that is, the total energy consumed divided by total production, relative to 1970. Sources of energy data and accounting convention are in (*1*) and (*4*). The denominator is real output (*2*).

seven decades. What has been true for materials such as steel and cement is rapidly becoming true for other materials. During the 1970s, the consumption of almost all the bulk materials experienced saturation (*5*). For example, among the major industrial chemicals, only plastics are still growing faster than GNP (Table 2). In every category, growth rates have been declining rapidly (*6*).

A detailed examination of any of these products or markets shows four major reasons for declining relative consumption. These saturation effects apply even to plastics: (i) Markets for heavy consumer products are saturating. For example, while the application of plastics to motor vehicles is increasing, unit sales of vehicles are no longer growing with the economy. (ii) Innovative consumer products tend to have a low materials-to-cost ratio (kilograms per dollar). For example, although electronic equipment typically has a plastic structure or body, the ratio of weight to cost is low. (iii) Materials are being used more efficiently. For example, linear low-density polyethylene, introduced in the late 1970s, allows the use of thinner films and is taking over low-density polyethylene markets. This increasing efficiency is being driven, in part, by the competition among materials. The competition for materials for grocery bags and beverage containers is fierce, putting a premium on efficient design, and even beginning to bring in considerations of recycling. (iv) Improved materials are increasing product durability. Plastic pipes, other uses of plastic in construction, and plastic auto parts, which reduce rust and corrosion, often contribute to longer product life.

These developments in the use of the organic chemicals are accompanied by an adverse change in international trade. The United States has been a major exporter of organics. Exports soared in the late 1970s when oil and gas price controls gave U.S. manufacturers an additional advantage. During the past decade, however, industrial organic manufacturing facilities have been built in areas with oil and gas resources: Canada, North Africa, the Middle East, and Indonesia. The nations involved are gradually capturing the commodity manufacturing activity. U.S. producers are expanding in downstream products such as engineering plastics, growth hormones, drugs, and products based on microbiology, rather than in the bulk materials from which the more complex products are made. These new products are costly, but production in tons will be low so they will not require much energy (*7*). The consumption of products whose manufacture is energy-intensive is in relative decline in advanced industrial countries like the United States. For many products, the consequent decline in production has been strengthened by growth in net imports.

Overall developments in industrial energy use can thus be clarified by separating the historical change in aggregate energy intensity into the part due to the shifting mix in production, and the part due to efficiency improvement within each sector (*8*). Divisia analysis is an elegant method, based on moving energy weights, that enables a clean separation of these two effects (*9*). The results for total electricity use are shown in Fig. 4 (*10*). The contribution of the shift in the mix of production increased the aggregate electricity intensity in the 1960s, but then, with the decline in electricity-intensive production, the aggregate electricity intensity declined, especially in the 1980s. The growth in the real electricity intensity, the average of the intensities in the separate sectors, was thus slower in the period before 1970 than suggested by the aggregate. Since 1970, the real intensity of total electricity use has been roughly constant. There has been a balance between increasing electrification and the increasing efficiency of existing applications of electricity.

Statistical analysis of these trends in terms of prices should be considered. The assumption that price changes closely controlled these developments in energy intensity is questionable because of the complex temporal developments during this period. There have been strong and changing technology-induced trends, such as electrification. The decision-making climate suddenly became favorable to improvement of efficiency of all energy forms, independent of their individual pricing, as a result of the oil shocks. Finally, electricity price trends varied strongly across sectors. Electricity prices to fabrication and assembly sectors rose an average 2.8% per year in real terms in the period 1970 to 1985, while electricity prices to the most electricity-intensive sectors rose about 4.4% per year. The rapid changes in decision-making climate and in technology seriously compromise any interpretation of price-based statistical analysis of electricity intensity during this period.

The peaks shown in Fig. 4, in 1970–1971, 1975, and 1982, for the real electricity intensity are attributable to inefficient use of electricity during recessions (*11*). The data are consistent with the hypothesis that most electrical equipment was left on when production decreased.

The same analysis for fossil fuels shows a similar effect of the shifts in the mix of production. To date, however, sectoral data on fuel use are not available beyond 1981. The analysis shows that most of the decline in aggregate fossil fuel intensity both before and after the early 1970s was the result of real efficiency improvements, although the relative decline in energy-intensive production was also important.

The Remaining Opportunity to Improve Energy Efficiency

How much of the real efficiency improvement opportunity was exhausted during the late 1970s and early 1980s when society focused its attention on energy and a great deal of energy efficiency improvement was achieved? The answer is that the cost-effective

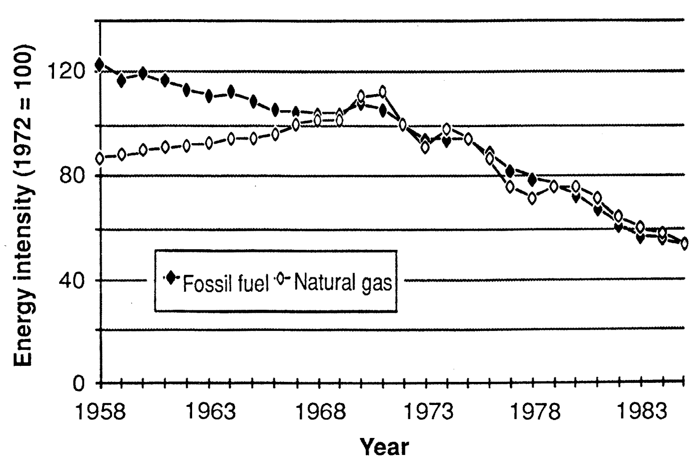

Fig. 2. The aggregate fossil fuel and natural gas intensities of U.S. manufacturing relative to 1972.

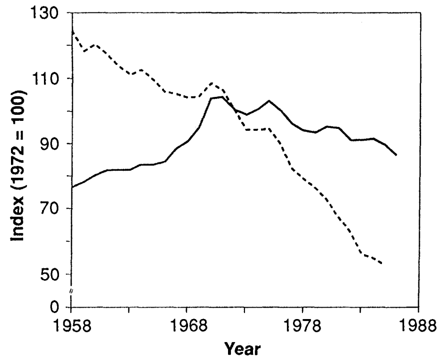

Fig. 3. The aggregate electricity (solid line) and fossil fuel (dashed line) intensities of U.S. manufacturing, where total electricity used (not purchased electricity) is considered, relative to 1972.

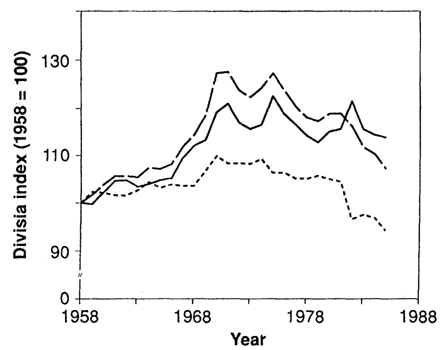

Fig. 4. Divisia analysis of electricity consumption by U.S. manufacturers. Total electricity use is considered, relative to 1958. Indices for the aggregate (long dashed line), real (solid line), and shift (short dashed line) intensities are shown. The real intensity is the best measure of physical changes in energy efficiency. The shift intensity describes the effect of changes in the composition of production. The aggregate intensity index equals the product of the real and shift intensity indices. Output in the materials-intensive sectors is described in physical (tonnage) terms (*6*); in other sectors real output (*2*) is used.

opportunity now available is larger than the savings so far achieved. Specific technologies provide one kind of evidence for this claim: (i) Although ultraefficient high-pressure sodium lamps are widely used for area lighting where color rendition is not important, fluorescent lighting, which is also widely used, seldom exists in its efficient form. Efficient fluorescent lighting involves high-reflectance fixtures, electronic ballasts, and high-efficiency bulbs and reduces electricity requirements by one-half or more compared to standard installations. (ii) Although energy management systems that turn off equipment and lighting in nonproduction hours and make adjustments in periods of low production have been applied in quite a few plants, most plants do not have sophisticated systems. (iii) Electronic motor controls are still relatively rare, so that new applications continue to be described in the technical literature.

Other evidence for the large opportunity for continuing efficiency improvement is provided by analysis of the energy intensity of specific processes and comparison with best practice. For example, in 1982 the International Iron and Steel Institute (IISI) described reference plants in which the best cost-effective technology is used (*12*). The reference integrated plant can be compared to the average for the U.S. integrated industry (which makes steel from ore). The average energy intensity for the integrated industry in the United States in 1983 was 9.5 megawatt hours (MWh) per metric ton (29.6 million Btu per short ton) of steel mill products (*13*), whereas the reference plant, producing a roughly similar mix of products, would consume 39% less energy. (In this comparison purchased electricity is evaluated at 2.73 fuel units per unit of electricity, following the IISI analysis.) A world-class facility would be much more efficient than the average of all U.S. facilities, which includes only one all new plant built in the last 25 years. Nevertheless, the target of a further 39% reduction is substantially greater than the 21% reduction in energy use per ton achieved by the entire U.S. industry from 1972 to 1985 (*14*). The latter percentage includes the benefits of relative growth in scrap-based production, which involves much less energy use per ton than integrated production.

In most other sectors of manufacturing the opportunity for energy conservation is much greater than it is for metals reduction. Most manufacturing involves physical changes which, according to the laws of thermodynamics, require extremely little, if any, energy input, in principle. Thus, while today's manufacturing of steel and aluminum from ore is 15 to 20% efficient (*15*), counting electricity at the fossil fuel heat rate, most manufacturing is essentially 0% efficient, according to first principles.

Evidence for the practical opportunity for further efficiency improvement also comes from interviews and study of practices at factories. The financial criterion for energy conservation investments varies widely, but it is typically 2 years simple payback or less (*16*). (Simple payback is the ratio of the installed cost of a project to its annual operating savings.) This short time horizon is part of a pattern of low priority given to identifying and realizing cost-savings opportunities at many existing plants.

In summary, a large opportunity for energy efficiency improvement remains for the following reasons: (i) Although, in absolute terms, there has been substantial investment in efficiency improvement in the past decade, little was invested relative to the cost-effective opportunity. (ii) The technology of efficient energy use is improving rapidly, creating major new opportunities.

Technical Change and the Real Electricity Intensity of Manufacturing

The future pace of improvement in end-use efficiency and in the pace of electrification are not well understood. Therefore, instead of presenting a model and forecast of these developments, this article presents a systematic discussion of the different areas of new technology and their potential effect on the real electricity intensity (*17*) in terms of representative examples. [Technical change in the use of natural gas is discussed by Burnett and Ban (*18*).] The presentation here is organized into three areas of technology: (i) improving the efficiency of existing uses of electricity, discussed in two parts, controls as such and process improvements; (ii) increasing electrification; and (iii) improved technology for on-site generation of electricity. Conservation and electrification examples are presented for each of the major functions of electricity use: motors (which use about 70% of the electrical energy), electrolysis (13%), process heat (8%), and lighting and miscellaneous (9%) (*19*).

Sensing and control. Every sector of manufacturing is being revolutionized by the introduction of new sensors, with electronic processing of the information into easily interpreted descriptors of product and process, and in many cases, with automatic control of the process. The control systems range from relatively simple combustion controls, which are based on sensing oxygen or carbon monoxide in the stack gas, to controls of petrochemical units that use on-line sensing of chemical composition and of variables such as temperatures, pressures, and flow rates. On-line analysis and control permit process optimization that can often be described as operating at the edge of a cliff; that is, the optimum point is close to sharp departures in process characteristics. For example, too little air for combustion may result in soot formation, with serious consequences.

The main role of some controls is to increase product yield for a given input of materials. Energy as well as other inputs per unit of production are thus decreased. Automatic controls being installed at steel rolling mills increase yield in two ways: (i) The thickness of product is controlled on-line, with feedback through hydraulic pressure on the rolls and through the current to the motors that control the tension in the sheet. In this way "giveaway," that is, product thicker than the specified minimum, can be almost eliminated. (ii) Poor quality, due, for example, to undulations, variations in thickness, and surface imperfections, can be immediately identified and quickly corrected to reduce rejection and the need to remelt and reroll. Substantial yield improvements are being achieved.

Energy management systems can be used both for submetering and as sophisticated time clocks to turn on the lights and equipment immediately before production start-up and turn them off immediately after the workday ends. They can also control peak electrical demand, if there are loads that can be reduced on short notice.

Submetering of electricity use at the departmental level in a plant is being used at a few plants. At one Canadian auto plant, electricity use by each department is measured at 15-min intervals, and a weekly summary is provided. After metering by department had been in place for 3 years, budgeting by department was instituted and a reduction of more than 5% in electricity use resulted (*20*). This reduction was achieved largely in nonproduction hours and in shifts with low rates of production. Systematic departmental submetering usually is costly to install as a retrofit to an existing plant. However, where the electrical distribution (bus) system is designed with metering in mind, as was the case at the Canadian plant, the submetering is almost free. At this plant, electricity costs are one of several monitored components in the overall cost-reduction goal for each department.

Table 1. The ratio of the cost of energy to valued added for 1985 (*3*). The electricity cost is for purchased electricity only. The energy cost includes purchased electricity and fuels (but not by-products of the process, such as biomass fuels in pulp and paper and petroleum refinery by-products, nor organic feedstocks). Sectors are defined in (*33*).

Sector	Standard industrial classifications	Electricity cost to value added (%)	Energy cost to value added (%)
Pulp and paper mills	261–263	11	29
Basic chemical	281, 286	11	26
Petroleum refining	291	12	36
Cement	324	20	45
Basic iron and steel	331	13	30
Primary nonferrous metals	333	94	112
Other manufacturing	20–25, 27, 30, 31, 34–39	2.0	3.1
All manufacturing		3.2	6.0

Table 2. Growth rates for production of industrial chemicals (*6*), expressed as an average percentage per year for the time period.

Industrial chemicals	Growth rate (percentage per year)		
	1959–1968	1968–1977	1977–1986*
Industrial products			
Plastics and resins	11	8.8	4.3
Synthetic fibers	12	6.1	0.3
Synthetic rubber	5	1.2	−2.1
Fertilizers	10	4.4	0.3
Basic chemicals			
Organics	10	6.1	0.3
Alkalies and chlorine	7	2.5	−0.2
Industrial gases	21	7.5	4.8
Other inorganics†	7	3.5	0.4
GNP (real)	4.2	2.5	2.6

*To 1986 for industrial products and to 1985 for basic chemicals. †This is the dominant group of inorganics.

Variable speed control (VSC) for motors is also being increasingly used. The most common form of VSC is based on semiconductor rectifiers that create a simulated alternating voltage composed of square pulses of modulated time (width). In recent years there have been significant reductions in the first cost of electronic controls for motors of up to several hundred kilowatts. Although VSC installations are still relatively costly, with substantial engineering (design) costs and with the equipment costing about three times the cost of the motor (*21*), the reductions in electricity use can be large, providing a good return on investment.

Three ways in which pumps and fan systems have been driven by motors in the past offer opportunities for savings by using VSCs: (i) design without controls (to meet peak requirements), (ii) flow control by throttling, and (iii) flow control by cycling on and off. The pumping of coolant for machining of automobile engines is an example of design without control. With existing constant-speed systems, high pressures are designed in, so that if all machines are in production there is plenty of flow. (Historically, "more was better" so the flow rates and pressures were almost always overdesigned.) With a VSC two major changes are made: (i) A fixed pressure adequate for the application is accurately maintained; it is substantially below the typical pressures in the fixed-speed system. (ii) The flow is turned off at each machining station, while the finished work is moved out and new work is moved into place, without affecting the flow and pressure at other stations. In a sample application the pressure at the pumps was reduced 30% below the initial 4.4 atm (64 psi), and average flow was almost cut in half, with power usage cut by more than 50% (*22*). An ancillary benefit of the reduced fluid pressure and flow in this example is reduced formation of an aerosol mist. Coolant mist is objectionable because it increases ventilation requirements and cleaning costs. Lower motor speeds should also reduce motor maintenance.

Most manufacturers have not yet surveyed their motor applications and load patterns to determine the opportunity for VSCs, so the potential for this technology is unknown. An estimate for the automobile industry indicates that the adoption of motor controls, more efficient motors, and use of the more efficient belts will eventually reduce total electrical usage by 5% or more, at current prices (*20*).

Other conservation technologies. Reductions in electricity use per unit of processing have been and are continuing to be achieved in established areas of electricity use. Electric arc steelmaking, aluminum smelting, and compressed-air system savings are some examples.

The electric arc furnace for melting and processing of scrap steel is a well-established technology. Its market share is rapidly increasing and the technology is evolving, including substantial reduction in electricity use per ton of product. The portion of steel produced in arc furnaces increased from 15% in 1970 to 38% in 1987 and may increase to as much as 50 or 60%. Making steel from scrap is much cheaper at characteristic scrap prices than processing ore, but contaminants tend to restrict the products made from scrap. Many energy-related improvements are being made in arc furnaces, such as sophisticated automatic controls, preheating of the charge with fuel, heat and dust recovery, and completion of chemical adjustments after discharge (ladle refining). Power consumption, in best practice, has dropped 25% in 20 years (*23*). In spite of the increasing relative role of the arc furnace, the declining production of steel and the declining electricity intensity of the furnace mean that nationally the total consumption of electricity by arc furnaces has been and will probably continue to be fairly steady.

Aluminum smelting required about 15.8 kWh/kg (7.2 kWh/lb) in 1986 average U.S. practice, or 16 cents/lb at the 1986 average electricity price to smelters of 2.2 cents/kWh. Best practice involves about 17% less electricity use. The Office of Industrial Programs at the Department of Energy (*24*) has been supporting development work on a new anode and cathode for the standard Hall-Heroult electrolytic cells, which would, if successful, reduce the electricity requirement about 15%.

In the present cell, a pool of molten aluminum underlies the bath containing an electrolyte and the Al_2O_3 feed. The aluminum metal forms the cathode. The anode is made of carbon, which is consumed in the reaction $Al_2O_3 + \frac{3}{2}C \rightarrow 2Al + \frac{3}{2}CO_2$ (The carbon thus helps to reduce the electricity requirement.) There are several voltage losses in the cell, the largest one being the *IR* drop in the bath (where *I* is current and *R* is resistance). The average distance between the anode and cathode is about 4.5 cm, to allow for undulations in the molten aluminum associated with the high electromagnetic fields and to avoid contact between the anode and the metal. This *IR* drop consumes about as much energy as the ideal electrochemical interaction.

The proposed technologies are based on new materials, a wettable titanium boride–graphite cathode and an inert cermet anode, and on improved controls that these stable components allow. With these, the liquid aluminum would be kept drained, and the distance between anode and cathode would be reduced to about 1 cm. This stable configuration allows reduction of several voltage losses, providing overall electricity savings in spite of the absence of CO_2 formation. In addition, carbon savings and labor savings would substantially lower the production cost. In principle, the new technologies would be very attractive.

Successful development of these technologies may now be within reach, after many years of work. Would they, if successful, be widely adopted in the United States? The critical economic consideration is the price of electricity to U.S. aluminum smelters. It is already much higher than the world average of 1.5 cents/kWh to smelters (*24*); yet it is much lower than prices to other U.S. customers, so it may be forced even higher. Because of high electricity prices, new smelting plants will not be built here; they are being built in Canada, Brazil, and other locations with low cost of electricity. The question is how long will existing U.S. facilities be operated? With the retrofit technology under discussion, the operating costs at any plant could be reduced, and U.S. costs would be reduced more than those of foreign countries because of high wages and electricity prices in the United States. This might be enough to keep most U.S. plants operating for many years.

A rather different kind of conservation technology is a device for reducing air leakage in compressed air systems serving large sheet-metal stamping presses, for example, for automobile parts (*20*). The lower die of the press often involves a movable insert supported by an air cushion. As the press descends, the sheet metal is clamped by the frames of the upper and lower dies; then it is drawn as the insert is pushed down under the descending upper die. The quality of the stamping depends on a smooth response from the cushion. Historically, die cushions have been pistons in cylinders pressurized with air from the plant system. These units leak little in new or recently rebuilt presses, but as little as 3 months, use will often produce leaks of 0.05 m^3/s. In a large stamping plant with 200 presses this leakage translates into a compressed air load implying about 4 MW of electric load.

Die cushion leaks are troublesome because repair requires taking the press out of service for several weeks; otherwise a leak must be fed with air constantly because if the cushion "bottoms" it may be difficult to raise. Recently, press owners have begun replacing the pistons with heavy-walled rubber air bags, with extremely favorable results (*25*). Some of these installations have been in service for more than 5 years and there is little leakage.

This technology has two major benefits aside from reduced electricity costs: more consistent product and greatly reduced maintenance (with the cost savings in maintenance and replacement comparable to those in electricity). A reduction of 25% in compressed air requirements has been achieved at a stamping plant in Michigan from this technology after conversion of one-half of the presses.

These examples illustrate a property of many electricity conservation technologies and many new applications of electricity. They are specific to a manufacturing process and cannot be summarized by a short list of generic technologies. In addition, the examples suggest that, although it is difficult to substantially reduce the energy intensity of endothermic chemical processing, it is practical to greatly reduce the overall energy intensity of fabrication and assembly in manufacturing. Efficiency improvements in the fabrication and assembly of automobiles (that is, starting from basic materials such as steel and plastics) are under way, which should reduce the electricity intensity by about 30% at present prices (*20*). In Japan, with electricity prices almost double those here (compared by using purchasing power parity rather than the exchange rate), the electricity intensity of comparable activities is actually 50% less than in the United States (*26*).

Electrification. In many functions, electricity has special attributes that enable it to be used much more effectively than other energy forms and, indeed, to be used in applications where other energy forms will not work. As explained by Schmidt (*27*), electric heating processes can achieve almost unlimited energy densities in materials. In arc plasmas, temperatures of 10,000°C are routine, compared with a maximum of about 3,000°C achievable with the best combustion processes. At plasma temperatures, heat transfer rates to materials are high and most of the energy content of the plasma is recoverable; chemical reactions occur at hundreds of times the rates achievable at combustion temperatures. Electromagnetic energy in the form of lasers and electron beams can be focused to produce power densities on surfaces more than a million times those of combustion-heated processes.

The ability of electromagnetic energy to interact with materials directly at the atomic and molecular level gives rise to unique applications, such as electrolytic separations and radiation curing of coatings. Dielectric dissipation (as with microwaves) can produce high rates of heating within the body of a material (so-called "volumetric" heating). This speeds the heating process and results in more uniform energy distribution within the workpiece, often with improved product quality and yield (*27*).

Because electromagnetic fields are essentially massless, they can be controlled with great speed and precision. This property is important for process automation. The high speed with which modern computers and sensors can detect process conditions and make intelligent control decisions is of little value if the speed of response of the system being controlled is slow. Thus, from the standpoint of controllability, electrically based processes tend to have a significant advantage (*27*).

Of the many new applications of electricity, two examples are given here: plasma processing and freeze concentration. In a plasma reactor, energy is deposited when an electric arc is struck between a set of electrodes in a gas stream. Plasma reactors are under development for smelting of iron ore, primarily in Sweden (*28*). Chemical reduction would still be involved, as with the present blast furnace, but the heating would be accomplished with a plasma torch. In the United States, such plasma processing will probably not replace smelting based directly on coal in the foreseeable future because coal is relatively cheap and electricity is expensive here (*29*). A more likely near-term application is plasma torch treatment of dust from electric arc furnaces (*29*), which is a hazardous waste because it contains lead, cadmium, and chromium. A plasma furnace under development with support from the Electric Power Research Institute (EPRI) can provide the energy to reduce and melt the dust, enabling separation and recovery of the main components.

Freeze concentration is based on the preference in phase change for one component in mixed liquids, as in the common vaporization separation process. Heat is removed from the mixture until crystallization begins, then the crystals are physically separated and melted (in a manner that extracts heat from the upstream mixture). The separated crystals are usually very pure (*28*). One development program is freeze concentration for the dairy industry, supported in part by the Department of Energy (DOE) and EPRI. Evaporators are now typically used to make dried milk. It is estimated that only one-eighth as much energy (counting fuel used at the power plant) is required by the electrically driven freeze process as with the existing fuel-fired evaporators. In addition, the quality of the product may be better, possibly opening new markets for fluid milk concentrate.

Cogeneration. New technology is also affecting the proportion of electricity purchased from utilities as opposed to that generated on site. Economies can be achieved, even with small generation systems, when both heat and work are produced together. Providing moderate- or low-temperature heat as the by-product of the work from a heat engine is much more efficient than providing heat directly by burning fuel. For lowest cost, the cogeneration facility should be near the site where the heat is needed, and the heat requirements should be fairly steady over the year.

Most cogeneration in industry used to be accomplished with a boiler, a steam turbine to drive the generator, and by delivery of exhaust steam to the site where heat is needed. A typical system of this kind converts only 10 to 15% of the energy into electricity (*30*). (The standard central station power plant has a much higher ratio of electricity generation because it condenses the steam, producing a partial vacuum at the back of the turbine.) In recent years natural gas–fired combustion turbines have been more frequently adopted for industrial cogeneration. Air passes through compressor turbines and is combined with fuel in a combustion chamber, as in an aircraft jet engine. The combustion gases then drive power turbines, which drive the compressor and the generator. The hot exhaust gases pass through a waste heat boiler to provide steam for heating. A typical system of this kind converts 24 to 30% of the fuel energy into electricity. The gas-turbine technology thus provides a much higher ratio of electricity to steam (and a better match to the typical loads) than cogeneration based on steam turbines.

The new technology is the steam-injected gas turbine, which incorporates a modern aircraft engine (*31*). The steam not needed for process use is injected back into the combustion chamber (and fuel input is increased), increasing the mass flow and power output. For example, the system based on General Electric's engine for widebody planes such as the 747 produces 33 MW without steam injection and 51 MW with it. These systems have begun to be installed in 6- and 51-MW versions for industrial cogeneration. With a full steam injection, they convert 34 to 40% of the fuel energy into electricity. Perhaps more important to their economies is that the system efficiency remains high over a wide range of steam/electricity ratios. The efficiency can be substantially increased with a more advanced version, in development, which has cooling between two stages of compression (intercooling). Moreover, as a result of ongoing military research and development on jet engines, the efficiency will continue to improve.

One potentially important application of gas-turbine cogeneration technology involves combustion of black liquor, a by-product of the chemical pulping of wood chips in the manufacture of kraft paper. The pulp and paper industry provides much (38%) of its own power, a tradition because of the isolation of the mills and heavy demand for moderate- and low-pressure steam. Much of the cogeneration is now accomplished with the use of giant recovery boilers, so-called because in combustion of the black liquor the pulping chemicals are recovered. If the liquor can be gasified and the fuel is suitable for a gas turbine, there would be several advantages (*32*), including a higher ratio of electricity to steam (better matching mill needs) and improved safety (recovery boilers being subject to explosions). The potential importance lies in the large scale of paper industry cogeneration, the industry's expertise in the area, and their aggressive approach to cogeneration.

Conclusions

New technology is having a major influence on energy use in manufacturing. Many technologies are being used to increase the efficiency of existing electrically powered processes or create new applications for electricity. In this article only a sampling of the many technologies has been presented. The sampling illustrates two aspects of manufacturing process change in the United States: technology push and technology pull. Technology push, that is, development of new technology, can be strongly enhanced by public and quasi-public support for research and development. Much of the new technology is DOE or EPRI supported or it is foreign. One mechanism for such support is research centers such as the EPRI Center for Metals Processing.

Technology pull (meaning, in this case, demand by industrial customers for innovative process technology) tends to be weak in the United States. Under U.S. conditions this has meant that energy conservation technologies are adopted only slowly in cases when the main benefit is merely cost reduction (unless the return on investment is extraordinarily high). Investments are more readily made when the benefits of the technology include increased reliability or improved product quality.

Many new electrical process technologies are being introduced to improve productivity. Most are not, however, electrically intensive. Their attractiveness is usually associated with high efficiency: their selective role and ease of control. In contrast, most new processes that are electricity-intensive will not see rapid adoption at the electricity prices prevalent in the United States.

So, even though there are many technological opportunities, their impact on electricity consumption is limited. Moreover, the two tendencies, for efficiency improvement and electrification, have opposite impacts. In the past 15 to 20 years the result has been an essentially constant real electricity intensity (Fig. 4). There is no hint that electricity intensities in manufacturing are going to grow, even as the relative role of electricity continues to increase. This suggests that growth in electricity use will be governed by the growth in production, or roughly 2% per year growth in electricity use by manufacturers (with manufacturing value added continuing to grow slightly more slowly than GNP). This is a far cry from the 7% per year growth that used to characterize electricity demand. Nevertheless, it is substantial growth. For electric utilities, the demand outlook is less optimistic, however, as there is now a tendency for self-generation to increase.

The rate of consumption of electricity by manufacturers is not, however, an automatic result of production and electricity prices. It is also strongly influenced by the development of new technology and by the climate for decision-making on production-process and self-generation investments. Although the real electricity intensity of manufacturing is expected to be roughly constant, it could grow or decline considerably. For example, modest public policies, motivated by the environmental and economic pressures associated with growth in electricity use, could accelerate the development and adoption of cost-effective efficiency improving technologies, resulting in a substantial rate of decline (1% per year) in the real electricity intensity.

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"He's been at it too long. Now, when the bell rings, Dr. Pavlov salivates."