Increased Energy Efficiency in Manufacturing: What Can Be Done?

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	1985 Energy Savings (Quads/year)	Capital Cost		Energy Total Cost	
		Conservation ($ billions)	Energy Supply ($ billions)	Conservation ($/10^6 Btu)	Energy Supply ($/10^6 Btu)
STEAM RAISING PROCESSES					
– Topping engines	1.5	54.0	73.2	8.43 (2.9¢/kWh)	10.55 (3.6¢/kWh)
– Economizers	0.6	3.4	3.4	1.03	2.69
LOW-TEMPERATURE DIRECT-FIRED PROCESSES					
– Topping engines	0.4	18.6	24.6	8.66 (3.0¢/kWh)	10.55 (3.6¢/kWh)
– Regenerators	0.7	2.0	4.0	0.48	2.69
HIGH-TEMPERATURE DIRECT-FIRED PROCESSES					
– Bottoming engines	0.35	3.5	7.1	4.09 (1.4¢/kWh)	10.55 (3.6¢/kWh)
– Recuperators	1.0	3.8	5.7	0.97	2.69
– Combined process heat recovery (e.g., waste heat boilers)	0.2	0.3	1.1	0.26	2.69
ADDITIONAL SAVINGS DUE TO PROCESS CHANGES					
– Electric generating fuel savings	0.5	<70.0	10.2	7.75 (2.6¢/kWh)	10.55 (3.6¢/kWh)
– Direct process fuel savings	3.75	<20.0	21.4	0.99	2.69
TOTAL INDUSTRIAL SECTOR	9.0	<116.0	151.0	3.35	5.1

Table 1. Summary of energy savings and costs for industrial conservation measures.

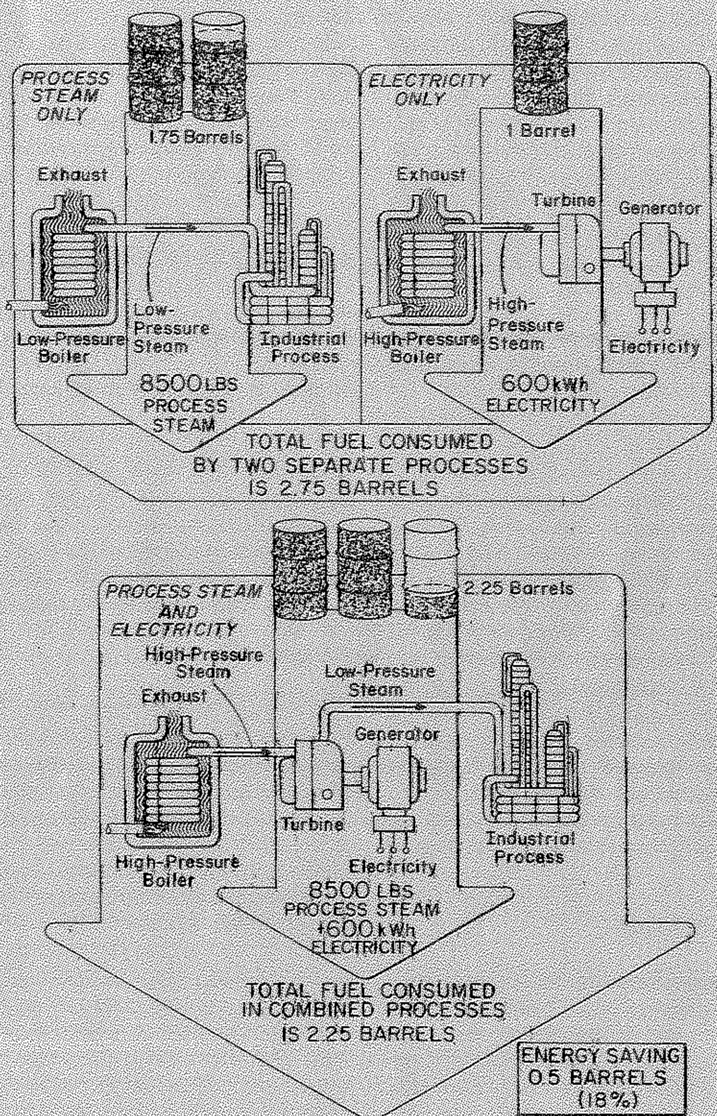

Figure 1. Cogeneration of electricity and process steam by using a back-pressure turbine.

Increased efficiency in energy use in manufacturing can make important contributions to the resolution of the energy problem, not only from the standpoint of effective use of resources but more importantly from that of the national economy and security.

Because of the scarcity of liquid and gaseous fuels and the high cost of new energy sources, international fuel prices have increased much faster than the prices of other commodities. Reasonable estimates indicate that the gap between relative prices of energy and other factors of production will keep widening for many decades to come. The change in relative prices raises the question: "Is it possible to reoptimize manufacturing processes so as to achieve the same result at equal or lower overall cost, but using less energy?"

The answer to this question is an unqualified yes, based upon firm technical and economic considerations. By 1985, we estimate the saving to be about 4 million barrels of oil per day, an amount almost equal to that consumed by all automobiles today. It can be achieved using known and proven technology to improve efficiency. It would require about $35 billion less than the investment needed to develop equivalent new fuel supplies. It would enhance the economy, create more jobs, and decrease our dependence on foreign oil.

Thermodynamic efficiency

Presently, manufacturing in the U.S. consumes about 40 percent of the nation's energy, more than any other sector of the economy, and has an average thermodynamic efficiency of only about 13 percent.

The low energy efficiency in manufacturing is not widely appreciated, even by engineers themselves, because of the practice of applying incomplete thermodynamic criteria in the calculation of process effectiveness. Recently, several publications have called attention to the shortcomings of defining efficiency solely on the basis of energy. The laws of thermodynamics indicate that neither energy, nor heat, nor enthalpy, nor Gibbs free energy are satis-

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factory. The relevant quantity is a property called available useful work that is, in turn, related to another important property called entropy.

The low thermodynamic efficiency indicates that great opportunities exist for substantial fuel saving. In the short term, such savings can be achieved through investments in known technology. In the long term, development of entirely new processes will make it possible to achieve even larger fuel savings.

Energy savings/capital requirements

Based upon extensive studies of various industries, we estimate that approximately 22 percent (9 quadrillion Btu per year) of projected 1985 energy usage in manufacturing could be saved by means of conservation measures with capital and total costs equal to or less than those needed to obtain comparable amounts of new energy supply. The degree to which this potential will actually be realized depends in large part upon the development of a coherent national energy policy.

A list of energy-saving measures and their required capital investments is given in Table 1. Also included in the table are the estimated total capital investments required for incremental fuel supplies that would have to be developed if the savings were not achieved. Capital costs for fuel supply from source to consumer are based on $1.8 billion per quad per year for coal, $6.8 billion for oil or gas, and $60 billion per quad per year of electricity generated equally from coal and nuclear power plants.

We see from this table that the 9-quad per year savings can be achieved at a capital investment about $35 billion less than the investment for the equivalent incremental fuel supplies. The total cost difference is even more dramatic: $3.35 per 10^6 Btu saved versus $5.01 per 10^6 Btu produced from new supplies. The total cost difference is the largest for energy conservation measures that do not involve generation of electricity.

Individual industries will vary substantially from the average 22-percent figure for savings because of wide differences in the relative efficiency of current practices compared to the most advanced technology available in each particular industry. Also, various industries have a different mix of energy-saving opportunities with regard to fuel types.

The three largest sources of energy inefficiency in manufacturing result from:

1. Inefficiencies associated with burning high-grade fuel to produce low-temperature process heat.

2. Inefficiencies associated with the rejection of high-grade waste heat to the environment.

3. Inefficiencies inherent to specific basic manufacturing processes.

The third group of inefficiencies can only be attacked through a systematic analysis of processes specific to each industry, a task that requires intimate and detailed knowledge of the individual process technologies. On the other hand, the first two categories of inefficiencies can be treated in a broader fashion for a wide cross section of industry, and they can be given high priority in any program for industrial energy conservation. Fuel-fired kilns, furnaces, ovens, and dryers all belong in these categories and afford tremendous opportunities for energy savings through various process rearrangements (e.g., recuperation, regeneration, cascading, topping engines, and bottoming engines).

Even without consideration of product-specific data, we can identify a major portion of the total potential saving in industry by referring only to certain functions that are common to most manufacturing industries, such as steam raising and direct-combustion heating of materials.

Steam raising

The raising of low-pressure process steam accounts for 40 percent of industrial energy usage, an amount exceeding the fuel consumption of all U.S. automobiles. Such steam is generally used at relatively low pressure and temperature; typically, 50 to 150 psi and 300 to 350°F. The normal method of raising process steam in fuel-fired boilers is very inefficient because the steam produced is at a relatively low temperature although the heat from the combustion of the fuel is at a much higher temperature.

Several steps can be taken to improve efficiency. The installed cost for an average size residual-oil-fired boiler is about $8 per pound per hour of steam flow when the first-law efficiency is 0.8. By adding economizers to the package, we can increase efficiency by ten percent and cost by $2 per pound per hour. The fuel saving, 110 Btu per pound of process steam, represents a capital cost of $3.2 billion per quad of fuel per year (6000 hours average usage). Retrofitting of economizers on existing boilers can be accomplished for about $3 per pound per hour of steam, or $4.8 billion per quad per year. These investments are smaller than the cost of new petroleum supply, estimated at $6.8 billion per quad per year.

None of the above measures takes full advantage of the opportunity to curb the major cause of inefficiency in the production of process steam. In order to realize significant energy savings, we must make more effective use of the high-temperature heat resulting from the combustion of fuels. In practice, this can be done by means of various topping engines which generate motive power or electricity in combination with the raising of process steam. Alternatively, we can raise steam by upgrading low-temperature energy from the environment or from the exhaust of other processes by means of heat pumps. Each unit of fuel energy delivered to an engine-driven heat pump can provide two to three units of process steam energy, depending upon the pressure required.

The use of topping engines is often referred to as cogeneration. Various types of cogeneration systems can be employed to raise process steam, such as back-pressure steam turbines, and gas turbines or diesel engines with exhaust recovery boilers.

Figure 1 illustrates the use of a back-

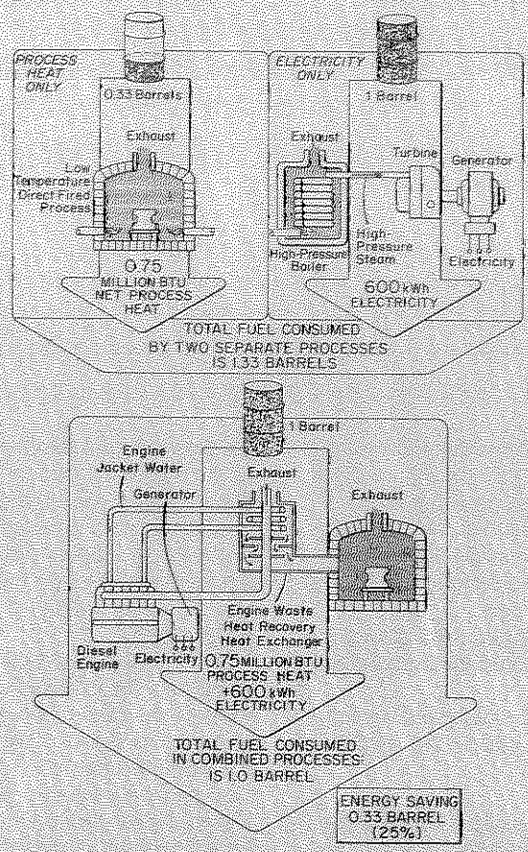

Figure 2. Cogeneration of electricity and process heat by using a diesel engine.

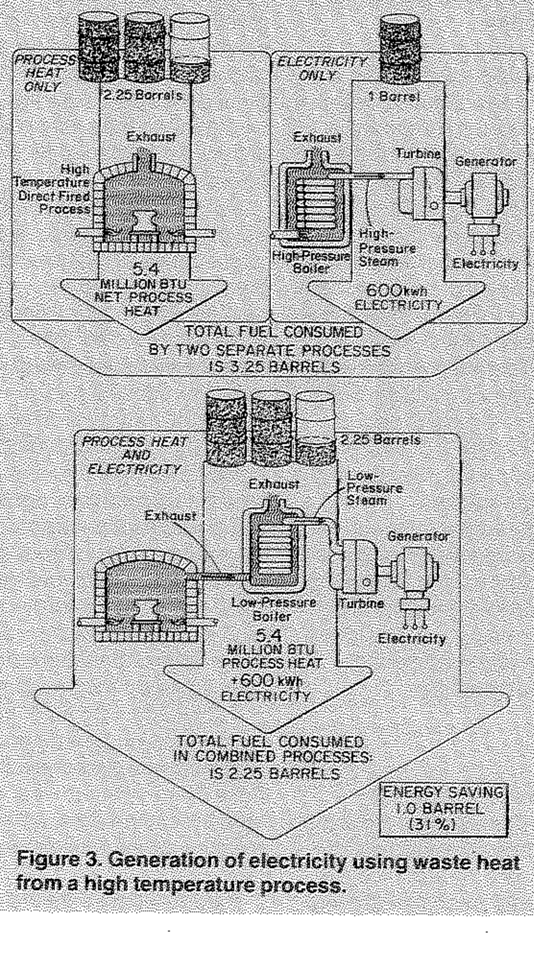

Figure 3. Generation of electricity using waste heat from a high temperature process.

pressure steam turbine as a topping engine to effect cogeneration. It can be seen that the combined process produces the same amount of process steam as the separate low-pressure-fired boiler approach but also generates 600 kWh of electricity. In the separate processes the two tasks consume 0.5 barrels of petroleum more than in the combined process. Alternatively, we can say that the 600 kWh of electricity is obtained for an incremental fuel expenditure of only about 0.5 barrel, or 3 million Btu (roughly 5000 Btu per kWh) instead of 6 million Btu (10,000 Btu per kWh) consumed by a modern central station utility plant.

Considerable latitude exists for varying the ratio of electricity to steam. Steam turbine topping engines normally yield about 50 to 70 kWh for each million Btu going to process steam. With diesel topping engines, electricity production rises to as much as 400 kWh for each million Btu going to process steam. Incremental fuel consumption is about 5000 Btu per kWh for steam turbine topping engines and 6800 Btu per kWh for diesel topping engines, both being smaller than the 10,000 Btu per kWh rate of utility generating plants. If relatively little electricity is needed on-site, and if no opportunity exists for distributing surplus power to utilities, it is possible to shift the ratio of electricity to process steam downward (e.g., to 30 kWh per million Btu of steam) by means of heat pumps in combination with steam turbine cogeneration systems.

We estimate that process steam and electricity cogeneration measures could yield about 1.5 quads of fuel savings in 1985 if we were to exploit most of the opportunities that have a capital cost equal to or less than that for new conventional electricity supply capacity, about one-third of the total potential.

Direct-fired processes

1. Low-temperature processes (<800°F)

Low-temperature processes, such as baking, drying, and curing, incur large inefficiencies because high-quality fuel heat is used to accomplish a task that requires only a low-grade energy supply. Thus, such processes are amenable to efficiency-improving measures similar to those discussed for boilers. Where the temperature requirement is very low, for example 200 to 300°F, diesel or steam turbine topping engines can be used for cogeneration of electricity (Figure 2). For intermediate temperatures, opportunities exist for using waste heat derived from the exhaust of a high-temperature furnace (e.g., metal heat treating) or from a simple cycle gas turbine cogeneration unit. Also, it may be possible to recycle a portion of the low-temperature furnace exhaust to preheat materials or incoming process air.

The thermodynamic efficiency for a process such as a dryer for textiles or food grains is only about twelve percent. Adding a diesel topping engine to the process (cogeneration of electricity) not only yields a dramatic increase in efficiency, but also permits substitution of low-grade residual oil for scarce natural gas. The topping engine achieves an overall efficiency of 44 percent by eliminating part of the inefficiency that occurs when high temperature combustion products are diluted with air to accomplish a low-temperature heating function.

The dryer example provides an excellent illustration of the opportunity that exists for fuel substitution in most low-temperature industrial heating processes. It is often claimed that gas fuel is absolutely necessary for many processes requiring a clean environment in ovens, kilns, and crop dryers. This statement is true only for high-temperature processes where heat exchanger problems might preclude the separation of combustion products from the stock-heating media. There is no valid reason why a separate combustion system, burning almost any type of fuel, cannot be used to heat clean air (through a heat exchanger) for delivery to a process oven or dryer. The optimum solution, of course, is to use a topping engine with the required heat exchanger in the engine exhaust. In this way, the clean process environment is retained; gas usage is eliminated entirely; and efficiency is improved by a large factor.

Obviously, the topping engine approach will cost far more than a simple, once-through system using only a gas burner with air dilution ports. The critical consideration from a national policy viewpoint, however, is the fact that this conservation measure will yield much more energy per dollar of capital invested than will comparable investments in new energy supply.

Low-temperature direct-fired process heaters would represent about five quads of total energy usage by 1985. Topping engines could theoretically yield as much as 250,000 MW of electrical generating capacity if all low-temperature processes were converted to cogeneration with diesel topping engines. Since many low-temperature processes are relatively small in scale and subject to intermittent operation, only about 20,000 MW of this cogeneration capacity is likely to be implemented, and much of the remaining conservation potential will be obtained by means of heat exchangers to recycle process heat and thereby reduce fuel requirements by anywhere from 15 to 30 percent.

2. High-temperature processes (> 800°F)

Many of the heating processes required for the manufacture of metals, ceramics, glass, and cement are carried out in furnaces at high temperatures, sometimes in excess of 2000°F. As the processing temperature increases, the inefficiency due to cooling of combustion gases becomes less significant. Other loss mechanisms increase, however, and the efficiency is lowered. Insulation losses generally increase with temperature, but the largest losses occur because of high quality energy obtained in exhaust gases and in the materials leaving the furnace.

A variety of energy-saving measures can be employed to improve the efficiency of high-temperature furnaces. In addition to the obvious approach of reducing heat loss by means of more effective insulation, there are opportunities for recycling exhaust heat to preheat combustion air (recuperation), for recovery of energy from parts leaving the furnace to preheat incoming parts (regeneration), for the use of exhaust heat for steam raising or other process heat purposes, and for the cogeneration of electricity from exhaust heat by means of bottoming engines (Figure 3).

Need for coherent energy policy

Our studies have disclosed a number of factors that inhibit the adoption of cost-effective conservation measures in industry: 1. Average prices of energy are well below the replacement cost of energy supplies; 2. the regulated rate of return on investment by utilities is about one-half the average rate of return on investments by manufacturers; 3. the expected rate of return from investments in new practices (e.g., conservation) is about twice as large as that from mainstream business investments in manufacturing; and 4. federal, state, and local regulations inhibit the adoption of cogeneration by manufacturers. Clearly, the first two factors are based on economics whereas the last two are not.

The Administration and Congress have considered legislative initiatives that would induce or compel industry to move faster in the direction of increased energy efficiency. These initiatives have been frustrated, however, by the complexities of the industrial sector and the lack of a practical efficiency measure that would cover all processes. Understanding and controlling all of these processes has always appeared to be impossible because it would have required a huge and wasteful bureaucracy.

Our studies have disclosed that the complexity can be eliminated by considering only the two energy-intensive processing functions of steam raising and heating or drying of products. They account for 60 percent of all fuels consumed by industry, an amount greater than that consumed in transportation. pe