CHAPTER 18

INDUSTRIAL ENERGY CONSERVATION*

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ABSTRACT

Industrial processes are extraordinarily diverse, so the physical conditions for energy conservation are diverse. The opportunities for conservation also depend on the economic and technological outlook of each industry. This chapter briefly examines the subject as a whole and explores a few examples to a little depth. These issues are touched upon: the structure and trends in use of energy, the thermodynamic factors that influence energy intensity,and examples of technical change enabling the reduction of energy intensity--from operations to conservation equipment to revolutionary changes in manufacturing process. The future of the energy-intensive industries and energy conservation is also discussed.

I. INTRODUCTION

During the first seven decades of the twentieth century energy prices fell dramatically and the energy forms purchased by final consumers became much easier to use. Energy use rose six fold in the United States during this period, an average growth of over 2 percent per annum. The energy supply industry created an enormous capital base: oil and gas fields, refineries, power plants and energy transportation systems. A huge construction industry grew up to create these kinds of facilities. Moreover, energy users adapted their capital to the cheap easy-to-use energy: heavy manufacturers came to rely primarily on relatively simple natural gas-fueled equipment; commercial buildings were designed to overwhelm user and climatic variations with energy rather than through efficient design; and during the 1950s and 1960s automobile and appliance energy efficiencies fell as the real prices of gasoline and electricity fell.

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*Notation: When customary U.S. units are used, to avoid confusion I use $\overline{M}$ to represent one million, and K one thousand, tons are short tons. I denote the metric ton by tonne. Thus 1 $\overline{M}$Btu/ton = 278 Mcal/tonne = 1.163 GJ/tonne.

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This pattern dramatically changed in the 1970s: Fuel costs increased, energy conversion costs significantly increased, and certain energy supplies were temporarily interrupted.

The nation's response has been equally dramatic if not as well publicized: U.S. energy use doubled in the 17 years preceding 1973; but in 1984 it was about 1% less than in 1973.[1] This halt in energy growth is not primarily associated with a slowdown in the growth of economic activity. Energy consumption per unit of economic activity has been falling rapidly since 1970.

In Figure 1.1 the recent history of energy consumption by industry is shown. Absolute energy use declined 12% from 1973 to 1984. The ratio of energy consumed by industry to the constant-dollar Gross National Product (GNP) declined a startling 32% during the same period. In Western Europe and Japan, however, energy prices rose even more sharply and even more energy conservation has been carried out. Most of the cost-effective conservation investments remain to be made in U.S. industries.

Declining energy use per unit of economic activity is and will remain in the forseeable future a much more important factor than increased energy production. For this reason I believe that society should give at least as high a priority, in education and research and in capital spending, to improving the efficiency of energy use, as it gives to new sources and supplies of energy. In this article I will discuss the factors that affect the use of energy by industry and the potential for continued reductions in energy use per unit of production.

THE STRUCTURE OF INDUSTRIAL ENERGY USE

The US Department of Energy includes manufacturing, mining, agriculture, and construction in the industrial sector.[1] Industrial energy use divides roughly: manufacturing 78 percent, mining 10 percent, agriculture 6 percent, construction 6 percent.[2] Overall, industrial energy use is 38% of total energy use in the US (1984).[1]

Industry mainly uses gas, electricity and oil. Gas and oil consumption have been dropping rapidly while electricity consumption climbed gradually from 1973 to 1979 and has been stagnant in the five years since. (Figure 1.2). Oil use is somewhat specialized; it is primarily used as a fuel in petroleum refining, as a feedstock in making organic chemicals and as a motor fuel in mining, construction, and agriculture. Coal is used primarily in steelmaking. Coal is also, of course, a major fuel in generating electricity. Wood is an important source of energy for the forest products, especially the paper, industry.

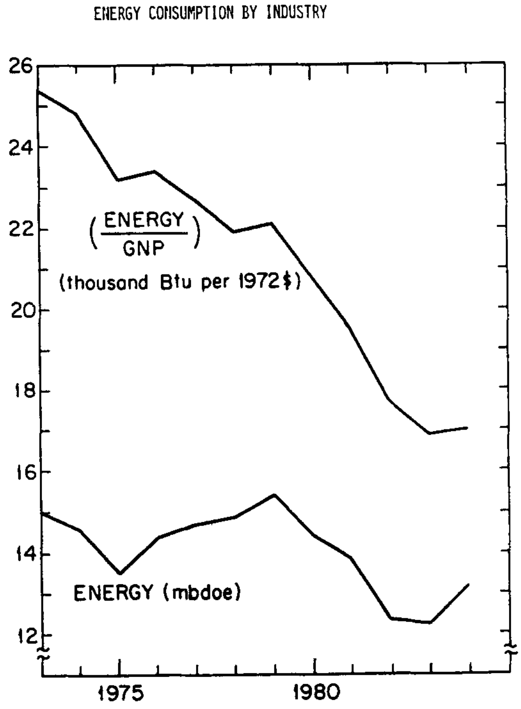


Fig. 1.1. Energy Consumption by Industry.
1 Mbdoe = 2.12 quads/yr = 70.8 GW
1 thousand Btu = 1.055 MJ
Source: Monthly Energy Review, Ref. 1.

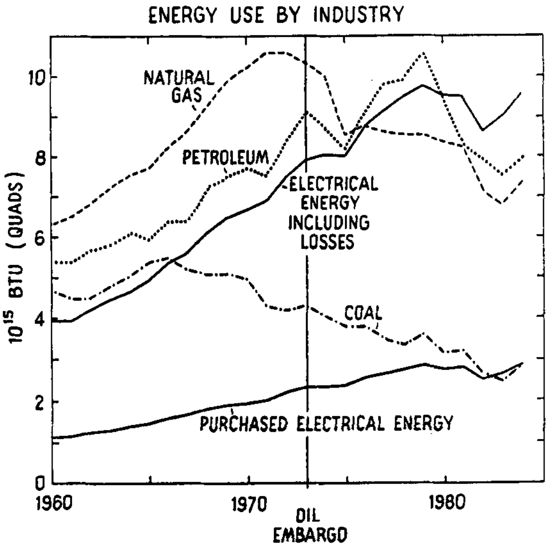


Fig. 1.2. Source: Ref. 4

A matrix of energy use by manufacturing sector and by energy carrier is shown for 1980 in Table 1.1. Looking at the second from last or the last columns, one sees that the basic materials sectors predominate. These sectors are (in order of energy use): chemicals, primary metals, petroleum refining, paper, and stone, clay and glass. The energy consumption in these sectors is 81 or 77 percent of the manufacturing total, depending on whether electrical use is counted in terms of electrical, or carrier, energy or primary energy, respectively. As a result of this dominance, specific discussion in this article will refer to the basic materials industries. The reason why fabrication and assembly industries, even when considered heavy industries, use much less energy than the basic materials industries is that fabrication and assembly are physical rearrangements at the macroscopic level with extremely small minimum thermodynamic requirements.

The reader shouldn't be misled by the detail in Table 1.1. The data available on industrial energy use is very limited. Annual collection of energy data by the Census has been discontinued since 1981. In any case Census data does not include captive energy (including biomass energy) or fuels used as feedstock for organic chemicals, which are important in some industries as seen in Table 1.1. One must depend on a variety of disparate sources and on extrapolations to obtain and update a table like this. The information on agriculture, mining, and construction is much poorer.

In this brief report most of the discussion will refer to aggregate energy use. In practice the different forms are substitutable one for the other only to a limited extent (e.g. using boilers which can burn more than one fuel), unless major new investments are made.

It will be useful to organize our discussion of changes in industrial energy use in terms of the two factors shown by the equation:

$$(\text{energy use}) = (\text{level of activity}) \times (\text{energy intensity})$$

Thus energy use in steel making is the product of the tons of steel produced and the energy consumed per ton of steel. Both factors have been and will be changing. Energy intensity alone is addressed in this article. Materials flows and their effects on energy use have been addressed elsewhere.[5,6]

TABLE 1.1

ENERGY USE IN MANUFACTURING IN 1980 (Quadrillion Btu)

SIC	Manufacturing Sector	Coal & Coke	Petroleum Products	Natural Gas	Other	Total Fuels	Purchased Electricity	Total Carriers	Generation & Transmission Losses	Total Primary
20	Food	0.13	0.12	0.52	0.03	0.81	0.140	0.95	0.33	1.28
21	Tobacco	0.01	0.00	0.00	0.00	0.02	0.005	0.02	0.01	0.03
22	Textiles	0.04	0.05	0.11	0.01	0.21	0.088	0.29	0.21	0.50
23	Apparel	0.00	0.01	0.02	----	0.04	0.021	0.06	0.05	0.11
24	Lumber	0.00	0.05	0.07	0.03	0.15	0.050	0.20	0.12	0.32
25	Furniture	0.00	0.01	0.02	0.00	0.03	0.013	0.05	0.03	0.08
26	Paper - purchased f.f.&e.[a]	0.24	0.38	0.43	0.06	1.11	0.170	1.28	0.40	1.68
	- wood derived[b]				[1.05]	[1.05]		[1.05]		[1.05]
27	Publishing	----	0.01	0.04	0.00	0.06	0.033	0.09	0.08	0.17
28	Chemicals - excl. feedstock	[0.35]	[0.20]	[1.59]	[0.12]	[2.26]	[0.454]	[2.72]	[1.08]	[3.80]
	- feedstock		[2.11]	[0.59]		[2.70]		[2.70]		[2.70]
	- total	0.35	2.31	2.18	0.12	4.96	0.454	5.42	1.08	6.50
29	Petroleum - purchased	[0.01]	[0.06]	[0.97]	[0.03]	[1.07]	[0.110]	[1.18]	[0.26]	[1.44]
	- captive[c]		[1.68]			[1.68]		[1.68]		[1.68]
	- total	0.01	1.74	0.97	0.03	2.75	0.110	2.86	0.26	3.12
30	Rubber	0.02	0.03	0.09	0.00	0.15	0.074	0.22	0.18	0.40
31	Leather	----	0.00	0.01	0.00	0.01	0.005	0.02	0.01	0.03
32	Stone, clay & glass	0.37	0.07	0.57	0.01	1.02	0.104	1.12	0.25	1.37
331	Steel - purchased	[0.45]	[0.11]	[0.60]	[0.04]	[1.19]	[0.193]	[1.38]	[0.46]	[1.84]
	- captive[c]	[1.00]				[1.00]		[1.00]		[1.00]
	- total	[1.45]	[0.11]	[0.60]	[0.04]	[2.19]	[0.193]	[2.38]	[0.46]	[2.84]
3334	Aluminum	----	[0.08]	[0.17]	[0.01]	[0.27]	[0.265]	[0.54]	[0.63]	[1.17]
33	Primary metals total	1.53	0.23	0.99	0.05	2.80	0.560	3.36	1.33	4.69
34	Fabricated metal prod.	0.01	0.04	0.22	0.01	0.27	0.086	0.36	0.20	0.56
35	Non-electrical machinery	0.03	0.03	0.16	0.01	0.23	0.104	0.33	0.25	0.58
36	Electrical equip.	0.01	0.02	0.11	0.01	0.15	0.093	0.24	0.22	0.46
37	Transportation equip.	0.05	0.04	0.14	0.02	0.24	0.102	0.34	0.24	0.59
38	Instruments	----	0.01	0.03	0.00	0.06	0.020	0.08	0.05	0.13
39	Misc. Mfr.	0.00	0.01	0.01	0.00	0.03	0.012	0.05	0.03	0.07
	TOTAL MANUFACTURING	2.83	5.16	6.70	0.39	15.09	2.245	17.34	5.34	22.68

Notes:

[a] fossil fuel and electricity.

[b] wood-derived fuels are not included in industry totals.

[c] captive fuels are fuel materials extracted by the firm that burns them.
(The Census omits coal used for coking and petroleum at refineries diverted to fuel use, the two major categories of captive fuels.)

Source: Marc Ross, Natural Resources Journal (Ref. 3).

II. THE ENERGY INTENSITY OF MANUFACTURING

A. DETERMINANTS OF ENERGY INTENSITY

The energy intensities for certain basic materials are shown in Table 2.1. This is the energy used within each manufacturing sector to produce an average ton of product. (Note that the particular numbers depend on accounting conventions.) Ideal thermodynamic minimum energies to manufacture these materials are also shown in Table 2.1. Only in the case of reduction of metal ore are the availability requirements really large.[7] Some chemical rearrangements in petroleum refining and petrochemical production also have significant availability requirements. Physical rearrangement, such as the separation of components in wood to make paper and the shaping of metals, requires very little energy ideally. Typically those process stages with large availability requirements like reducing iron ore in a blast furnace or reducing alumina in an electrolytic cell not only require a great deal of energy use, but are carried out fairly efficiently. (Carrier energy use is roughly 50% efficient or higher in these cases.) Because so much energy is involved, it nevertheless pays to continue striving to make the process more energy efficient. The great majority of process stages in industry do not, however, have substantial availability requirements and are in this ideal sense astonishingly energy inefficient. In these cases huge relative energy savings are, in principle, possible and are in some cases are being achieved.

Not only is the energy efficiency poor for almost all processes which are exothermic or weakly endothermic, but it often costs very little to substantially reduce energy use in accomplishing the same purpose. That is, the cost as a function of energy efficiency tends to have a very broad minimum. This is illustrated by Figure 2.1, which presents a simplified picture of a rather complex situation. If the availability required per unit of service is low or negative (part a of the figure), very large decreases in the energy intensity of the process can be achieved economically (especially through technological change as suggested by shifting from t_1 to t_2). Since the cost curve has a broad minimum, the optimum, and thus the desirable level of conservation is not well determined. In other words higher energy prices motivate a decrease in the energy intensity as suggested by the steep curve at upper left in Figure 2.1a, but they do not determine how far one should strive to decrease the energy intensity. For this reason corporate and public policies often play a strong role in controlling the level of energy conservation. They, rather than costs, often determine the energy intensity which will be achieved.

The situation is rather different when the laws of thermodynamics require the use of a lot of availability (part b of the figure). Here the scope for percentage reduction of energy intensity is relatively

TABLE 2.1

ENERGY INTENSITIES FOR SELECTED BASIC-MATERIALS

	Energy Intensity 1980 (Gcal/tonne)		Thermodynamic Minimum[c] (Gcal/tonne)
	primary energy[a]	carrier energy[b]	
Paper	7.3[d]	5.6[d]	--[e]
Steel	9.4	7.9	1.7
Chemicals	---	17 (for polyethylene)	--
Aluminum	46[f]	21[f]	7.0[h]
Petroleum Refining	1.17	1.08	0.1
Cement	1.7	1.4	0.2

[a] with purchased electricity evaluated at about 2.9 Mcal/kwh (11,500 Btu/kwh) as per Table 1.1.

[b] with electricity evaluated at 0.86 Mcal/kwh (3413 Btu/kwh).

[c] Gyftopoulos et al, Ref. 6.

[d] wood derived fuels not included.

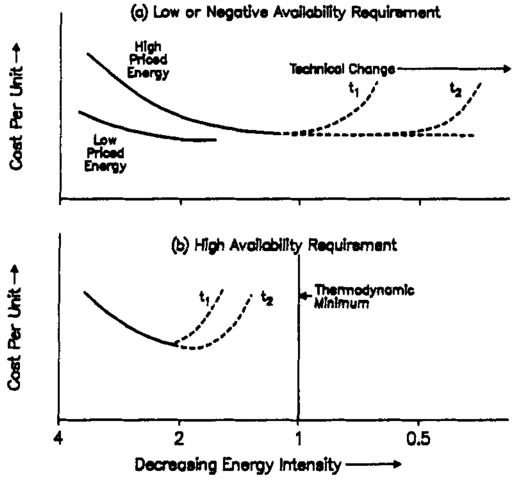
[e] For paper the absolute value of the minimum is small and its sign depends on accounting conventions and product.

[f] The energy intensities are per tonne of shipped product. If the base is taken to be tonnes of primary plus secondary metal the energy intensities are 17% higher and if the base is tonnes of primary metal it is 37% higher.

[h] per tonne of primary metal.

FIGURE 2.1

COST OF SERVICE VS. ENERGY INTENSITY (SCHEMATIC)



small because most processes are already fairly efficient. Concomitantly, cost considerations rather powerfully determine the optimum level of energy intensity.

Because of conservation efforts, the energy used to produce a unit of a given material has been declining. This decline began in some areas before the oil embargo of 1973. It has accelerated since then (Table 2.2). The rate of decline in the average energy intensity since 1972 has been about 2% per year. This decreasing energy use per ton has been largely driven by increasing prices for energy (Figure 2.2.). Energy prices paid by industrial customers roughly tripled relative to the average price of other purchases 1973-1982. Compared to industrial value added--the cost of labor, management and capital--the average cost of energy to industry has risen from 5% in the late '60s and early '70s to over 10%.

The cost of energy in 1980 compared to value added in particular basic materials manufacturing sectors is shown in Table 2.3. While manufacturing exclusive of basic materials has a cost of energy to value added ratio of only three percent, several major basic materials sectors have ratios of 1/4, 1/3, or more. It is seen that several basic materials sectors (as defined by two-digit Standard Industrial Classifications) have high energy-cost subsectors. The pattern tends to be that upstream activities are energy- intensive (in this context, high energy use per dollar of value added) and that downstream activities are labor-intensive. Energy analyses based on all-industry averages or even on 2-digit SIC averages must be examined critically because of these order-of-magnitude differences in the energy-cost ratio among various subsectors of industry.

I repeat, however, that direct cost considerations are not the only important motivation for industrialists to increase energy efficiency. The threat of energy shortages is another important motivation as is the societal goal to reduce the dependence on imported oil. Some manufacturers have a technological orientation; they like to do things right, within cost constraints. In addition, there is a pattern to major innovations in manufacturing processes: they tend to create savings in all factors of production: labor, capital, materials and energy.

B. TECHNICAL CHANGE AND ENERGY INTENSITY

The kinds of technical change which lead to improved efficiency of energy use can be roughly categorized:

1) Changes in operations and maintenance, and retrofits with low cost equipment, which lower energy use.
2) Changes in energy-intensive equipment or energy conservation add-on technologies which involve significant investment (typically $50,000 to a few tens of million dollars) and are largely justified by reduced energy costs.
3) Changes in the major processes of production. Often major processes require a new facility costing $100 million or more, but not necessarily.

TABLE 2.2

REDUCTION OF ENERGY INTENSITY[a] IN THE BASIC MATERIALS INDUSTRIES (1972-1983)

	Percent
Chemicals[b]	31
Steel	18
Aluminum	17
Paper[c]	26
Petroleum refining[d]	10
Energy Weighted Reduction	21

[a] Generally energy per pound of product, unadjusted for for environmental and other changes. Purchased electricity accounted for at 10,000 Btu/kwh (2.5 Mcal/kwh).

[b] Not including fuels used as feedstock.

[c] Not including wood-based fuels.

[d] Changes in inputs and outputs and environmental regulations have had a particularly strong impact on petroleum-refining energy. Adjusted for such changes, energy intensity was reduced 26%.

SOURCE: Trade Association Reports (Ref. 9).

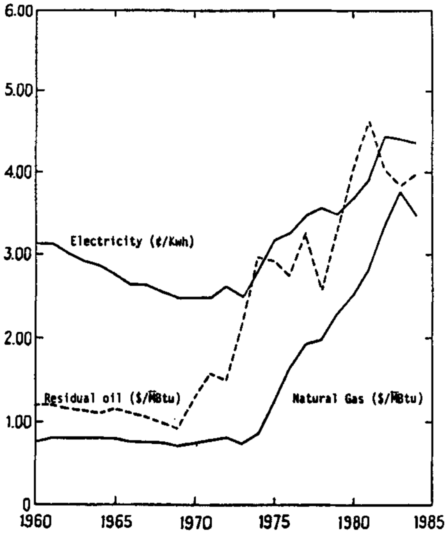


Fig. 2.2. Price of Energy to Industrial Users. National Average, 1980$. Source: Ref. 4

TABLE 2.3

THE RATIO OF THE COST OF ENERGY TO VALUE ADDED, AND TO VALUE OF SHIPMENTS, PERCENT (1980)

SIC	Industrial Sector	Compared to Value Added	Compared to Value of Shipments
26	Paper & Allied Products[a]	16	6
261-3	Pulp & Paper Mills[a]	31	11
28	Chemicals & Allied Products[b]	12,23	
281	Industrial Inorganics	27	
286	Industrial Organics[b]	21,76	
29	Petroleum Refining	35	4
32	Stone, Clay, & Glass	15	8
3241	Hydraulic Cement	45	
33	Primary Metals	23	8
331	Basic Steel	32	
3334	Primary Aluminum	46	
20-39	Manufacturing except sectors 26, 28, 29, 32 and 33	3	2

[a] Cost of wood-derived fuels not included.
[b] Energy cost without cost of organic feedstocks and with cost of organic feedstock are shown, respectively.

Source: Marc Ross, Natural Resources Journal (Ref. 3).

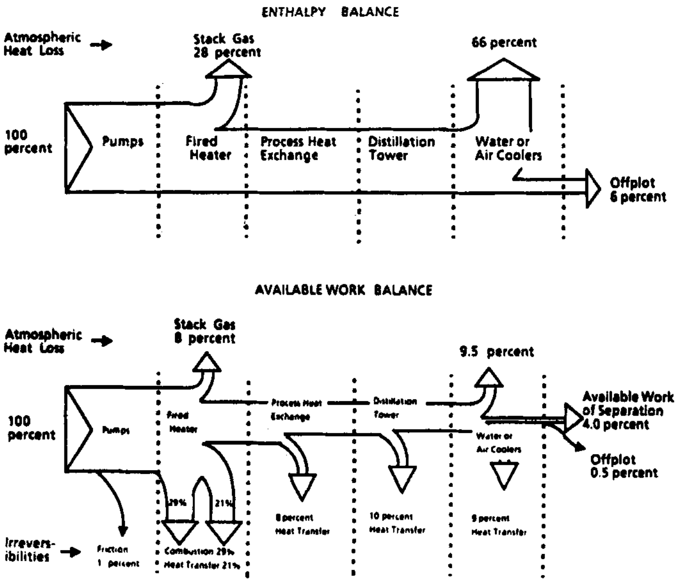


FIGURE 2.3 Enthalpy and Available Work Balance for a Crude Separation Unit

The available data from the first decade after the oil embargo suggest that comparable reductions in energy intensity have occurred through operational improvements, and through a combination of investments in major process change and energy-conservation equipment.

1. IMPROVED OPERATIONS

This is, in part, what is called housekeeping. In order to make good progress a well-qualified staff is needed to carry out energy conservation activities, with top management leadership and support. Among general practices and technical changes are management practices such as:

- inspections to encourage conservation activity,
- training programs for operation of energy-intensive equipment,
- scheduling of energy-intensive activities, such as turning off motors when not in use, and turning down heaters as appropriate,
- systematic maintenance programs,
- accounting procedures to charge energy costs to production departments, not to general overhead, and

low-level investment programs such as:

- direct metering of major energy-using facilities, and
- sophisticated inspection and maintenance equipment such as infrared scanners.

One way to improve operations which has proved successful at some plants is employee participation in energy conservation, including systematic solicitation of employee suggestions for technical changes (e.g. using quality circles).

2. ADD-ON EQUIPMENT

HEAT AND POWER RECOVERY

Heat recovery is one of the most important conservation technologies, but its importance can be exaggerated as shown by second-law analysis.[10] In Fig. 2.3 energy use in a crude distillation unit at a petroleum refinery is shown from first-law (enthalpy) and second-law (availability) perspectives. The second-law analysis shows that about 30% of the availability of a fuel is lost in the (irreversible) process of combustion. Most of the rest of the availability is lost in the thermal degradation of heat in distillation. That is the essence of the distillation process: the entire mass of material is raised to the maximum temperature by direct heating and then various components decline in temperature as they rise through the tower. A moderate amount of availability (8%) is lost with the hot gases up the heater stack. Most of the enthalpy (66%) but relatively little availability (9%) is lost in cooling the product streams. This discrepancy results from the relation of the availability, B, the work available in principle from the heat Q, and Q. For an infinite reservoir, at temperature T:

$$B = \frac{T - T_0}{T} Q,$$

where T_0 is the temperature to which materials can be cooled.

In the case at issue where the reservoir is finite (assuming constant heat capacity)

$$B = C\int_{T_0}^{T} dT' \, (T'-T_0)/T' = Q \left(1- \frac{T_0}{T-T_0} \ \ell n(T/T_0)\right)$$

If for example the "dead state" is at 38°C (100°F), and the typical temperature of products is 150°C (300°F), then B/Q = .145, corresponding to the result shown for heat rejected by air and water coolers in Fig. 2.3.

The implication of this is that heat recovery from stack gas tends to be economically justified because the temperature is high. Heat recovered at high temperature can, for example, be transformed into steam and used elsewhere. On the other hand, if there is no use for low-temperature heat very nearby, it probably doesn't pay to recover it. Generation of electricity with organic Rankine cycle equipment is a possibile way to use excess low-temperature waste heat for which there is no nearby use; but it is marginal economically even if there is a large concentrated source of heat.

Power recovery from pressurized gas streams is also important. In many cases in present practice, steam or product gases are throttled, reduced in pressure through pressure reduction valves, but can instead undergo pressure reduction through turbines, generating electricity (or shaft power to be used nearby).

UTILITY SYSTEM IMPROVEMENTS

The energy utilities, steam and electricity, are often the first target for overall automatic control. Such a control system can keep instantaneous purchased power use below a pre-set goal, i.e. by controlling loads which have been identified as interruptible or temporarily reducible to a predetermined set point. (In the U.S., roughly one half of the cost of electric power at industrial plants is typically based on the peak power or kilowatt use, as contrasted with total energy or kilowatt-hour use.) It can also select rates of steam production by different boilers. Such general energy management systems are also sometimes designed to be centers for on-line information on the general status of each plant. Such an information center can be effective for dispatching maintenance personnel.

Cogeneration of work and heat, usually but not always electricity and steam, is frequently found at paper mills, petroleum refineries, chemical and other plants. Cogeneration now in place often involves the production of moderate pressure steam, perhaps 40 atmospheres (4 MPa or about 600 psig),in boilers, which is let down through a back pressure turbine (as contrasted with a turbine leading to a condenser) to produce work and lower-pressure steam. In the paper industry 100 atmosphere (10 MPa or 1500 psig) steam is often provided, enabling higher efficiency. Gas turbine systems also provide higher fuel savings per unit of process steam provided (i.e. assuming the additional electricity or work is needed). Although gas turbine technology is widely available it is only beginning to be very widely adopted by industry.

All the changes that might effect the utility system in an energy conservation program may call for substantial redesign of the system. Much less low temperature process heat may be needed because of applications of heat recovery and other forms of conservation. Substantial reductions in use of boilers and in opportunities for cogeneration may result.

COMBUSTION CONTROL

Accurate on-line sensing of CO and O_2 in the stack, digital analysis of the information and modification of fuel flow and air dampers enable combustion to be accurately stabilized much nearer to the ideal than manual or semi-automatic controls. Near stoichiometric conditions,the CO concentration in stack gas is a very sensitive indicator of the oxygen concentration in the combustion area. With advanced automatic controls the oxygen concentration can be reduced below 1% (5% excess air) in the combustion chamber. (It's higher in the stack due to leakage.) With coarser sensors, but with systematic attention to operations, the average oxygen concentration is typically higher, corresponding, perhaps, to 15%-25% excess air. (The average concentration is kept high to avoid major excursions to oxygen levels below stoichiometric which cause smoke, which fouls equipment and which is an air pollutant.) If excess air is reduced through the use of controllers from, say, 25% to 5% then the efficiency is improved roughly 2% for a stack gas temperature of about 260°C (500°F).

MOTOR-RELATED IMPROVEMENTS

The energy used for mechanical drive can be reduced: (1) at the motor by using high-efficiency motors properly sized to the load, and by using power factor and variable speed controllers, and (2) away from the motor by redesigning the load and the powered equipment (such as pumps and fans). I will briefly discuss variable speed control (VSC) applications.

The flow from many pumps in industry is controlled by throttling valves. The motor-impellor system is designed for higher flow than required; the required rate being achieved by throttling. Friction is also commonly used to control speed of flow at fans and compressors. In cases where required flow rates vary substantially with time and induction motors are used, replacement of variable throttling by VSC is is often cost effective. The energy savings increase with decreasing ratio of average actual flow to design flow.

The newest VSCs create an alternating wave form (of adjustable voltage and frequency) using digital synthesis of the wave form, solid state switching and rectifiers. Not only do such devices eliminate the energy waste inherent in throttling; they enable sensitive control of flow and reduce pump wear. Pumping capacity may also be increased and pump cavitation avoided at very low flows.

ADVANCED CONTROLS

Advanced automatic controls encompass: (1) sensing critical physical characteristics of production, (2) rapid analysis of those characteristics and determination of desired actions to modify the process (upstream or downstream), and (3) automatic implementation of some of these actions. At the same time, information is made conveniently available to operators so they can make an informed judgement on the state of the process and intervene as appropriate.

The critical element in developing these controls is typically the sensors. These devices must be accurate and respond rapidly. Often they have to operate in harsh environments (e.g. in corrosive atmospheres at high temperatures). Computational capabilities enable one to rapidly interpret signals thereby greatly expanding the effects which can serve practical sensing needs.

Two general approaches to system design have been made: Programmable controllers have evolved from the rack of relays or pneumatic controls in older plants. They have the advantage that the structure of control is familiar to operators. (It is essential that operators be able to learn and use the new techniques.) The other approach uses microprocessors which convert analog to digital signals and mathematically process the information, a technique of great power and flexibility. This approach has evolved from laboratory applications. The two approaches are growing together as programmable controllers acquire more mathematical capabilities, as microcomputer software becomes easier to work with, and as operating personnel become more sophisticated.

An important outgrowth of advanced controls is that through them one can learn in detail about the performance of the production process at the plant. By this means, all aspects of production can be scientifically examined and improved, or replaced by a better process.

3. MAJOR PROCESS CHANGE

Typically, process change is not primarily motivated by energy conservation but in many cases the conservation benefits are very large. Let us briefly consider two potentially revolutionary process changes. About 40% of the energy used in iron and steel mills (Table 2.1) is involved in shaping and treating starting from liquid steel.[12] No energy is required in principle because the thermal energy of the melt is much greater than any energy of rearrangement (which is small because essentially physical not chemical). As shown by Eketorp,[13] the series of reheatings and rollings which are carried out at present are required both to obtain the desired shape and to obtain the desired internal structure. (The uncontrolled solidification of thick shapes does not enable one to obtain a desired internal structure directly.) Controlled solidification, perhaps very rapid, of thin castings near their final shape offers revolutionary opportunities to directly determine internal structure in mass production. When the technology is fully developed it will eliminate almost all the energy use which now characterizes shaping and treating. The very large energy savings would be only one of the benefits. Some others would be increased yield, reduction of inventories and immediate feedback to steelmakers on the quality of steelmaking. This technology is now under development, primarily in Sweden, Germany and Japan; the opportunities are sill wide open.

Petroleum refining consists of two broad categories of process: (1) physical separation of molecules, broadly according to their molecular weight, and (2) chemical rearrangements such as breaking up heavy molecules and fusing light molecules. Let us consider a separation process. The physical mixing of n different kinds of molecules (without intermolecular interaction) involves an entropy increase, per mole of material, of

$$S_1 = -\sum_{i=1}^{n} R x_i \ln x_i$$

Where the x_i are the mole fractions of each species. If each kind of molecule is present in equal amount, $x_i = 1/n$ and $S_1 = R \ln n$. Now suppose that a refinery separation process for crude oil involves the separation of a mixture of n kinds of molecules, present in equal number, into m mixtures such that each mixture has n/m kinds of molecules. The entropy of the m separate mixtures is

$$S_2 = -m\,[R(1/m)\ln(m/n)] = R\ln(n/m)$$

The entropy change going from the single mixture to the m separate mixtures is

$$\Delta S = S_2 - S_1 = R \ln(1/m)$$

The minimum availability, or energy, needed to achieve such a separation is

$$\Delta B = - T\Delta S = RT \ln m$$

The separation of crude oil achieved by a crude distillation unit is roughly described by this analysis. With $m \simeq 10$ and T near ambient, say 300° K, $\Delta B = 1.4$ kcal/mole. The averabe molecular weight in crude oil is near 200 fo the absolute minimum energy to separate the crude is about

$$\Delta B = 4 \text{ kcal/kg}$$

A typical crude distillation unit consumes about 25 times as much energy so its second-law efficiency is 4% The losses responsible for this low efficiency were illustrated in Figure 2.3 and discussed at that point. Although the losses can be reduced, the larger part of them are inherent in the design of distillation. There is the challenge: Can a new process be invented, which would save energy and also be flexible in its handling of materials, offer good control of product qualities, be easy to maintain, etc.[14] No obvious candidate is in view at this time but I believe that the technological opportunity is very good.

Brief descriptions of many of the revolutionary process changes (for basic-materials manufacture) which are the focus of research and development have been provided by Hane et al.[15] Since process changes often dramatically change the thermodynamics of production, the greatest energy-conservation opportunities may be realized through them. R&D on production processes should thus be a key part of any comprehensive long-term conservation program.

III. CONCLUSIONS

A. THE MEDIUM-TERM PERSPECTIVE

THE VALUE OF SMALL PROJECTS

Through a wide variety of technical efforts the energy intensity in each of the energy-intensive industries has been reduced an average of about 20% from 1972 to 1983, and can be further reduced very substantially. The largest part of the energy-intensity reduction from 1972 to date has been due to improvements in production operations not requiring substantial investment. Two kinds of investment will play a larger role in the future: conservation equipment investments during the 1980s and '90s,and,more gradually, investments in radically new production processes (including R&D and innovation).

Engineers at large process plants have learned that comprehensive programs consisting primarily of smaller conservation projects (roughly $20 million and less) can enable existing plants to begin to approach the energy-intensity performance of state-of-the art plants. Let me digress to discuss how a good plan is developed. The first challenge is to identify as many opportunities for applying the diverse approaches to conservation as is practical. The second is to design and cost each promising project. The third is to sell the good projects to influential operators and managers. I comment only on the first. Typically it is detective work because at a factory one usually begins without adequately detailed information on the energy use and other physical physical parameters of a process step. While some conservation opportunities are evident to an experienced investigator, one generally also needs to measure energy use and a few other key parameters and their time dependence. The dependence of energy use on production rate, for example, will often reveal important opportunities for savings through management of energy use at reduced levels of production. One can also carry out a thorough parametric study of the variation in performance of a process unit. Although the cost of such an investigation may be high, major savings have often been realized through the resulting ability to identify conservation projects.[16]

The capital cost of a major program of small projects is of course far less than that of a new plant. The cost reduction which can be achieveed with such a program of small projects is substantial: In two sample programs energy use in a petroleum refinery would be reduced 28% and that in a steel mill 20% (Table 3.1). The overall cost of petroleum products at this refinery (including capital charges for the program) would be reduced 60¢/barrel, about 2% of sales price, and that of steel products $12/ton, about 2 1/2% of sales price. While not enough to redress the cost advantages held by some foreign producers, these costs reductions would be very significant to the earnings of the manufacturers. In other words, these investments in the firms' own facilities typically offer excellent returns.

TABLE 3.1. TWO SAMPLE ENERGY-CONSERVATION PROGRAMS*

	Steel mill	Petroleum Refinery
Reduction in energy use	20%	28%
Energy intensity with program[a]	22.6 $\overline{M}$Btu/ton[b]	422 KBtu/bbl[c]
Capital cost per unit of production capacity	$48/annual ton[d]	$650/bbl per day[e]
Simple payback overall	1.7 years	2.6 years
Simple payback of marginal projects	3.5 years	4.5 years
Net reduction in cost of production	$12.00/ton	60¢/bbl
Cost reduction compared to sales revenue	2 1/2 %	2%

*Source: References 12 and 17

[a] energy intensity with production at design rates. Electricity is evaluated at 10,000 Btu/kwh (2.5 Mcal/kwh).

[b] Purchased coke is evaluated at 1.33 times its heating value.

[c] includes coke combustion, but not hydrogen feedstock.

[d] annual ton of mill products.

[e] barrel per stream day of crude capacity.

DIFFICULTIES OF IMPLEMENTATION

While some firms in energy-intensive industries have made large investments to reduce their energy-related costs, most are proceeding very slowly. This can be frustrating for engineers who develop good energy-conservation projects. Why are the investments slow in coming?

One can view the underlying cause to be the slow growth or even decline of basic materials production in the U.S. This means that few new production facilities are being built. Suppliers to these industries lack the stimulus of new plant construction. Industrial R&D labs have been redirected, and technical staff has been reduced. Top management has become preoccupied with financial manipulation. The strategy adopted by many firms in these industries gives high priority to diversification into new businesses. While major efforts have been made to reduce costs, this has been accomplished by closing less efficient facilities and by operational changes. Most of these firms do not pay much attention to the opportunity to cut costs through investments to modernize existing plants.

Two specific characteristics of many of these firms which may help us understand the relative lack of investment in smaller modernization projects are (1) their financial perspective and (2) their centralized management. Most businesses based on energy-intensive manufacturing are no longer growing rapidly and many face strong foreign competition. Moreover businesses in the U.S. are being pressed to focus on short-term goals. (For example institutional investors typically hold common stocks only about half a year.) It is not surprising, then, that most firms in energy-intensive industries have assigned a low priority to technology while emphasizing financial measures such as refinancing. restructuring, and diversification. (A technical orientation is more common however, in the chemical industry.)

Most of the firms in question concentrate investment decision making at the top. The effect of this is not that top management pours over a huge number of small-project proposals. Instead the typical managerial procedure is to severely ration capital to divisions and plants while giving them responsibility for effective decisions on smaller projects, with the result that smaller discretionary projects (i.e. for cost cutting) face high _de facto_ hurdle rates.*

Not all firms in these industries have these characteristics. Some are well staffed with engineers at their plants and they give these engineers considerable scope. I believe we may see the more

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*The prevalence of capital rationing is well known. The relationship between size of project (and locus of primary decision making) and the effective hurdle rate was observed in an Alliance to Save Energy field study.[18] The high effective hurdle rates for smaller projects observed at these firms is a phenomenon quite separate from discrimination against projects in less favored plants and on less favored product lines. The small project-high hurdle rate correlation was observed for the best plants and product lines.

technologically oriented and decentralized firms achieve some success, even in the difficult business conditions which exist. My reason is that, although these industries are largely mature in terms of overall sales, revolutionary process innovations are being developed. Those firms with strong technical capabilities which are open to technical opportunities may do very well.

B. THE LONG-TERM PERSPECTIVE

Some of the most energy intensive industries in the Unites States face a grim future because there are isolated sites in other countries with cheap and hard-to-transport energy resources. The most important examples are hydropower and natural gas in Canada, low quality coal in Australia, hydropower in remote parts of Brazil, and especially, natural gas in the Middle East, Indonesia, North Africa and other sites remote from present concentrations of industry. Industries like primary aluminum and certain base organic chemicals will move to those sites.[6]

The competitive position of related downstream producers and of other energy-intensive industries based on more easily transported energy forms will depend to a large extent on their manufacturing technology. Plants located in the United States will continue to enjoy good access to many materials, especially coal, recycled materials and biomass. They also are close to a very big market and so have low transportation costs and close contacts with customers. If process technology is developed which sharply cuts capital, energy, and labor costs and if this technology is effectively adopted in the U.S. I believe the cost advantage now enjoyed, for example, by foreign producers of steel would be overcome (even though the foreign producers would also adopt new technology). Domestic manufacturers would be the primary suppliers for this country for all processes where labor requirements are not very high or where close contacts with customers are especially important. Of the uncertainties mentioned the most important is whether U.S. manufactureres will help develop and will adopt the best process technologies. On this point, the trends of the last two decades are not encouraging. Federal research and development policies are tending to drain talent away from research relevant to industry. While private firms do a lot of specific product R&D, few do research an basic technologies. Most of the research on the basic technologies which will become the industrial processes of the next century is being done in Europe and Japan.

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