Improved Technologies and Practice 3

There are many energy efficient technologies and practices—both currently available and under development—that could save energy if adopted by industry. Energy efficiency can be improved through cost-effective use of: 1) general housekeeping and maintenance programs, 2) energy management and accounting systems, 3) improved equipment and procedures for existing production methods, 4) new and better production methods, and 5) product changes (table 3-1). Most of the equipment and process enhancements are specific to particular industries, but several (e.g., heat recovery technologies, high-efficiency motors and variable-speed drives, sensors and controls, and cogeneration) have applications in many industries. These generic technologies are particularly attractive targets for government policies.

The costs and benefits of energy efficiency improvements vary widely. Minor operational changes, such as housekeeping and maintenance, are typically the cheapest, easiest to implement, and least risky, and usually, though not always, yield the smallest energy and cost savings. Production equipment changes and energy conservation add-on technologies involve larger investments, typically $100,000 to tens of millions of dollars, and may or may not be justified by reduced energy costs alone. Major process changes often require building a new facility, at costs typically exceeding $100 million, and are usually justified only by strategic, market development concerns. Energy savings are rarely sufficient to justify investments of this magnitude.

Potentially, the greatest increases in efficiency will come not from direct efforts to reduce energy consumption but from pursuing other economic goals like improved product quality, lower capital and operating costs, or specialized product markets. Many projects undertaken for nonenergy reasons yield energy efficiency gains as a secondary consequence. For example, glass

Table 3-l—Technologies and Practices Affecting Industrial Energy Intensity

Categories	Examples
Housekeeping	**Piping system insulation; steam leak repairs.**
Maintenance	**Equipment tune up to keep it operating near design efficiency.**
Energy management and accounting systems	**Energy use monitoring and control equipment.**
Equipment changes	
Equipment improvement	**Use of high-efficiency motors; use of adjustable-speed drives.**
Equipment sizing	**Use of smaller, less energy-consuming equipment.**
Fuel switching	**Use of gas vs. coal boilers; use of steam vs. electric drives.**
Process refinements	
Equipment integration	**Use of heat exchangers; use of PINCH techniques at plant design and retrofit stages.**
Cogeneration	**Balanced steam and electricity demands.**
Yield improvement and quality control	**Reduced scrap and rejects.**
Waste minimization	**improved process control or process innovation.**
Recycling	**Use of scrap in the paper, steel, and aluminum industries.**
Raw materials substitution	**Use of higher sulfur feedstocks in the petroleum industry.**
Computerized controls and sensors	**improved product yield, quality, and rests.**
Process change	
Same categories as for equipment changes and process refinements (above); extent of the changes and the technological and economic risks are greater.	**Thin slab casting of steel.** **Use of direct steel making techniques.**
Product shifts	
Amenity demand	**Shifts away from defense activities.**
Product demand	**Expansion of electronics in personal and business communications.**
Domestic production/trade	**Use of domestic steel vs. imported steel.**
Product refinement	**Use of unleaded gasoline.**
Materials substitution	**Use of plastics and aluminum for steel in automobiles.**
Product quality and performance	**Use of thinner and higher quality steel.**

SOURCE: Office of Technology Assessment, 1993.

producers adopted the energy-saving float process primarily for the production flexibility that it offered.[1] Steelmaker have installed continuous casters more for the improved product yield than the energy savings. Metal stamping plants have implemented new techniques for cushioning presses not for the 10 percent energy savings, but for the more consistent products and lower maintenance costs.[2] Sometimes, however, pursuing improved quality or specialized markets can diminish energy efficiency. Such is the case in petroleum refining where several factors have combined to increase the energy requirements per unit of product in recent years: 1) the reduction in capacity utilization; 2) the decline in crude oil quality; 3) the increasing demand for lighter products (gasoline and liquefied petroleum gases) relative to heavier products (residual oil); and 4)

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[1] Henry C. Kelly, Peter D. Blair, and John H. Gibbons, "Energy Use and Productivity: Current Trends and Policy Implications, " *Annual Review of Energy,* vol. 14, pp. 321-352, 1989.

[2] Marc Ross, "Improving the Energy Efficiency of Electricity Use in Manufacturing, " *Science, vol. 244,* pp. 311-317, Apr. 21, 1989.

the requirements for enhanced products such as reformulated gasoline.

At any given time, the mix of technologies used by industry ranges from outdated to state-of-the-art. Energy efficiency improves as older facilities are replaced with state-of-the-art ones.[3] In the petroleum refining, chemical, pulp and paper, steel, aluminum, cement, and glass industries, most state-of-the-art technologies use 12 to 38 percent less energy than the mix of processes currently used (table 3-2).[4] This comparison does not imply that these industries would find it economical to bring all their existing plants to state-of-the-art levels at once, but instead shows the energy savings that can be expected as plants are modernized. Energy efficiency also improves as advanced technologies are developed to become the state-of-the-art of tomorrow.[5] Advanced technologies, not yet commercialized, could possibly reduce energy use in the various processes by an additional 9 to 35 percent.

GENERIC IMPROVEMENTS

1 Housekeeping, Maintenance, and Accounting[6]

The first step in improving energy efficiency in industry is good housekeeping. Among the activities in this area are:

- carrying out inspections to encourage conservation;
- instituting training programs on operating energy-intensive equipment;
- scheduling energy-intensive activities;
- turning off equipment when not in use;
- installing and using energy monitoring equipment;
  wrapping tanks and pipes with insulation; and
- repairing leaks.

Housekeeping can often save surprisingly large amounts of energy, particularly in older plants. Indeed these activities have been credited with significant portions of the efficiency gains achieved in the 1970s and 1980s.[7] Many manufacturers had housekeeping programs years ago, but have slacked off recently, because they believe ''it doesn't pay'' and they cannot afford the staff to do the work.

Achieving substantial savings from housekeeping requires a well-qualified staff for carrying out energy conservation activities and top management leadership and support. Employee participation in energy conservation has proved successful at some manufacturing plants. This method can include systematic solicitation of employee suggestions for technical changes (e.g., using quality circles).[8]

Equipment maintenance is another important measure for improving efficiency. Equipment operates most efficiently when operating near

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[3] Throughout this chapter, state-of-the-art manufacturing technologies refer to the best available technologies with demonstrated technical feasibility in actual production environments, such as in a commercial or large-scale plant. Some of these technologies that are at an early stage of commercialization may require additional development efforts to become suitable for widespread industry adoption.

[4] The ethylene process, which is nearly at state-of-the-art levels now, is excluded from this comparison range. Note that the energy figures in table 3-2 and in the industry specific portions of this chapter are calculated with purchased electricity valued at the primary rate of 10,500 Btu/kWh, because of how the figures were reported in the original sources.

[5] Throughout this chapter, advanced manufacturing technologies refer to those technologies that are under development or have been seriously considered in concept and are expected to have an impact on the industry over the next 10 to 25 years.

[6] Marc Ross, 'Energy Use in Manufacturing, ' contractor report prepared for the U.S. Congress, Office of Technology Assessment, October 1988.

[7] U.S. Congress, Office of Technology Assessment, Industrial Energy Use, OTA-E-198 (Washington, DC: U.S. Government Printing Office, June 1983). Marbek Resource Consultants, Energy Demand in Canada, 1973-1987: A Retrospective Analysis (prepared for Energy, Mines, and Resources, Ottawa, Canada: August 1989).

[8] General employee participation in efforts to enhance product quality and productivity can also contribute to improved energy efficiency.

Table 3-2—Energy Use by Major Energy Consuming Industrial Processes[a]

Process	Current[b] (Year)		State-of-the-art (2010)	Advanced (2010)	
Petroleum refining. 602	(1989)		405	363	thousand Btu/barrel of crude oil
Miscellaneous chemicals					
Sulfuric acidc . . . . -1,860	(1988)		-2,120	-3,230	thousand Btu/ton of sulfuric acid
Nitrogen and oxygen[d]. 3,730	(1985)		3,150	2,820	thousand Btu/ton of oxygen and nitrogen
Ethylene. 58.2	(1988)		57.4	52.4	million Btu/ton of ethylene
*Pulp and paper*e					
Chemical process (kraft). 39.4	(1985)		26.7	20.0	million Btu/ton of paper
Mechanical (stone groundwood). . 35.1			29.0	—	
Semichemical. 36.6			26.5	20.5	
Thermomechanical. 40.9			31.9	28.2	
Chemimechanical (nonsulfur). . . . —			—	13.9	
Biological. —			—	23.2	
Repulping recycled paper. 23.8			18.5	14.8	
*Steel*f					
Basic oxygen process. 26.0	(1983)		16.1	—	million Btu/ton of finished steel
Electric process (scrap-based). . . 15.4			10.2	8.8	
Direct steelmaking. . . . . —			—	14.0	
Aluminum					
Alumina and aluminum production. 196	(1980)		162	137	million Btu/ton of aluminum
Aluminum smelting only. 160			135	110	
Cement 'J. 5,070	(1988)		3,780	3,110	thousand Btu/ton of cement
Glass					
Flat glass. 15,0	(1985)		10.3	6.9	million Btu/ton of glass
Container glass. 15.6			12.1	8.9	
Pressed and blown glass, ... 27.4			22.8	15.2	
Fibrous glass. 24.5			21.6	14.0	

a This table is a summary of detailed data presented in tables 3-4, 3-6, 3-7, 3-10, 3-12, 3-14, and 3-16.

b Average of currently implemented technologies.

c Figures for sulfuric acid are negative because the production process is exothermic—it produces more energy than it consumes.

d Assumes production of 58 percent nitrogen and 42 percent oxygen.

e Mi,of paper products is 8 percent newsprint, 30 percent printing and writing paper, 4 percent industrial paper, 7 percent tissue paper, 49 percent paperboard, and 2 percent construction paper.

f Steel figures embody: 65 percent continuous casting and 35 percent ingot casting in the Current Case; 95 percent continuous Casting and 5 percent ingot casting in the state of the art case; and 68 percent strip casting, 27 percent continuous casting, and 5 percent ingot casting in the advanced case, Mix of steel products is 21 percent hot rolled sheet and strip, 38 percent cold rolled sheet and strip, 9 percent heavy plate, 7 percent shapes and rails, and 25 percent bars and wire rods.

9 Cement produced from domestic clinker.

NOTE: The energy values in this table-and in tables 3-4, 3-6,3-7, 3-10,3-12,3-14, and 3-16-are unlike most others in this report in that they account for purchased electricity at 10,500 Btu/kWh. This inconsistency arises because of how the figures were reported in the original sources. That is generation and transmission losses are included.

SOURCE: Compiled from sources in tables 3-4, 3-6, 3-7,3-10, 3-12, 3-14, and 3-16.

design specifications. Poorly maintained equipment deviates from these specifications, and suffers large efficiency losses. For example, many pumps and fans are poorly maintained, and efficiencies can decrease markedly over time due to wear. One study of 84 large pumping systems, primarily in pulp and paper mills in Sweden and Finland, found that wear alone had reduced average pump efficiencies by 14 percentage points compared with their original performance.[9]

9 Eric D. Larson and Lars J. Nilsson, ''Electricity Use and Efficiency in Pumping and Air Handling Systems,'' paper presented at the American Society of Heating Refrigeration and Air Conditioning Engineers Annual Meeting, Indianapolis, IN, June 1991.

General maintenance is needed to keep equipment and processes operating at specifications.

Accounting systems can also be used to help motivate energy conservation activities. In many plants, energy costs are charged to overhead accounts not to the individual departments using the energy. This gives department managers little incentive to search for energy savings. Efficiency improvements can be encouraged with accounting systems that more accurately allocate energy costs within plants.

1 Energy Management Systems10

Leaving on electrical equipment between production shifts and when production is below capacity is common practice in industry. While it is sometimes more energy efficient to leave equipment on rather than shut it down and start it up again, turning equipment off or down usually saves energy. Energy management systems can be used to systematically turn off or turn down process equipment, lights, and fans. Microprocessors are connected to major energy distribution lines and/or equipment to record energy use and control the equipment. Such systems have not yet been installed in most factories.

Full scale energy management systems can be expensive initially, because of the costly installation of wiring and switching devices required. In some cases, auxiliary equipment may also be needed. For example, turning off sections of a compressed air system that are not in use requires satellite compressors to serve equipment that needs air around the clock, and/or check values

and controls to isolate sections of the system. The typical cost of an energy management system in an automobile plant with a load of 100 million kWh per year is about $750,000, with energy savings of about 10 percent.11 Exact costs and savings are, of course, site specific.

~ Motor Drive12

Motor drive, the largest functional use of electricity in industry, accounts for about two-thirds of the sector's electricity use. Motors are used to drive a variety of applications, including:

- pumps, fans, and compressors used in fluid processing, heating, ventilation, and air conditioning (41 percent of electricity used for motor drive in manufacturing firms);
- materials processing equipment used for crushing, grinding, cutting, mixing, and forming (32 percent); and
- materials handling machinery such as cranes, conveyors, elevators, and robotics (27 percent) .13

Efficiency improvements on the order of 30 percent are possible in these applications through the use of: l)high efficiency motors; 2) adjustable speed-drives; 3) power conditioning; 4) better pumps, fans, compressors, and other drive equipment; and 5) better system design.
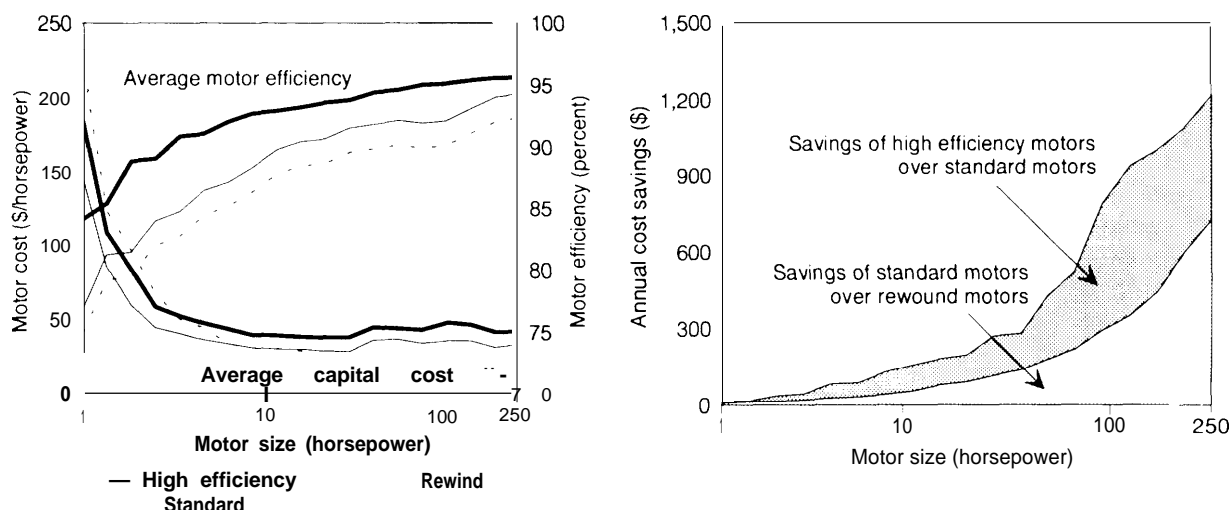
MOTORS

Standard motors, when well maintained and operated near their design points, convert electricity input into mechanical output with average technical efficiencies of 77 to 94 percent depend-

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[10] Marc Ross, "Energy Use in Manufacturing," op. cit., footnote 6.

[11] Marc Ross, "Improving the Energy Efficiency of Electricity Use in Manufacturing," op. cit., footnote 2.

[12] Drawn from U.S. Congress, Office of Technology Assessment, *Fueling Development: Energy Technologies for Developing Countries,* OTA-E-516 (Washington, DC: U.S. Government Printing Office, April 1992). Principal sources for the original were: Samuel F. Baldwin, ''Energy-Efficient Electric Motor Drive Systems,' Thomas B. Johansson, Birgit Bodlund, and Robert H. Williams (eds.), *Electricity: Efficient End-Use and New Generation Technologies, and Their Planning Implications* (Lund, Sweden: Lund University Press, 1989), pp. 21-58; Samuel F. Baldwin, "The Materials Revolution and Energy Efficient Electric Motor Drive Systems, " *Annual Review of Energy,* vol. 13, 1988, pp. 67-94; and Samuel F. Baldwin, "Energy-Efficient Electric Motor Drive Systems, " Princeton University, Center for Energy and Environmental Studies, Working Papers No. 91,92,93, and 94, February 1988.

[13] Electric Power Research Institute, *Electric Motors and Drives: Markets, Trends, and Applications,* Report No. TR-100423 (Palo Alto, CA: Electric Power Research Institute, June 1992).

Figure 3-I—Efficiency, Cost, and Cost Savings of High Efficiency, Standard, and Rewound Motors

This figure shows that for all sizes of motors, high efficiency models have a higher capital cost than standard models. The additional capital cost generally decreases as motor size increases. Costs are given per horsepower of motor capacity. Large motors cost more in total, but less per unit capacity. Annual cost savings are calculated based on a cost of electricity y of $.047/kWh, and a duty cycle of 5,000 hours per year with a load factor varying from 50 percent for the smallest motor sizes to 90 percent for the largest sizes.

SOURCE: OTA based on data from Steven Nadel, Michael Shepard, Steve Greenberg, Gail Katz, and Anibal T. de Almeida,*Energy-EtWent Motor Systems: A Handbook on Tehnology, Program, and Policy Opportunities*(Washington, DC: American Council for an Energy-Efficient Economy, 1991),

ing on their size (figure 3-1),[14] High efficiency motors operate at 84 to 96 percent technical efficiency.

High efficiency motors use improved design and better quality materials to decrease electrical (resistance), magnetic (core), mechanical (windage and friction), and stray losses. Electrical losses, caused by electrical resistance in wires, can be reduced by using lower-resistance materials (e.g., copper instead of aluminum) for stators and rotors. Magnetic losses can be reduced by using larger cross-sections of iron in the stators and rotors, thinner laminations, and improved

magnetic materials. Mechanical losses can be decreased by using improved bearings and fan design. Stray losses can be reduced by optimal design and careful manufacturing.[15] Further improvements may result from advances such as high-performance permanent magnet motors.

Though high efficiency motors typically cost 30 percent more than standard motors, the decreased electricity usage can offset the higher capital costs in a short time. An industrial motor can use electricity worth about four times its capital cost annually.[16] Changing to high efficiency models yields larger efficiency improve-

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14 The efficiencies of particular brands of motors vary from these averages by several percentage points.

15 Steven Nadel, Michael Shepard, Steve Greenberg, Gad Katz, and Anibal T. de Almeida, *Energy -Efficient Motor Systems: A Handbook on Technology, Programs, and Policy Opportunities* (Washington, DC: American Council for an Energy-Efficient Economy, 1991).

16 Operating 5,000 h/yr at 70 percent load, a 90 percent efficient motor annually consumes 2,900 kWh/hp. At $0.047/kWh this costs $136/hp. In comparison, motors cost roughly $34/hp. Note that the unit kilowatt (kW) is used to refer to input power, while the unit horsepower (hp) is used to refer to output power. One horsepower is equal to 0.7457 kW.

ments and percentage cost savings in the small motor sizes, but greater absolute cost savings in the large sizes.

For motors larger than 5 horsepower (hp), high or premium efficiency models accounted for approximately 10 percent of sales in 1985. This market penetration is expected to increase dramatically with the institution of the motor standards set forth in the Energy Policy Act of 1992.[17]

Larger motors are often rewound, not replaced, when they malfunction. Rewinding is initially less expensive than purchasing a new motor, but ultimately costs more because of degraded efficiency. The efficiency of a rewound motor is typically about 2 percentage points below that of a new standard motor (figure 3-1). Work is needed to find methods of reducing core damage caused by the high temperatures that arise during motor rewinding.

POWER CONDITIONING

Motors and other electric devices operate most efficiently when the power they receive is the proper voltage, phase balanced, and distortion-free. However, these conditions may not always be met, because of imperfections in the power supply. Power may arrive from the grid in less than perfect condition, or it can become distorted by malfunctioning or poorly arranged equipment within industrial plants. Facilities can keep their power in good condition by repairing faulty end-use equipment or by installing specialized power-conditioning equipment to improve the power factor, reduce line voltage fluctuations, balance three-phase power, and control line harmonics.[18] These tuneups can offer small, but cost-effective gains in energy efficiency, equipment performance, process control, and reduced downtime.

DRIVE CONTROL: ADJUSTABLE-SPEED DRIVES

In many motor drive applications, control of motor speed, startup, and torque (rotational force) is needed to match the drive power with the load. "Motor speed control offers the single largest opportunity for energy-savings in drivepower systems. '[19]

Drive speed can be easily controlled using direct current (DC) motors, but most industrial processes use fixed-speed alternating current (AC) motors because of their increased reliability and lower costs, In fluid flow applications, motors—and associated fans, pumps, and compressors—are run at constant speed and the flow is controlled with mechanical devices such as inlet vains, outlet dampers, and throttling valves. This is analogous to driving a car with the gas pedal floored, and controlling the speed with the brake. In other applications, such as mills and conveyors, various mechanical, electromechanical, and hydraulic methods are used to control the motors' speed. Most of these control techniques are plagued with problems, including high cost, low efficiency, or poor reliability .[20] Industrial and commercial pumps, fans, and compressors, for example, have estimated average losses of 20 to 25 percent or more due to throttling or other inefficient control strategies.

Recent advances in power electronics have led to a new form of motor control, electronic adjustable-speed drives (ASDs).[21] These devices can precisely control the speed of AC motors,

[17] The Energy Policy Act of **1992** is discussed in chapter 1.

[18] Nadel et al., op. cit., footnote 15; and William J. McDonald and Herbert N. Hickok, ''Energy Losses in Electrical Power Systems, ' *IEEE Transactions Industrial Applications,* vol. **IA-21, No. 4,** pp. 803-819, 1985.

[19] Nadel et al., op. Cit., footnote 15.

[20] Ibid.

[21] The electronic ASD is the most important new motor control technology, but not the only one. Other methods of control include sequencing controls for pumps and fans, lead-lag control systems for compressors, feedback control systems that regulate rather than bypass flow, and power factor controllers that can reduce energy use of small motors in grinders, drills, and other equipment that idle with zero load much of the time. Nadel et al., op. cit., foomote 15.

thus eliminating the need for DC motors and wasteful mechanical control mechanisms. ASDs are not needed for constant-speed full load applications, so no savings are realized in these cases.

In addition to enhancing efficiency, ASDs reduce the wear on equipment and improve the operating performance of motor drive processes. They reduce equipment wear and extend equipment life by:

. avoiding the back pressures generated by conventional systems;
● permitting constant lubrication of bearings;
● allowing operation at reduced speeds; and
● permitting slow, controlled startups and shutdowns to reduce electrical and mechanical stresses on motor drive equipment.

They improve performance by:

● controlling manufacturing equipment and processes better than conventional systems can;
● isolating the motor from the power line, which can reduce problems caused by varying or unbalanced line voltage;
● providing a "ride through' capability if there is a power failure for a few cycles;
● permitting operation at higher speeds than the 60-Hz line frequency allows; and
● being easier than conventional control devices to retrofit to existing equipment.

ASDs are not without drawbacks. In particular, they can distort the shape of the normal voltage waveform in the power grid. The harmonic distortion can reduce the efficiency of motors and transformers, can also interfere with computers and communications equipment. Techniques are available to control this problem, and further work to lower the costs of control is ongoing. With proper design upfront-as opposed to onsite remediation after installation-harmonic control is relatively low cost and straightforward.

ASDs currently cost about $90 to 360per hp for motors larger than 10 hp, and can result in energy savings of 15 to 40 percent in many cases.[22] The capital costs of ASDs have declined some 7 to 12 percent in real terms over the past 4 years.[23] Costs are likely to continue declining slowly as ASD technology and manufacturing processes improve, and as greater economies of scale are achieved.

The industrywide electricity savings possible by the use of ASDs are not yet well understood. Total savings will depend on a variety of factors, including the rates of cost reduction and market penetration of ASDs, and the types of part- or variable-loads driven. Further, the individual savings achieved may depend on the development of new engineering design rules that fully exploit the opportunities presented by ASDs.

ASSOCIATED EQUIPMENT

The energy efficiency of motor driven systems can often be improved by using better designed and better built pumps, fans, compressors, pipes, ducts, fittings, and materials processing and handling equipment. Pumps and fans, the most common motor driven equipment, can be made more efficient by reducing internal friction through smoother and more carefully contoured internal surfaces, tighter tolerances, and higher quality bearings. Further efficiency gains are often possible by operating pumps at higher speeds. Friction and the corresponding energy losses can be reduced in piping and systems by using smoother or larger diameter conduits and by careful choice and spacing of the fittings.

MOTOR SYSTEMS DESIGN

Motors and their power conditioning apparatus drive, control devices, and associated equipment form large and complex systems. Better design of these systems can be the source of significant energy savings.

22 Nadel et al., op. cit., footnote 15.

23 Eric D. Larson and Lars J. Nilsson, op. cit., footnote 9.

Component oversizing is a common problem among motor drive systems. Larger than needed equipment is often used to ensure that systems can meet the demands placed on them at every stage of the process. For example, motors are oversized: to handle starting electrical, mechanical, and thermal stresses, particularly with high-inertia loads; to provide a safety margin for the worst-case load over their lifetimes; and occasionally to handle plant expansion or be widely interchangeable within a plant. Motors and other components may be also oversized partly to compensate for difficulties in accurately predicting system flow rates and friction factors in advance, and to allow for the effect of the buildup of deposits on duct and pipe walls over time. The increased energy and capital costs of the larger equipment are perceived to be less than the risk of equipment failure. In manufacturing, for example, average electricity costs in the United States are equivalent to just 1.6 percent of total production costs;[24] the cost of motor failure and unplanned shutdown of the entire process line can be a much more severe penalty .[25]

The inefficiencies of equipment oversizing are compounded because of the interconnectedness of motor drive systems. When each successive element of a system is sized to handle the load presented by the previous component plus a safety margin, oversizing can quickly become excessive. The losses of the entire system can be great (figure 3-2).

The reasons for equipment oversizing are often codified into standard engineering design rules, such as manufacturing safety margins. The flexibility of ASDs may allow some relaxation of the design rules that lead to extreme oversizing, potentially reducing both energy use and capital investment.

I Steam Production and Cogeneration

Steam is used throughout industry to heat fluids and materials, and in some processes to modify the pressure characteristics of fluids and gases. Smaller quantities of steam are used to heat plant buildings. Steam is typically generated in boilers, some of which are linked to turbine and generator sets in order to cogenerate electricity. The electricity is used within the plant or sold onto the grid. In 1985, industry consumed 7.1 quads of energy to generate steam and electricity (70 billion kWh).[26] In that year, the nearly 37,000 industrial boilers had a combined capacity of 1.5 trillion Btu/h steam. The largest steam producers and electricity cogenerators are the process industries (i.e., pulp and paper, chemicals, petroleum refining, and food) and primary metals producers. They account for 79 percent of industrial boiler capacity and 94 percent of industrial cogeneration of electricity (figure 3-3).
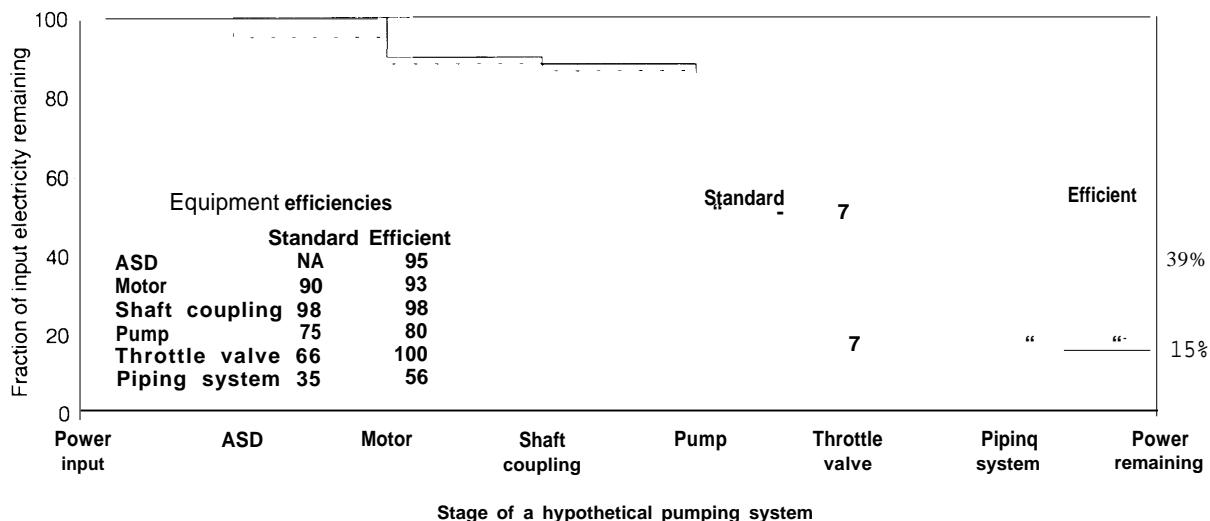
Industry uses a variety of fuels to boil water into steam. The most heavily used are combustible process wastes and byproducts such as wood wastes and black liquor in pulpmaking, still gases in petroleum refining, coke oven and blast furnace gases in steelmaking, and various wastes in beer brewing and sugar processing. Process wastes and petroleum byproducts account for 42 percent of fuel use in steam production and cogeneration, but are the primary fuels in only 12 percent of the population of industrial boilers. They are used only in a few large industries where their value as fuel exceeds that of their reuse as process materials or feedstocks. Natural gas is the most

24 U.S. Department of Commerce, Bureau of the Census, *1990 Annual Survey of Manufactures: Statistics for Industry Groups and Industries*, Report No. M90(AS)-1, March 1992.

25 A.D. Little, Inc., *Energy Efficiency and Electric Motors*, U.S. Department of Commerce, NTIS PB-259 129 (Springfield, VA: National Technical Information Service, 1976).

26 Except where noted, all figures in this section pertaining t. fuel use, boiler capacity, and cogeneration capacity are based on 1985 data from Gas Research Institute, *Industrial Natural Gas Markets: Facts, Fallacies and Forecasts* (Chicago, IL: Gas Research Institute, March 1989).

Figure 3-2—Energy Losses in Hypothetical Standard and Efficient Electric Motor-Driven Pumping Systems

Equipment efficiencies	Standard	Efficient
ASD	NA	95
Motor	90	93
Shaft coupling	98	98
Pump	75	80
Throttle valve	66	100
Piping system	35	56

Stage of a hypothetical pumping system

KEY: ASD - adjustable speed drive.
This figure shows the useful **energy remaining at each stage of the pumping systems. The efficiency profiles are those of hypothetical pumping systems, and do not represent industrywide averages. The energy losses that occur in the generation, transmission, and distribution of electricity are not included.**

SOURCE: Adapted from Samuel F. Baldwin, "Energy-Efficient Electric Motor Drive Systems,"Thomas B. Johansson, Birgit Bodlund, and Robert H. Williams (eds.), *Electricity:Eflicient End-Use and New Generation Technologies Their Planning Implications* (Lund, Sweden: University Press, 1989), pp. 21-58.

used commercial fuel for steam production and cogeneration. It is also the fuel used in the largest number of boilers. Smaller amounts of coal and fuel oils are also used to produce steam (figure 3-4).

Many industrial facilities installed dual- and multi-fuel steam systems after the oil shocks of the 1970s. Approximately 50 percent of boilers are now capable of using more than one fuel. Dual- and multi-fuel systems are a major source of industry's fuel switching capabilities. They provide flexibility to react to market conditions and leverage to obtain favorable fuel contracts with utilities.

BOILERS AND STEAM TURBINES

Steam is produced in four basic equipment configurations: 1) steam-only boilers, 2) steam turbine cogeneration sets, 3) combustion turbine cogeneration sets, and 4) combined-cycle cogeneration sets.[27] The first two configurations incorporate boilers. Large boilers (50 million Btu/h or larger) are based on water tube technology and used to satisfy plants' basic requirements for process and power steam. Smaller boilers are predominantly fire tube units used for space heating and for backup or smaller process requirements.[28]

In a steam-only setup, the steam is piped directly from the boiler to its point of use. Steam-only boilers accounted for 60 percent of the total fuel used for industrial steam and electricity production in 1985. In a steam turbine cogeneration system, steam from the boiler is expanded in a steam turbine that turns a generator to produce electricity. Topping cycle cogenera-

[27] Diesel engines can also be used in cogeneration systems, generally in applications 30 kW or smaller. They currently account fOr less than 1 percent of industrial cogeneration capacity.

[28] RCG/Hagler, Bailly, Inc., *Combustion System Technology and Application Assessment: Industrial Boiler Combustion Systems* (Chicago, IL: Gas Research Institute, October 1988).

Figure 3-3—Electricity Cogeneration in
Manufacturing industries, 1988

Total: 102 billion kWh
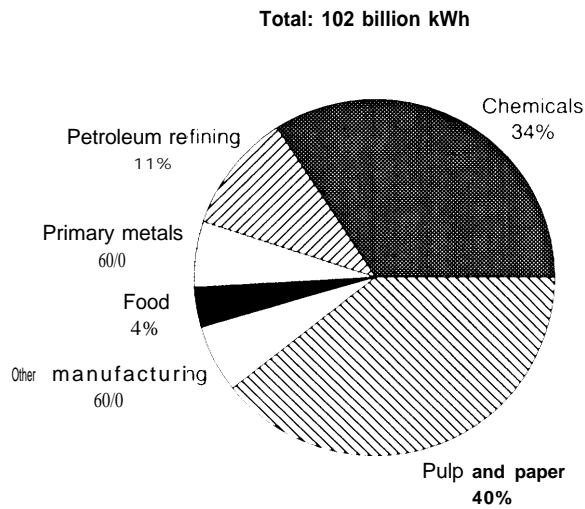
SOURCE: U.S. Department of Energy, Energy Information Administration, *Manufacturing Energy Consumption Survey (MECS), Consumption of Energy 1988,* Report No. DOE/EIA-0512(88), May 1991.

tion cogeneration is run through a steam topping turbine to produce additional electricity before it is piped to the process stream. Combustion turbine and combined cycle systems tend to be used where the ratio of electricity generated to steam produced is relatively high. In 1985, these systems accounted for 5 percent of fuel use for industrial steam production and cogeneration and 32 percent of the installed cogeneration capacity. Their share of cogeneration capacity grew from about 15 percent in 1980, because over 60 percent of the 6,700 MW of capacity added during 1980 to 1985 was combustion turbine or combined cycle.

COGENERATION

The principal technical advantage of cogeneration systems is their efficiency of fuel use. In producing both electrical and thermal energy together, cogeneration systems consume less fuel than is required to produce both forms of energy

tion systems, the most widely used configurations, run the steam first through the generator and then to the process (figure 3-5). Bottoming cycle systems run the steam through the generator after it has been used in the process. In 1985, steam turbine systems accounted for 35 percent of fuel use for industrial steam production and cogeneration and 68 percent of the 18,700 MW of installed cogeneration capacity.

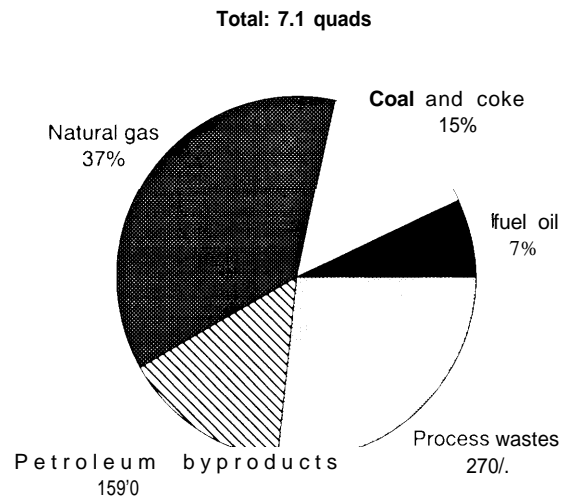## COMBUSTION TURBINES AND COMBINED CYCLE SYSTEMS

Combustion turbine and combined cycle cogeneration systems, which are fueled primarily by natural gas, rely on heat recovery units rather than boilers to produce steam. In a combustion turbine system, gas is burned in a turbine to turn an electricity generator and the exhaust gases are run through a heat recovery unit to generate steam (figure 3-5). In a combined cycle system, which is a hybrid of the combustion turbine and steam topping technologies, steam produced in combus-

**Figure 3-4-Fuel Use in Steam Raising
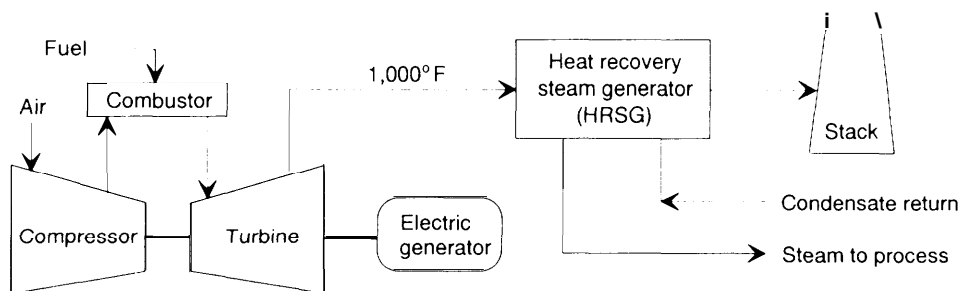and Cogeneration, 1985**

Total: 7.1 quads

NOTE: **Petroleum byproducts are principally still gases.**

SOURCE: **Gas Research Institute,** *Industrial* Natural Gas *Markets: facts,* **Fallacies** *and Forecasts* **(Chicago, IL: Gas Research Institute, March 1989).**

Figure 3-5-Flowchart of Steam Turbine and Combustion Turbine Cogeneration Systems
Steam turbine, topping cycle
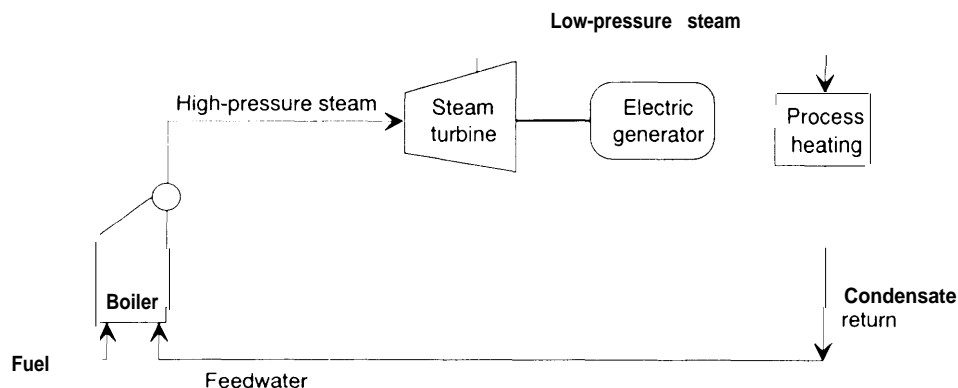
Combustion turbine with a heat recovery steam unit

SOURCE: Energetic, Inc., *Industry Profiles; Steam Generation* and Cogeneration, prepared for U.S. Department of Energy, Office of Industrial Technologies, Report No. DE-ACO1-87CE40762, December 1990. Original cited source is SFA Pacific, Inc.

separately, though more than is needed to produce either form alone.[29]

Cogeneration and other onsite electricity generation technologies have been used in industry since before the turn of the century. They were originally used to counter the expense, unreliability, and unavailability of electricity provided by utilities. When utility service improved, electricity purchases from utilities grew faster than onsite

generation. As a result, onsite generation declined in importance.

Cogeneration capacity has grown rapidly since 1980, because of the incentives established by the Public Utility Regulatory Policies Act (PURPA) and the reversal in the long-term decline in real electricity prices. In fact, cogeneration has been the fastest growing industrial application for heat and power. Cogeneration capacity in the manu-

29 U.S. Congress, Office of Technology Assessment, *Industrial and Commercial Cogeneration*, OTA-E-192 (Washington, DC: U.S. Government Printing Office, February 1983).

Table 3-3-Characteristics of State-of-the-Art Cogeneration Systems

Technology	Typical unit size (MW)	Simple cycle heat rate (Btu/kWh)	Steam to electricity ratio (lb/kWh)	Overall system efficiency (percent)
Steam topping turbine				
Backpressure only. 0.5-60		**14,000-40,000**	**10-30**	**75-85**
Condensing with extraction. . . . 10-100		**10,000-40,000**	**0-30**	**70-80**
Combustion *turbine.* **. 0.5-100**		**10,000-15,000**	**2.5-10**	**65-75**
Diesel engine. 0.1-30		8,500-11,500	1-3	75-85

SOURCE: **Energetic, Inc.,** *Industry Profiles: Steam Generation and Cogeneration,* **prepared for the U.S. Department of Energy, Office of Industrial Technologies, Report No. DE-ACO1-87CE40762, December 1990.**

facturing industries grew from 12,000 MW in 1980, to 18,700 MW in 1985, to about 25,000 MW by the end of 1989.[30] In these industries, electricity cogeneration rose from 68 to 102 billion kwh during 1980 to 1988. In 1988, cogeneration accounted for about 12 percent of manufacturers' electricity needs.31

PURPA made electricity sales onto the grid were more lucrative than they had been before. This increased the popularity of combustion turbine and combined cycle cogeneration technologies, because they produce greater amounts of electricity per unit of steam than steam turbine systems.

ENERGY EFFICIENCY

The energy efficiency of thermal systems can be improved by: developing and implementing better steam production and cogeneration technologies; properly maintaining steam distribution systems; increasing the use of wastes and byproducts as fuels; and increasing the effectiveness of steam and other thermal processes. Uncertainties

regarding the emissions requirements of steam generation systems and the relative economics of purchased vs. self-generated electricity will play large roles in the choice of new technologies.

Use of more efficient boilers, economizers, and other heat recovery systems improves the energy efficiency of steam production and cogeneration systems.[32] State-of-the-art cogeneration systems have efficiencies ranging from 65 to 85 percent (table 3-3). Those systems that produce large amounts of steam relative to electricity generally have the higher efficiencies, while those that produce greater proportions of electricity have lower efficiencies. Advances in combustion turbine technologies (e.g., steam injection) and combined cycle systems may be able to raise the efficiencies of the more electricity-focused systems to levels comparable to those that emphasize steam.

Energy losses can also be reduced with proper attention to steam distribution systems. This includes maintenance of steam traps and in-

30 Figures for 1980 and 1985 are from Gas Research Institute, op. cit., footnote 26. Figure for 1989 is from Energetics, Inc., *Industry Profiles: Steam Generation and Cogeneration*, prepared for U.S. Department of Energy, Office of Industrial Technologies, Report No. DE-AC01-87CE40762, December 1990.

31 The 1988 electricity profile of manufacturers was: 728 billion kWh of purchased electricity; 102 billion kWh of cogenerated electricity; 10 billion kWh of electricity produced by onsite generators fueled with combustibles such as diesel and fuel oil; 3 billion kWh of electricity produced onsite from renewable sources, primarily low head hydropower; 817 billion kWh of **electricity consumed; and** *24* billion kWh of electricity sold. U.S. Department of Energy, Energy Information Administration, *Manufacturing Energy Consumption Survey, Consumption of Energy 1988,* DOE/EIA-05 *12(88),* May 1991.

32 Economizers preheat boiler feedwater using heat absorbed from the combustion products after they have passed through the steam-generating and super-heating sections of the boiler.

creased insulation of steam carrying pipes. According to insulation manufacturers, there are 29,000 miles of uninsulated steam pipes in U.S. factories.[33]

Technologies, such as fluidized-bed reactors, that can increase the potential use of low-value or previously unusable process wastes and byproducts as fuels also enhance efficiency. Fluidized beds facilitate greater use of solid and other nonstandard fuels, reducing the need for premium fuels while decreasing waste management problems.[34] Though more fluidized-bed units are being used, industry still generally views these systems as cost-prohibitive relative to conventional boiler systems.[35]

Steam is not always the most efficient method, from a thermal standpoint, of delivering heat to a process stream. There are trends toward less use of steam and greater use of direct heat or vapor recompression in manufacturing processes.

I Process Controls and Sensors[36]

Computerized process controls and sensors are used to improve the performance of individual pieces of equipment or entire processes. Examples of such devices are:

- burner controls that vary the air-to-fuel ratios in combustion systems;
- motor controls that adapt motors' speeds to their loads;
- process controls that sense characteristics such as temperature, chemical composition, and flow rate and immediately optimize them to maintain product quality, minimize waste, or vary other process parameters; and
- energy management control systems (discussed above).

Almost any process can be made more energy efficient by measuring and optimizing parameters at each point of the process. The primary advantages of process controls though, are productivity and product quality, not energy efficiency.

The importance of process controls is increasing as microelectronics technology improves. While industry has made a start in applying some automatic controls (i.e., first generation burner controls and process controls), opportunities remain for further applications. Improved sensors have the potential for r-educing energy use in individual industries by 5 to 20 percent, with overall savings for the entire industrial sector of 10 percent.[37]

I Heat Recovery and Process Integration[38]

Waste heat arises whenever fuel is burned or process materials are cooled. Capturing the waste heat and applying it to other processes has enormous potential for saving energy in industry. Recovered waste heat is commonly used in producing steam, preheating materials (such as water destined for a boiler or a product stream destined for a heater or furnace), and preheating of fuel or air destined for combustion. Industry has implemented a great deal of waste heat recovery since the oil shocks of the 1970s.

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[33] Cited in Alliance to Save Energy, American Council for an Energy-Efficient Economy, Natural Resources Defense Council, and Union of Concerned Scientists in consultation with tbe Tellus Institute, *America's Energy Choices: Investing in a Strong Economy and a Clean Environment: Technical Appendixes,* 1992.

[34] Energetics, Inc., Industry Profiles: Steam Generation and Cogeneration, op. cit.. footnote 30.

[35] RCG/Hagler, Bailly, Inc., op. cit., footnote 28.

[36] U.S. Congress, Office of Technology Assessment, Energy Technology *Choices: Shaping Our Future,* OTA-E-493 (Washington, DC: U.S. Government Printing Office, July 1991) and *Changing by Degrees: Steps to Reduce Greenhouse Gases, OTA-O-482 (Washington* DC: U.S. Government Printing Office, February 1991).

[37] U.S. Department of Energy, Office of Industrial Programs, Research *and Development in Sensor Technology,* Report No. DOE/NBM-7012450, April 1987.

[38] U.S. Congress, Office of Technology Assessment, Energy *Technology* Choices: *Shaping Our Future,* op. cit., footnote *36.*

The **two** principal traditional approaches to heat recovery are: 1) transferring heat from high-temperature waste heat sources to more useful media such as steam, and 2) raising the temperature of low-temperature streams so they can be useful as heat sources. Heat exchangers are used for the former approach and vapor recompression and heat pumps are used for the latter.

Process integration is another method of preventing waste heat losses. This technique involves designing processes so that the number of heating and cooling steps are minimized and that heat sources are in close proximity to processes where the heat can be used. ''PINCH' analysis is a systematic design methodology that can be used to further process integration, in either existing or greenfield plants. It helps identify the optimum process configuration for low energy use as well as low capital and operating costs. PINCH also helps reduce pollutant emissions and increase production capacity.

I Catalysts39

Catalysts are used in many industries to facilitate chemical reactions. The petroleum refining and chemicals industries rely heavily on catalysts to perform a variety of functions, including raising gasoline octane levels, removing impurities, and converting low-grade hydrocarbons to higher value products. Improved catalysts can increase chemical reaction rates and lower operating temperatures and pressures, thereby reducing heating and compression requirements and improving energy efficiency.

The discovery and use of new synthetic zeolites as catalysts have contributed to energy efficiency gains in both the petroleum refining and chemicals industries. Considerable effort has been spent to identify and develop unique zeolites for use in synfuels production, petrochemical manufacture, and nitrogen oxide (NO=) abatement.[40] In the pulp and paper industry, catalytic reactions can be used to recover organic acids from waste streams. Typically, the wastes are dumped because there is no method for extracting the acids unless the streams are first concentrated. A catalytic process can convert the organic acids to hydrocarbons, which can be easily separated from water.[41]

I Separation[42]

Physically separating two or more components in a mixture is one of the most energy-intensive processes in the industrial sector. Separations account for about 20 percent of industrial energy use.

Distillation, the most common method of separating liquids, is particularly energy-intensive. However, distillation retrofit projects offer significant potential for energy savings. For example, a small increase in the number of trays in a distillation column can reduce energy use. Also, improvements in distillation control technologies result in lower energy consumption as well enhanced product quality. It is estimated that improvements in the distillation process can reduce energy consumption by 10 percent.[43]

Alternative approaches to conventional distillation include vacuum distillation, freeze crystallization, solvent (liquid-liquid) extraction, membrane techniques, pressure swing adsorption, and mercury or asbestos diaphragm electrolytic processes. The increased cost-effectiveness of turbocompressors and advances in vacuum pumps and cryogenic technology have vastly increased the relative attractiveness of both vacuum distillation and freeze crystallization. Crystallization is

[39] Ibid.

[40] Oak Ridge National Laboratory, *Energy* Technology R&D: *What Could Make a Difference?* vol. 2, Part 1, ''End-Use Technology,'' ORNL-654411 V2/P1, December 1989.

[41] Ibid.

[42] U.S. Congress, Office of Technology Assessment, *Energy* Technology *Choices: Shaping Our Future,* op. cit., footnote *36.*

[43] Oak Ridge National Laboratory, *Energy Technology R&D: What Could Make a Difference?* op. cit., footnote 40.

Figure 3-6-Energy Use in the Production of Virgin and Recycled Containers
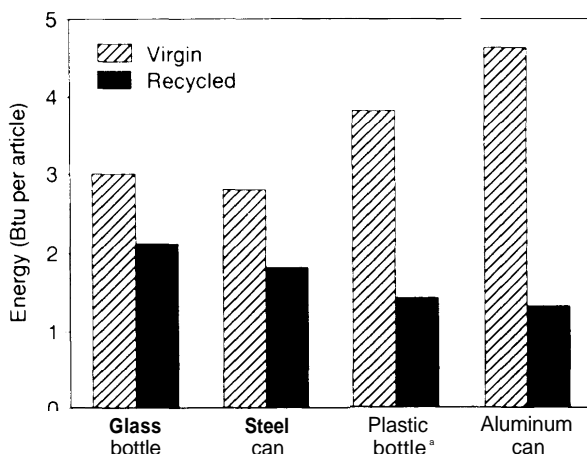
a Theoretical value, **plastic bottles are not now made of recycled material.**

SOURCE: Marc H. Ross and Daniel Steinmeyer, "Energy for Industry," *Scientific American, vol. 263, No. 3,* September 1990, pp. 89-98.

often a more energy efficient separation technique than evaporative (distillation) processes, because freezing requires less energy (about 150 Btu/lb of water) than boiling (about 1,000 Btu/lb of water).

One of the most promising alternative separation methods is solvent extraction. This technology uses specialized solvents to selectively dissolve components of liquid-liquid mixtures. Its use in the chemicals industry is growing. In 1984, the Office of Technology Assessment (OTA) noted that the use of solvent extraction in a synthetic fiber plant saved an estimated 40,000 barrels of oil equivalent annually.[44]

Membrane separations are based upon the principle that components in gaseous or liquid mixtures permeate membranes at different rates because of their molecular characteristics. One of the major advantages of membrane separation systems is that they can improve product quality. Gas separation is perhaps the largest growth market for membrane technology, but there are many other potential applications in the chemicals and food and beverage processing industries.

I Materials Use: Yield Improvements (Waste Reduction) and Recycling (Waste Use)

Improved use of process materials holds large potential for energy savings. Rejected (off-specification) products require nearly as much energy and materials to produce as do salable products. Process yield improvements result in less waste generation and save the energy embodied in the rejected products. They also result in large cost savings and extend production capacity. Continuous casting in the steel industry is an example of a yield-improving technology that saves large amounts of energy. Computer control and sensors (see discussion above) are an integral part of most yield-improving technologies.

Recycling scrap, whether from downstream fabricators or postconsumer wastes, results in energy savings in most industries. In aluminum production, 5 percent as much energy is required to melt scrap as to smelt the same amount of molten metal from ore. Smaller, yet significant, energy savings are possible for other materials (figure 3-6).

Reuse of process wastes and byproducts for their materials or energy value saves energy and reduces disposal treatment costs. Use of traditionally discarded wastes, such as organic byproduct gases, organics in waste streams, water, and steam

44 U.S. Congress, Office of Technology Assessment, *U.S. Vulnerability to an Oil Import Curtailment: The Oil Replacement Capability, OTA-E-243 (Washington DC:* U.S Government Printing Office, September 1984).

condensate, offers many energy-saving opportunities.

PROCESS INDUSTRIES

1 Petroleum Refining[45]

Petroleum refineries process the various hydrocarbon compounds in crude oil into fuels and other useful products. The hydrocarbons are first separated from one another, then converted and reorganized into more valuable forms, and finally blended into products. Along the way, contaminants such as sulfur and heavy metals are removed and beneficial compounds such as detergents are added. Four major types of processes are used in petroleum refining: separation, conversion, reorganization, and finishing.

Typical refinery products, from lightest to heaviest, include: liquefied petroleum gases (LPG); gasoline and aviation jet fuel; petroleum solvents; kerosene; heating oil and diesel fuel (the middle distillates); residual fuel oil; petroleum coke; and asphalts (bitumens).46 Depending on their geographical location, customer demand, and seasonal needs, refiners can substantially alter their product slate. In winter, for example, less gasoline and more heating oil are produced.

Petrochemicals, such as ethanol, styrene, ethyl chloride, butadiene, and methanol, are also often produced at refineries. These intermediates are used as feedstocks in the manufacture of plastics, synthetic rubbers, synthetic fibers, and other products. There are many advantages to producing these chemical building blocks at refineries,

and the oil industry has undertaken their manufacture on a large scale.

Most of the energy consumed in petroleum refining comes from the petroleum itself. A rule of thumb is that it takes one barrel of oil to refine ten. Refinery gas accounts for nearly half of the energy used, Petroleum coke, residual fuel oil, and LPG are also commonly used. Natural gas, accounting for 20 percent of energy use, is the most heavily used purchased fuel.

On average, about 600,000 Btu are used to process a barrel of oil into its various products (based on 1989 data) .47 The most energy-intensive steps are the reorganization and distillation (separation) processes. Widespread adoption of state-of-the-art technologies can reduce energy consumption by about one-third (tables 3-4 and 3-5).[48] The biggest improvements are in the early stages of refining, the separation, coking, and visbreaking steps. Advanced technologies, not yet commercialized, could possibly reduce energy use an additional 10 percent.[49] Most of these potential gains come from general conservation measures such as alternate-fuel fluidized-bed boilers, improved combustion processes, and low-grade waste heat recovery, and from improvements in the akylation process.

The greatest single loss of energy in a refinery occurs during the final cooling of process streams. Where feasible, the low-level heat is transferred to other process streams, thus reducing the energy needed for cooling. The opportunities for recovering significant amounts of low-level heat are much greater in new facilities, designed to optimize heat recovery, than in existing plants. In

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45 ''Petroleum processing, ' ''Cracking,''''Hydrocracking,'' and "Reforming processes, " *McGraw-Hill Encyclopedia on Science and Technology (New* York, NY: McGraw-Hill, 1987). ''Petroleum,'' *The Academic American Encyclopedia, Online* Edition (Danbury, CT: Grolier Electronic Publishing, 1991). Energetic, Inc., Industry *Profiles: Petroleum,* prepared for U.S. Department of Energy, Office of Industrial Technologies, Report No. DE-AC01-87CE40762, December 1990.

46 Liquefied petroleum gases (LPG) are ethane, propane, butane, and various other natural gas and petroleum Products.

47 Energetic, Inc., *Industry Profiles: Petroleum,* op. cit., footnote 45.

48 Supra, foomote 3.

49 Supra, foomote 5.

Table 3-4-Energy Use by Petroleum Refining Technologies

Process	Process mix (bbls of process stream per bbl of crude oil)			Energy use (thousand Btu per bbl of process stream)		
	Current (1989)	State-of-the-art (2010)	Advanced (2010)	Current (1989)	State-of-the-art (2010)	Advanced (2010)
Separation						
Atmospheric distillation. 1.00	1.00	1.00		99	38	84b
Vacuum distillation. 0.44	0.44	0.44		96	58	**35**
Conversion						
Delayed coking/visbreaking^c. . 0.12	0.13	**0.13**		134	58	71b
Catalytic cracking. 0.35	0.35	**0.35**		129	123	**90**
Catalytic hydrocracking. 0.07	0.08	**0.08**		223	202	**201**
Reorganization						
Catalytic reforming. 0.24	0.24	0.24		349	349	**349**
Alkylation. 0.06	0.06	0.06		627	561	**313**
Isomerization. 0,03	0.03	0,03		154	154	**154**
Hydrogen production 0.16	0.16	0.16		323	323	**323**
Finishing						
Catalytic hydrotreating. 0.57	0,58	**0.58**		180	177	180b
*Not **accounted fore**. . . . .* 1.00		—		104	—	—
Genera/ corrservatione. 1.00	1.00	**1.00**		·		-54
Total. 1.00	**1.00**	**1.00**		602	405	363

a Average of current implemented technologies.
b Most improvements from advanced technologies are included in the General conservation category.
c Energy use values are averages for coking operations.
d Units for production are billion cubic feet, and for energy use are thousand Btu per thousand cubic feet of hydrogen.
e Bbls are barrels of crude oil.

NOTE: Purchased electricity is counted at 10,500 Btu per kWh; generation and transmission losses are included. Estimated losses in 1989 were approximately 44.0 thousand Btu per barrel of crude oil.

SOURCE: Energetics Inc., *Industry Profiles: Petroleum,* prepared for the U.S. Department of Energy. Office of Industrial Technologies, Report No. DE-AC01-87CE40762, December 1990,

general, improved heat exchange can reduce refinery energy use by about 9 percent.[50]

Process heaters and steam boilers also offer opportunities for reducing energy use. The options include: using stack gas analyzers and combustion control instrumentation to improve combustion; using air preheater **to** reduce stack gas temperatures and heat incoming combustion air; and installing convection sections at the heater outlets to heat incoming feed or to generate steam.

Continued improvements in computer control systems and sensors offer energy-savings bene-fits, as well. In addition to reducing energy use, these systems improve process performance, increase output, and optimize product specifications. A number of energy management control systems are available today. One control system company estimates that energy savings of 5 to 10 percent can be realized in the petroleum refining industry.[51]

SEPARATION: DISTILLATION

Distillation is the primary process for breaking down crude oil into its constituent hydrocarbons.

50 R.O. Pelham and R.D. Moriarity, "Survey Plants for Energy Savings, " *Hydrocarbon Process,* vol. 64, No. 7, pp. 5 1-56; reported in Oak Ridge National Laboratory, *Energy Technology R&D: What Could Make a Difference?* op. cit., footnote 40.

51 Oak Ridge National Laboratory, Energy *Technology R&D: What Could Make a Difference?* op. cit., footnote 40.

Table 3-5-Major Energy Saving Features of Improved Petroleum Refining

Process	State-of-t he-art	Advanced
Separation		
Atmospheric distillation	Reflux-overhead vapor recompression (20) Staged crude preheat (13) Air preheater (12) Intermediate reboilers and condensers (7) Split tower operation (5) Improved fractionation (4) Improved instrumentation and control (1) Two-stage condensation (<O.5)	Advanced vapor recompression (15) Advanced control strategies for thermal effi-ciency (5)
Vacuum distillation	Mechanical vacuum pumps (35) Improved fractionation (3)	Dry vacuum column operation (33) fluid atmospheric resid process (ART) (28)
Conversion		
Delayed coking/visbreaking	Fluid coking to gasification (FLEXICOKING) (57) Mechanical vacuum pumps (19)	fluid-bed vacuum resid process (ART) (102) Soaker visbreaking (60) HDH hydrocracking (reduced hydrogen and severity) (27)
Catalytic cracking	Turbine power recovery train (6)	FCC/improved catalysts and process (39)
Catalytic hydrocracking	Hydraulic turbine power recovery (21)	New catalysts (low temperature **and pressure**) (22)
Reorganization		
Alkylation	Improved catalysts (66)	Polymerization processes (31 4)
Finishing		
Catalytic hydrotreating	Hydraulic turbine power recovery (3) Operating modification (lower pressure, less recycle) (1)	
General conservation		Alternate-fuel fluidized-bed boilers (25) Improved combustion processes (17) Low-grade waste heat recovery (13)

NOTE: **Figures in parentheses are estimates of energy savings, in thousand Btu/barrel of the particular process steam. In general conservation, the energy savings are in thousands of Btu/barrel of crude oil.**

SOURCE: Energetic, Inc., *Industry Profiles.' Petroleum,* prepared for the U.S. Department of Energy, Office of Industrial Technologies, Report No. DE-AC01-87CE40762, December 1990.

It operates on the principle that the various hydrocarbons boil at different temperatures. When the heated crude oil is fed into a distillation column (tower), the lighter hydrocarbons (frac-tions) vaporize and rise. As they ascend the fractions decrease in temperature and condense into liquids. They then flow downward into hotter sections of the column and are revaporized. This process continues until the various fractions have achieved the appropriate degrees of purity. They are then tapped at various positions along the tower. The lighter fractions are tapped off from the top of the tower; heavier fractions are tapped from lower on the tower.

The initial processing of crude oil is done in atmospheric distillation columns. Temperatures within the columns gradually rise to about 640 'F. Large amounts of steam (about 1 to 2 lb/gal of oil) are added to reduce the boiling temperatures by partial pressure effects. Light end fractions, such

as propane and butane, come off the top and are sent to the gas fractionation plant. Napthas, kerosene, heating oil, diesel fuel, and heavy gas oil are tapped successively lower on the column and are sent to various conversion and finishing processes. The heavier, high-boiling-point, bottom-of-the-barrel products are sent to a vacuum distillation unit for further separation.

Light end products are separated from one another in a series of gas fractionation columns. In a fractionation column, the gases are brought into countercurrent contact with condensate. With proper adjustment of the condensate and gas flow rates, the more volatile hydrocarbons are concentrated into the gas and the less volatile ones are concentrated into the condensate. Placed in a series, fractionating columns can be used to separate the light ends into fuel gases, propylene, propane, butylenes, iso-butane, and n-butanes.

Heavy constituents are not removed in the atmospheric distillation step, because of their high boiling points and their temperature sensitivity. They are distilled in vacuum distillation columns. The partial vacuum lowers their boiling points to a range where distillation can occur without excessive thermal decomposition.

Separation accounts for 23 percent of the energy used in refining. State-of-the-art technologies such as vapor recompression, staged crude preheating, air preheater, and intermediate reboilers and condensers can reduce energy use at this stage by about 55 percent.

CONVERSION: CRACKING

Cracking is used to convert heavier, lower value hydrocarbons into lighter, higher value ones. This is accomplished by breaking apart the chains of hydrocarbon molecules to decrease their size and by adding hydrogen to raise their hydrogen-to-carbon ratio. Cracking is carried out by catalytic, hydrocracking, and thermal methods.

Catalytic cracking is used to convert intermediate- and high-boiling point distillates into gasoline. It is used to shift refinery output to meet changes in market demand, because of its flexibility in converting a wide variety of fractions. Feed oil and a powdered catalyst are pumped together into a fluidized-bed reactor, which is coupled to a catalyst regenerator. The hydrocarbon molecules are broken by carbonium ions formed on the catalyst (typically silica-alumina zeolite) during various reactions occurring at 850 to 1,025°F. During cracking, coke is deposited on the catalyst. When the catalyst is regenerated, the coke is burned to provide the heat for the cracking reaction.

Hydrocracking is used to convert highly aromatic fractions, which severely degrade the catalysts used in catalytic processes, into high-octane gasoline and aviation jet fuel. The feed oils are pumped along with hydrogen through a two-stage, freed-bed catalytic unit operating at high pressure (1,000 to 2,500 psig) and moderate temperature (500 to 750 F). Two main reactions occur in a hydrocracking unit, the addition of hydrogen to the molecules and the subsequent conversion of the fractions into the product fuels.

Thermal cracking methods are used to convert low-grade residual oils. These fractions cannot be converted by catalytic methods, because they subject catalysts to excessive coke buildup and contamination by inorganic components. The fluid coking, delayed coking, and visbreaking processes used on the low-grade residuum coming from the vacuum distillation step are based on the thermal cracking mechanism. Petroleum fractions are pumped through steel tubes coiled within a furnace. The 850 to 1,1OOOF temperatures cause thermal decomposition of the hydrocarbons to take place. The heat breaks the carbon-to-carbon bonds in the molecules by a flee-radical mechanism.

Conversion accounts for 13 percent of the energy used in refining. Use of state-of-the-art technologies such as fluid coking to gastification, mechanical vacuum pumps, and hydraulic turbine power recovery can reduce conversion energy by about 16 percent.

REORGANIZATION: REFORMING

Reforming, an extension of the cracking process, is used to raise the octane number of gasoline. Octane ratings are enhanced by reorganizing hydrocarbon molecules, principally by changing their structure but also by increasing their volatility (decreasing their size).[52] Reforming can be accomplished by thermal methods, but catalytic techniques have made them obsolete. Catalytic reforming is usually conducted by heating the feed (naptha) to 840 to 965°F in a furnace and then passing it over hydrogen-dehydrogenation catalysts, in the presence of hydrogen, in a fixed-bed reactor.[53] Moving-bed and fluidized-bed reactors can also be used. The resulting product (reformate) is stabilized (light end fractions are removed) and used directly as gasoline or as a blending stock for aviation jet fuel.

The main reaction is dehydrogenation, so hydrogen is produced in large quantities, The hydrogen is recycled through the reactor to provide the atmosphere necessary for the chemical reactions and to protect the catalyst from carbon buildup. Excess hydrogen is vented and used as a reactant in hydrocracking, hydrotreating, and chemical (e.g., ammonia) manufacturing, or as a fuel.

Reorganization accounts for 29 percent of the energy used in refining. These processes have relatively low production levels, but are the most intense energy users in the refinery, averaging about 380,000 Btu per barrel of product.[54] Little improvement in energy efficiency can be expected from using state-of-the-art technologies. The development and use of advanced polymerization processes, though, could possibly cut energy use in the alkylation process by half,

FINISHING: TREATING

Treating processes are used to remove detrimental components from petroleum fractions. Hydrotreating is the most widely used finishing process. It is a catalytic process that can be used to remove impurities (e.g., sulfur, nitrogen and oxygen), to stabilize products, correct color and odor problems, and improve other product deficiencies. Other finishing processes, such as solvent extraction, solvent dewaxing, acid treatment, and clay treatment are used to a lesser extent to perform selected finishing functions.

Finishing accounts for 17 percent of the energy used in refining. Use of state-of-the-art or advanced technologies are expected to yield little improvement in the efficiency of these processes.

ENERGY EFFICIENCY[55]

Environmental concerns about automobile emissions (carbon monoxide and nitrogen oxide) will increasingly govern the characteristics of refined products and refinery operations. Motor fuels must meet both high octane and high environmental quality standards. To meet these standards, refiners are making greater use of hydrocracking and reforming processes. Use of alkylation and isomerization processes is also increasing. The increased operating severity (increases in processing temperature, pressures, and feedstock rates) in these energy-intensive processes will continue to exert upward pressure on energy consumption in refineries. Advanced tech-

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[52] Changes in the molecular structure include the conversion of n-paraffins to isoparaffins, olefins, and aromatics, and of naphthenes to aromatics. The most important chemical reorganization reactions that occur reforming are dehydrogenation, hydrogenation, aromatization cyclization, isomerization, polymerization and alkylation.

[53] The composition of a reforming catalyst is dictated by the feed and the desired product, Typical catalysts are molybdena-alumina, chromia-alumina, and platinum on an alumina or silica-alumina base.

[54] In the case of hydrogen production, 323,(X30 Btus per thousand cubic feet of hydrogen.

[55] Energetic, Inc., Industry Profiles: Petroleum, op. cit., footnote 45.

nologies to increase octane and concurrently reduce processing energy are needed.56

1 Chemicals

The chemical industry encompasses over 12,000 plants producing more than 50,000 chemicals and formulations. 57 Among the products are organic and inorganic chemicals, plastics, synthetic rubber, soaps, paints, industrial gases, fertilizers, pesticides, and pharmaceuticals. There are chemical plants throughout the United States, but the highest concentration is located near the supplies of energy and feedstocks—the oil and gas producing regions in Texas, Louisiana, and Oklahoma.

Chemical producers are the second largest energy-consuming industry. Natural gas is the principal fuel in most chemical production processes, but electricity plays a large role in the production of those agricultural chemicals, chloralkalies, and industrial gases that are produced electrolytically. Large quantities of natural gas and LPG are used as feedstocks. Natural gas (methane) is used as a feedstock in the production of ammonia (a major component of fertilizers), hydrogen, methanol, and carbon black. LPG are used in the production of many petrochemicals including ethylene, propylene, vinyl chloride, and styrene. Feedstocks account for about 34 percent of the chemical industry's energy use.58

Steam, used for process heating and pressurization purposes, consumes about 35 percent of the energy used in the chemicals industry. Because of this heavy use of steam, cogeneration is particularly attractive in this sector. An additional 13 percent of energy is used for direct process heating purposes such as fluid heating. Except in the industrial gases and chloralkalies industries, electricity use in chemicals production is dominated by pump, fan, compressor, and related mechanical drive needs. Materials movement is also a large use. Motor drive functions account for 16 percent of energy consumption.59

Chemical production is highly energy intensive because of the number and complexity of the process stages involved. Six of the most energy intensive processes are described in box 3-A. In 1988, the industry consumed about 11,600 Btu per dollar of product shipped, which was approximately double that of the manufacturing sector as a whole.60 The high-volume, low-value bulk chemicals such as sulfuric acid, industrial gases, and ethylene are especially energy intensive to produce.

The chemical industry is composed of a very diverse group of industries. Each has its own particular energy needs and problems. Several of the larger chemical industries are profiled below to illustrate the many different issues and problems that are faced.

SULFURIC ACID61

Sulfuric acid is the most produced chemical in terms of tonnage. An inorganic chemical, it is used as a processing agent in industries such as phosphate fertilizer production, petroleum refining, chemicals production, and ore processing.

Sulfuric acid (H_2SO_4) produced by the contact process. Sulfur is burned in air to produce

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56 Alternatively, petroleum refineries' energy consumption could be reduced through the adoption of automobile engine technologies that have less strict fuel requirements.

57 U.S. Department of Commerce, International Trade Administration *U.S. Industrial Outlook 1991* (Washington, DC: U.S. Government Printing Office, January 1991).

58 Office of Technology Assessment estimates, based on data from the Industrial Sector Technology Use Model (ISTUM1), see table 2-3.

59 Ibid.

60 U.S. Department of Energy, *Manufacturing Energy Consumption Survey, Consumption of Energy 2988,* op. cit., footnote 31.

61 Energetic, Inc., *Industry Profiles: Chemicals,* prepared for the U.S. Department of Energy, Office of Industrial Technologies, Report No. DE-AC01-87CE40762, December 1990.

Box 3-A–Energy-Intensive Processes in Chemical Manufacturing

. Electrolytic processes in which electricity is used in direct chemical conversion.

. Fuel-heated reaction processes which require some type of heat to force a chemical reaction to take place. Energy sources include steam (except for high-temperature reactions), natural gas, residual fuel oil, distillate fuel oil, and even fluidized-bed coal combustion. Where precise temperature regulation is required, natural gas and distillate fuel oil are used.

● Distillation processes which involve evaporation and condensation to physically separate end products from feedstocks and/or byproducts.

● Refrigeration processes which involve compression and expansion of a refrigerant, such as ammonia or a fluorocarbon, to cool feedstocks or products below ambient temperatures.

● Evaporation processes which use passive-evaporation to cool feedstocks or products. in general, the evaporated water is lost to the atmosphere, and the heat energy is unrecoverable.

● Machine driven processes which are used to pump, compress, or move feedstock and end product materials. Machine drive arises from electric motors, steam turbines, or gas turbines. A subcategory of machine drive processes-mixing and blending (especially in polymerization processes)--can be very energy intensive due to the high viscosity of the materials.

SOURCE: U.S. **Congress, Office of Technology** Assessment, Industrial *Energy Use,* OTA-E-198 **(Washington, DC: U.S. Government Printing Office, June 1983) adapted from Robert Ayres,** *Final Report on Energy Consumption by Industrial Chemicals Industry,* DOE **contract No. DE-ACO1-79CS40151, Oct. 7, 19S1.**

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sulfur dioxide (SO2), then catalytically oxidized to SO3, and finally absorbed in aqueous acid to form H2SO4. To meet SO2 emissions regulations, most new plants use a double absorption process. Each of the three steps are exothermic, so modem acid plants are net energy producers. Most of the heat is recovered as steam and used in adjacent phosphoric acid plants. Small amounts of steam are also used for sulfur storage and melting. In some plants, the steam is run through steam turbine cogeneration units to produce electricity. The largest internal energy consumer in a sulfuric acid plant is the main blower (driven by steam turbine or electric motor) used to move the gases through the operation.

Great efforts have been made to maximize energy production from sulfuric acid production. The work has primarily centered on using waste heat to generate steam at higher pressure for use in cogeneration equipment. Additional energy can be produced by substituting low pressure steam for dilution water, using waste heat recovered from acid coolers (currently lost to cooling water), and using improved catalysts allowing lower "light-off" temperatures and/or less dilution air.

Maximum energy efficiency corresponds to maximum electricity cogeneration. The profitability of this endeavor is affected greatly by local conditions, i.e., electricity price rates, proximity to steam users, and utility capacity profiles.

Currently, a typical double absorption process without extensive heat recovery can produce 14 percent more energy than the average technology being used (1988 data) (table 3-6). An advanced plant using the features described above with maximum electricity output to the grid could possibly produce 73 percent more energy than the current average technology. These efficiencies have been achieved at the pilot scale, but not yet demonstrated on a commercial scale.

Table 3-6-Energy Use by Selected Chemical Production Technologies

Process	Energy use (thousand Btu/ton of end product)		
	Current	State-of-the-art	Advanced
		(2010)	(2010)
Sulfuric acid (1988)b			
Energy consumption....................	232	—	—
Export steam......................., ,..	-2,093	—	—
Total (net energy production)...........	-1,861	-2,117	-3,226
Nitrogen and oxygen production (1985)c			
Separation, ... ,........., ... ,..........	540	351	244
Compression (80 percent of production)....	409	409	409
Liquefaction (20 percent of production), ...	1,720	1,720	1,720
Electricity losses.......................	2,517	2,124	1,902
Total...............................	*3,728*	*3,146*	*2,818*
Ethylene (1988)			
Feedstock energy.....................	53,600	53,600	49,000
Process energy......................	4,600	3,800	3,400
Total...............................	58,200	57,400	52,400

aAverage of currently implemented tehnologies.

bFigures for Sulfuricaid are negative **because the production process is exothermic--it produces** more energy than it consumes.

cAssumes production of 58 percent nitrogen and 42 percent oxygen.

NOTE: Purchased electricity is counted at 10,500 Btu/kWh; generation and transmission losses are included. Estimated losses were approximately 117 thousand Btu/ton of sulfuric acid (1988) **and 2.5 million Btu/ton of oxygen and nitrogen (1985).**

SOURCE: Energetic Inc., *Industry Profiles: Chemicals,* **prepared for the U.S. Department of Energy, Office of Industrial Technologies, Report No. DE-ACO1-87CE40762, December 1990. Some data modified by the Office of Technology Assessment.**

NITROGEN AND OXYGEN[62]

Nitrogen and oxygen, the second and third highest tonnage chemicals, are used for a variety of purposes in industrial processes. Nitrogen is used variously as a purge gas (to prevent oxidation), pneumatic fluid, and cryogenic medium in the chemical, metals, food, and electronics industries. Oxygen is used as an oxidizing agent in steelmaking, nonferrous metals production, chemical and petrochemical production, and wastewater treatment. Transportation of these industrial gases is costly, so dedicated plants are commonly built right beside major consumers. Most nitrogen and oxygen is produced by the cryogenic distillation process. It is the most economical process for high-volume, high-purity

production. Other production methods are cryogenic distillation, pressure-swing adsorption (PSA), membrane separation, and chemical-based processes.[63]

Cryogenic distillation-Air is first dried and cleaned of impurities, then liquefied, and finally separated into more the volatile nitrogen (boiling point -320°F or 77.4°K) and the less volatile oxygen (-297°F or 90.20K) in a rectifier. The double column air separation system is capable of providing both liquefied or gaseous oxygen and nitrogen. However, liquid production is kept to a minimum, because withdrawing the products in liquid form requires about three times as much power as comparable gaseous production and also reduces the rated capacity of the equipment.

[62] Ibid.

[63] Electric dissociation of water for hydrogen and oxygen production has very little Commercial importance.

Cryogenic distillation is a very energy-intensive activity. A great amount of electricity is used to drive the feed air compressor. On average, the industry uses about 15.7 kWper ton of oxygen produced each day (table 3-6). The energy consumption is broken up into three processes: separation, compression, and liquefaction. State-of-the-art and advanced technologies affect primarily the separation stage. A state-of-the-art plant uses 16 percent less energy than the average current technology. The remaining inefficiencies in these modem processes arise principally from non-idealities in the refrigeration process, thermal inefficiencies in heat exchangers, and losses of refrigeration through heat leaks. An advanced plant could possibly use 24 percent less energy than the current average.

Pressure swing adsorption--Air is separated by preferentially adsorbing either nitrogen or oxygen onto physical absorbents or molecular sieves. Older PSA units produced gas with purities in the 90 to 95 percent range and increased purity could only be realized by decreasing product output. New advances in absorbent materials now permit purities approaching that of cryogenic units. PSA is more efficient than cryogenic distillation, but is presently only economical for smaller, lower purity production applications.

Membrane separation-Air is separated through the differential diffusion of its constituent gases through a semipermeable membrane. Energy consumption is lower than in cryogenic distillation, but the economics depend primarily upon the cost and development of suitable membrane materials. Membranes are used mostly in small-scale separation units.

Chemical separation—The Moltex process produces 99.8 percent pure oxygen via a reversible chemical reaction of oxygen with molten alkali *nitrates* and nitrites. Though the chemical process uses 40 percent less energy than cryo-genic distillation, its economics are only marginally better. Significant displacement of the mature cryogenic technology has yet to occur.

ETHYLENE64

Ethylene is the highest tonnage organic chemical produced in the United States. It is used principally as a building block for polymers (principally polyethylene) and other industrial chemicals, including ethylene dichloride, ethylbenzene, and ethylene oxide.

Production of ethylene occurs in four sections: 1) thermal cracking, 2) gas compression and treatment, 3) product separation, and 4) refrigeration. Thermal cracking of hydrocarbons in the presence of steam is the most widely used process. Cracking is done at about 2,900 F and 30 psia pressure, followed by rapid quenching to below 1,760°F. Ethylene is recovered by low temperature fractionation at 500 to 550 psia and purified at about -85°F to remove hydrogen, methane, and ethane.65

About 90 percent of the energy used in the production of ethylene is consumed as feedstock. The common feedstocks are ethane and propane (from natural gas processing plants) and refinery gas, naptha, and heavy gas oil (from petroleum refineries). Use of heavier, oil-based feedstocks is increasing. Most new plants are designed to crack naptha or heavy gas oil and are flexible enough to crack either, depending on price and supply.

The main source of processing energy is the fuel used in cracking furnaces, principally to supply heat for the endothermic cracking reaction. Fuel use increases sharply with heavier feedstocks, although much of this energy is ultimately recovered from the flue gases and hot products.

On average, current plants consume about 29,100 Btu/lb of ethylene (26,800 feedstock and 2,300 processing energy) (table 3-6). State-of-the-art technologies such as PINCH-optimized refrigeration and heat integration systems can save

64 *Energetic,* Inc., *Industry Profiles: Chemicals,* op. cit., footnote 61.

65 "Ethylene," *McGraw-Hill Encyclopedia on Science and Technology (New York,* NY: McGraw-Hill, 1987).
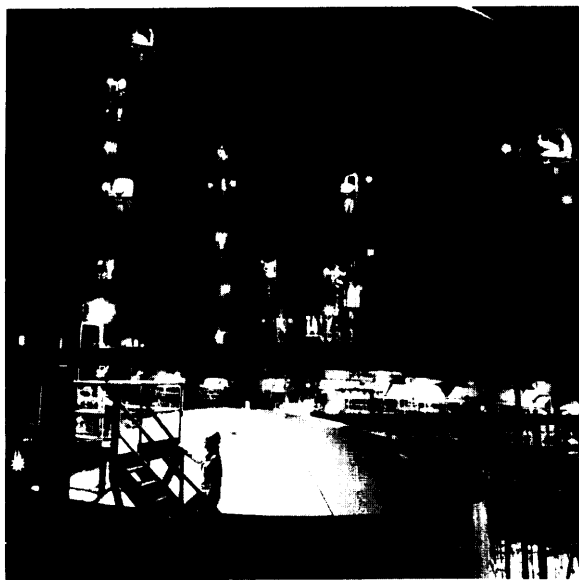
An ethylene glycol production plant. Glycol is used for making polyester fibers, photo film, and plastic bottles.

about 17 percent of processing energy. Advanced technologies embodying even more heat integration and optimization and other improvements might yield another 9 percent improvement in processing energy and similar percentage improvements in feedstock energy.

EFFICIENCY[66]

In the 1980s, the chemical industry restructured itself by closing inefficient and obsolete plants, streamlining production processes, reorganizing corporate activities, and placing more emphasis on specialty chemicals with high profit margins. As a result, the chemical industry currently uses relatively state-of-the-art technolo-

gies. There remain, however, large opportunities for new cogeneration capacity.

Pulp and Pape[67]

Paper mills process cellulose fibers, primarily from wood, into writing paper, newsprint, magazine stock, paperboard, cardboard, sanitary tissues, and various other decorative and structural papers. The wood is first ground and pulped to separate the fibers from each other and suspend them in water. Later, the pulp is filtered onto wire screens, dried, and formed into paper. Along the way, the fibers may be beaten for strength, bleached for whiteness, or sized to improve their writing characteristics. There are five principle process steps in paper production: 1) wood preparation, 2) pulping, 3) bleaching, 4) chemical recovery, and 5) papermaking.

Wood fiber is the predominant ingredient in paper. However, trees cut specifically for paper manufacture provide only slightly more than half of the fiber used. The remaining fiber is secondary material obtained by recycling used newsprint, spent packaging, and other waste paper. The waste residues of lumber operations and wood chips from saw mills provide additional material.[68]

On average, about 35 million Btu are used to produce a ton of paper (based on 1988 data).[69] The most energy-intensive steps are the papermaking, pulping, and chemical recovery steps. Widespread adoption of state-of-the-art technologies can reduce energy consumption by an estimated 29 percent (tables 3-7 and 3-8) from current

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66 Decision Analysis Corpration of Virginia, Energy Consumption Patterns in the *Manufacturing Sector,* prepared for the U.S. Department of Energy, Energy Information Adrninistration Oct. 15, 1990.

67 "Paper," *McGraw-Hill Encyclopedia on Science and Technology (New* York, NY: McGraw-Hill, 1987). "Paper," *The Academic American Encyclopedia, Online Edition* (Danbury, CT: Grolier Electronic Publishing, 1991). A. Elaahi and H.E. Lowitt, Energetic, Inc., *The U.S. Pulp and Paper Industry: An Energy Perspective,* prepared for U.S. Department of Energy, Office of Industrial Programs, Report No. DOE/RL/01830-T57 (Springfield, VA: National Technical Information Service, April 1988). Energetic, Inc., *Industry Profiles: Paper,* prepared for the U.S. Department of Energy, Office of Industrial Technologies, Report No. DE-AC01-87CE40762, December 1990.

68 Fibers can also come from nonwood sources, including: esparto grass, bagasse (the plant residue left after the juice has been extracted from sugarcane), cereal and flax straws, reeds, cotton and linen rags, waste cotton from cotton mills, and various other plant sources. The choice of materials depends on the intended end use of the paper. *The Academic American Encyclopedia, Online Edition,* ibid.

69 Energetic, Inc., Industry *Profiles: Paper,* Op. cit., footnote 67.

Table 3-7—Energy Use by Pulp and Paper Production Technologies

Process	Process mix			Measure	Energy use (million Btu/ton of product)			Product
	Current (1988)	State-of-the-art (2010)	Advanced (2010)		Current (1988)	State-of-the-art (2010)	Advanced (2010)	
Wodpreparation.	0.71	0.71	0.71	tons of wood per ton of pulp	0.5	0.4	0.4	*wood*
Pulping								
Chemical: kraft.	55.3	55.2	42.5	%pulp produced	8.3	4.9	4.4	Pulp
Chemical: sulfite.	1.8	2.1	1.4	% pulp produced	8.6	6.3	5.7	Pulp
Chemical: otherb	1.6	1.5	1.4	% pulp produced	16.0	8.8	7.9	Pulp
Semichemical: neutral sulfite. . . .	5.0	5.0	2.1	% pulp produced	9.8	7.2	6.5	Pulp
Mechanical: stone groundwood. .	2.0	2.1	—	% pulp produced	14.5	13.2	—	Pulp
Mechanical: refiner mechanical[c]. .	2.0	—	—	% pulp produced	18.6	—	—	Pulp
Ther momechanical.	2.8	5.0	5.0	% pulp produced	19.7	15.8	15.8	Pulp
Chemimechanical.	—	—	—	% pulp produced	—	14.5	—	Pulp
OPCO process.	—	—	—	% pulp produced	—	—	12.6	Pulp
Non-sulfur process.	—	—	10.6	% pulp produced	—	—	3.2	Pulp
Biological.	—	—	5.7	% pulp produced	—	—	11.4	Pulp
Alcohol.	—	—	2.1	% pulp produced	—	—	2.2	Pulp
Waste paper.	19.6	20.4	20.4	% pulp produced	4.3	4.0	4.0	Pulp
Market pulp drying.	9.9	8.7	8.7	% pulp produced	4.2	4.0	1.3	Pulp
Subtotal.	1.11	1.13	1.13	tons of pulp per ton of paper	7.9	5.5	4.9	Pulp
Bleaching.	0.3	0.3	0.3	fraction of pulp bleached	7,5	5.6	4.5	Pulp
Chemical recovery								
Kraft.	55.3	55.2	42.5	% pulp produced	10.1	6.4	4.2	Pulp
Sulfite.	1.8	2.1	1.4	% pulp produced	7.5	4.8	3.1	Pulp
Semichemical.	5.0	5.0	2.1	% pulp produced	6.0	3.8	2.5	Pulp
Subtotal.	0.62	0.62	0.46	fraction of pulp with a chemical recovery stage	9.7	6.1	4.1	Pulp
Papermaking								
Newsprint.	7.6	8.0	8.0	% paper produced	8.2	5.5	3.7	Paper
Printing and writing paper.	27.8	30.1	30.1	% paper produced	13.8	9.3	5.6	Paper
Industrial paper.	6.4	4.0	4.0	% paper produced	14,1	9.5	5.7	Paper
Tissue paper.	7.0	7.3	7.3	% paper produced	11.2	8.3	8.3	Paper
Paperboard.	37.5	37.6	37.6	% paper produced	13.6	9.2	5.5	Paper
Recycled paperboard.	11.2	11.3	11.3	% paper produced	13.6	9.2	5.5	Paper
Construction paper.	2.4	1.7	1.7	%. paper produced	12.7	8.6	5.1	Paper
Subtotal.	1.00	1.00	1.00	ton of paper	13.1	8.9	5.6	Paper
Auxiliary equipment								
Lighting, space heating, and power plant.	1.00	1.00	1.00	ton of paper	2.9	2.7	2.7	Paper
Total.	1.00	1.00	1.00	ton of paper	34.5	24.6	18.0	Paper

a Average of currently implemented technologies.

b Chemical processes for dissolving pulps and alpha pulps.

c For state-of-the-art, refiner mechanical pulping is assumed to be replaced by thermomechanical pulping with heat recovery.

NOTE: Purchased electricity is counted at 10,500 Btu/kWh; generation and transmission losses are included. Estimated losses in 1988 were approximately 4.3 million Btu per ton of paper.

SOURCES: A. Elaahi and Howard E. Lowitt, Energetic, Inc., *The* U.S. *Pulp and Paper Industry: An Energy Perspective,* prepared for the U.S. Department of Energy, Office of Industrial Programs, Report No. DOE/RL/01830-T57 (Springfield, VA: National Technical Information Service, April 1988). Energetic Inc., *Industry Profiles: Paper,* prepared for the U.S. Department of Energy, Office of Industrial Technologies, Report No. DE-AC01-87CE40762, December 1990.

Table 3-8-Major Energy Saving Features of Improved Pulp and Paper Production

Process	State-of-the-art	Advanced
Pu/ping		
Chemical	Continuous digesters for large units. (S) Displacement heating for small units. (S)	Alcohol-based solvent pulping. (S) Biological pulping in which enzymes cause designation reactions to occur at ambient temperatures. (M)
Mechanical	Thermomechanical pulping with heat recovery. (s)	Non-sulfur chemimechanical pulping. (S) OPCO pulping process (sodium sulfite-based). (s)
Bleaching	Displacement bleaching. (S) Oxygen bleaching in the first extraction stage. (M)	Biobleaching in which biological enzymes replace bleaching chemicals. (S)
Chemical recovery	Waste-heat recovery technologies in lime kiln, including: chain systems to enhance heat transfer; lime product coolers to preheat combustion air; and flash dryers to predry the lime mud. (S) Turbumix system, whereby lime mud is mixed in the gas flow to create a fully turbulent flow. (S) Tampella Recovery System. (M) Multiple-effect falling-film evaporators for black liquor evaporation and concentration. (M) Vapor recompression evaporation of black liquor. (M)	Freeze concentration of black liquor (presently not economical). (S) Black liquor gasification in a combined cycle cogeneration system. (M) Black liquor hydropyrolysis. (M) Black liquor dry pyrolysis. (M) NSP process, uses a cyclone gasifier to process solids prior to firing the pyrolysis gases in a boiler. (M)
Papermaking		
Forming	Top-wire (hybrid) formers. (M)	
Pressing	Increased water removal through: extended nip press; higher nip pressures; wider nips (longer residence time); use of steam boxes in press section; and upgrade of clothing and auxiliary equipment. (M) Hot pressing using one or more steam showers to heat water in the sheet. (M)	Displacement pressing. (M)
Drying	Reduced air heating by using enclosed hoods and countercurrent flow of air and product. (M) Infrared moisture profiling. (M)	Impulse drying. (S)
Auxiliary processes and process control	Use of boiler waste heat in bark dryers. (M)	Total mill automation and information system. (M) New sensors and expert systems.

KEY: (S) = significant savings, 50 to 100 percent of energy used in particular process; (M) = moderate savings, 25 to 50 percent of energy used in particular process.

SOURCE: A. Elaahi and Howard E. Lowitt, Energetic, Inc., The *U.S. Pulp and Paper Industry.' An Energy Perspective,* prepared for the U.S. Department of Energy, Office of Industrial Programs, Report No.DO13RU01830-T57 (Springfield, VA: National Technical Information Service, April 1988).

average practices. The potential reductions are greatest for the papermaking stage. Advanced technologies, not yet commercialized, could possibly reduce energy use an additional 27 percent.

WOOD PREPARATION

Paper production begins with wood preparation, which consists of removing the tree bark and chipping the wood into small pieces. This process requires comparatively little energy.

PULPING

Pulping breaks apart the fibers in the wood and cleans them of unwanted wood residues. The principal pulping methods use chemical techniques, mechanical techniques, or a combination of the two. Chemical pulping techniques account for 80 percent of U.S. production. Each pulping method involves tradeoffs in terms of cost, yield, and paper quality.

In chemical pulping, the wood chips or other fibrous materials are cooked in an aqueous solution at high temperature and pressure. Steam provides the heat and pressure in the cooking vessel (digester). The kraft process, the most widely used pulping technique, uses a solution of sodium hydroxide and sodium sulflde. The sulfite process uses a sodium sulfite solution. Cooking times may be as long as 12 hours. The cooked pulp is then washed to remove the chemicals and screened to separate out undigested wood knots and other unwanted materials.

Chemical processes dissolve most of the lignin (the "glue" that holds the fibers together), and much of the hermicellulose, and leave the cellulose fibers relatively undamaged. The absence of lignin and the relatively minor physical damage done to the fibers results in strong, high-quality paper that can be bleached to high brightness. However, the yield is only 40 to 60 percent of the dry weight of the wood, because the lignin and other components are removed.

In mechanical pulping, the cellulose fibers are torn apart by pressing logs against wet grindstones or by passing wood chips between counter-revolving grooved metal disks -(refiners). The lignins and other residues are not removed, so the yield may be nearly 95 percent of what was originally in the tree. However, the fibers are broken and damaged by the mechanical processes. The shorter, weaker fibers and the presence of lignin makes this pulp appropriate for less expensive grades of paper, such as newsprint.

Combining mechanical methods with chemical and/or steam treatments produces pulps of varying yields and quality. In thermomechanical pulping (TMP), wood chips are softened with steam before they are refined. This produces paper that is significantly stronger than that from mechanical pulp, but still weaker than that from chemical pulps, with only a small sacrifice in yield. In chemical thermomechanical pulping, the wood is treated with both chemicals and steam before refining. This produces a still stronger pulp. Lastly, semichemical pulping uses even more chemicals, but not enough to render the mechanical stage unnecessary.

Technologies that integrate fermentation into the conventional pulping process can offer also energy savings. They include biopulping using enzymes derived from wood rot funguses, chemial pulping with fermentation and black liquor phase separation, and ethanol organosolv pulping. Energy savings of 28 percent in the pulping process using enzymes compared with mechanical techniques have been demonstrated in Sweden.[70] Currently, pulping cycles using these techniques are too slow for commercial application. A substantial amount of research is still needed for each of these processes.

Pulping accounts for 26 percent of the energy used in pulp and paper production. State-of-the-art technologies such as continuous digesters, displacement heating, anthraquinone pulping, and increased use of thermomechanical pulping

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70 A. Elaahi and H.E. Lowitt, op. cit., footnote 67.

with heat recovery and cogeneration can reduce the energy use of this stage by about 26 percent from current average practices. Advanced technologies could possibly reduce energy use an additional 10 percent.

BLEACHING

Most pulps are relatively dark in color. Bleaching whitens the pulps for use in writing, printing, and decorative papers. Various grades of paper require different levels of treatment. Writing paper requires a full bleaching; newsprint requires only a light treatment; and corrugated cardboard generally needs no bleaching. The process must be carefully controlled so that the cellulose fibers are not weakened.

Bleaching brightens paper by altering and/or removing the lignin, which causes the dark color of pulp. Chemical pulps, which contain low concentrations of lignin, are bleached by breaking up the lignin and removing it. This is accomplished with alternating treatments of oxidizing agents (chlorine, chlorine dioxide, hypochlorite, hydrogen peroxide, and oxygen) and alkali solutions (sodium hydroxide). Sulfite pulps are generally lighter in color than kraft pulp and therefore need less bleaching. They require no bleaching at all when used in newsprint. High-yield, mechanical pulps are treated with hydrogen peroxide or sodium hydrosulfite to reduce the light absorption of lignin without dissolving it.

Bleaching uses about 7 percent of the energy used in paper production. State-of-the-art technologies such as displacement bleaching can reduce the energy use at this stage by about 30 percent from current average practices.

CHEMICAL RECOVERY

The kraft and sulfite processes use large quantities of chemicals to separate the cellulose fibers. Regenerating these chemicals for reuse is important for economic and waste disposal reasons. When the chemicals are recovered, enough energy is extracted from the wood byproducts to make many paper mills self-sustaining with respect to energy.

Chemical pulping processes produce waste streams of black liquor, which contains spent chemicals and wood residues. Black Liquor is concentrated in evaporators and then burned in boilers, many of which are connected to steam turbine cogeneration systems. The wood residues fuel the boiler and the spent process chemicals remain behind as smelt at the bottom of the boiler furnaces. This smelt is treated with lime to convert the sodium carbonate back into sodium hydroxide. The lime is then itself regenerated by being burned in lime kilns. Sodium sulfide, the other major chemical in the kraft process, is also recovered from the smelt. The relatively small quantities of chemicals lost during processing are made up by adding sodium sulfate, which is either purchased or recovered from the manufacture of bleaching chemicals.

Chemical recovery accounts for 19 percent of the energy used in paper production. State-of-the-art technologies such as waste heat recovery units and turbomix systems can reduce the energy use of this stage by 37 percent from current average practices. Advanced technologies could possibly reduce energy use an additional one-third.

PAPERMAKING

The papermaking stage consists of stock preparation (beating), sheet forming, pressing, and drying. Before the fibers are formed into sheets, they go through a mechanical pounding and squeezing process called beating to make them more flexible, thereby increasing their matting, or felting, capacity. Pigments or dyes are added to the pulp at the beating stage, along with filler materials that help preserve the paper or give it a better opacity and finish. Sizing materials may be added to improve the "feel" and printability of paper.

Once prepared, the pulp is formed into paper sheets. The fibers are deposited in a sheet on a screen, drained and pressed to remove the bulk of the water, and then dried. The two most common papermaking machines in current use are the

Fourdrinier and the cylinder machine. Both are continuous processes. In the Fourdrinier, the pulp-and-water mixture is dispersed at a controlled rate through a headbox onto a moving wire-mesh screen. As the screen moves away from the headbox, various suction devices drain the water from the pulp, leaving a sheet of matted pulp that still contains a high proportion of water. The sheet then moves on to a woolen felt screen, which takes it through a series of presses, where more water is removed. Finally, the sheet passes over a number of heated drums that evaporate the remaining water. Many new papermaking machines incorporate two moving wire-mesh screens between which the pulp is pumped, and water is extracted from both sides. The ''twin-wire' machine produces a paper that is practically identical on both sides, an important property for printing papers.

The cylinder machine differs from the Fourdrinier principally in the "wet end, " or forming operation. Instead of the moving wire screen, a screen-covered rotary cylinder is half-submerged in the pulp vat. As the cylinder rotates, a sheet of matted pulp is formed on its exterior surface and then picked up by a moving belt, where it is treated to remove the remaining water, as in the Fourdrinier process. A series of cylinders maybe used, each one depositing an additional layer of pulp on the belt, so that multilayer sheets are built up to make thick papers and paperboard.

Upon leaving the paper-forming machine, the dried paper is wound onto large reels, slit to the required widths, cut into sheets, trimmed, and then packaged. In some cases, the paper is calendared or coated. It may also be converted into bags, boxes, corrugated shipping paper, and other products.

Papermaking is the largest energy consuming process of the mill. It accounts for 38 percent of the energy used in paper production. The most energy-intensive activities are drying (65 percent of papermaking energy use) and stock preparation (30 percent).

Energy Use (million Btu per ton of paper)

|	Current average	State-of-the-art
Stock preparation.	3,4	2.8
Sheet formation.	0.3	0.1
Pressing.	0.3	0.3
Drying.	7.4	4.4

State-of-the-art technologies such as top-wire formers and improved mechanical and thermal water removal techniques can reduce the energy use of this stage by about 32 percent. Improved presses (e.g., the extended nip press), used to squeeze the water out of the paper before drying, reduce energy use and also improve fiber-to-fiber bonding, resulting in higher strength and higher quality sheet. Advanced technologies, such as impulse drying, could possibly reduce energy use an additional 27 percent.

WASTE STREAM ENERGY

There is a great amount of energy embedded in the waste products of the paper industry. Wood wastes and residues supply the heat and electricity required for pulping, bleaching, drying, and evaporating the spent black liquor. If the harvesting waste and the bark are also burned to produce energy, and if water is conserved by countercurrent washing of the pulp, a bleached kraft pulp mill can be self-sufficient in energy .71

The typical pulp and paper operation has three principal waste streams that can provide energy: hog fuel, black liquor, and forest residues. Hog fuel is the bark, sawdust, and other scrap produced in reducing logs to feedstock for the pulping process. Hog fuels can supply about 2.6 million Btu/ton of pulp produced. Black liquor, from the chemical pulping process, an average energy content of about 11.2 million Btu/ton of pulp. Other residues are currently left in the forest when harvesting the trees. A portion of these

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71 "Paper," *McGraw-Hill Encyclopedia on Science and Technology,* op. cit., footnote 67.
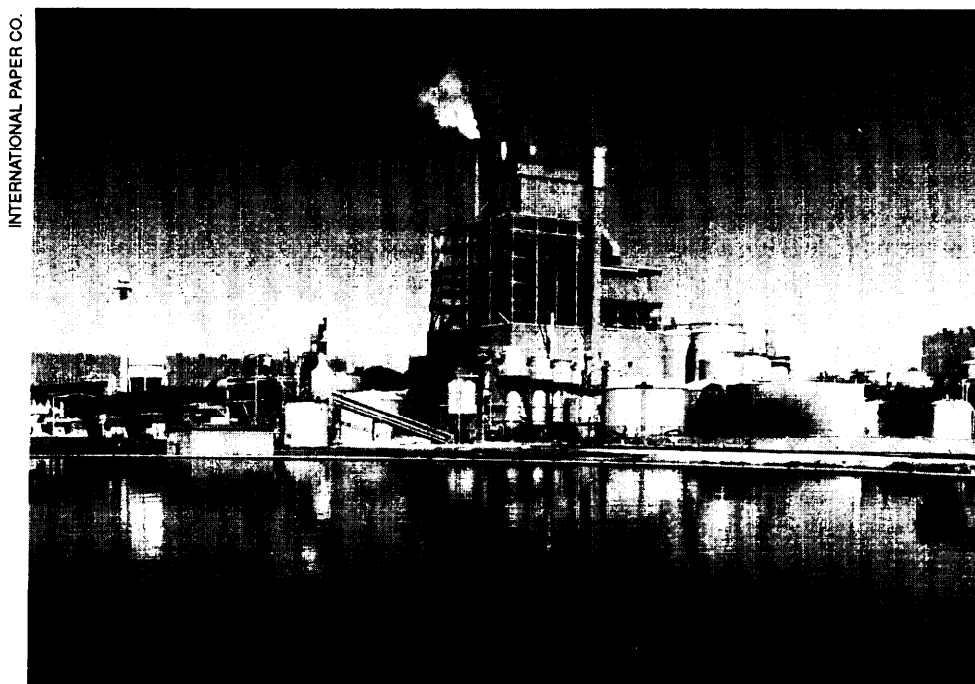
A recovery boiler at a pulp and paper mill. Such a boiler can meet a significant portion of a mill's energy needs by burning waste from the pulping process.

forest residues might be collected. However, the technical, economic, and environmental difficulties in using forest residues are significant. For example, the long term effects on forest soils would need to be examined closely. If fully recovered, the estimated energy content of forest residues would be about 21.5 million Btu/ton of pulp. Combined, these energy resources could provide 35.3 million Btu/ton of pulp.[72]

Most kraft pulp mills currently use their black liquor for cogenerating steam and electricity onsite. High-efficiency, steam-injected gas turbine or combined cycle technologies might be able to generate as much as 4,000 kwh of electricity per ton of pulp produced if all of the hog fuel, black liquor, and recoverable forest residues were used. Onsite electricity needs are typically about 740 kWh/ton of paper, so there would be a substantial amount of power that could be sold to the grid.

RECYCLING

Waste paper recycling is growing and may be a source of further energy savings. According to the Environmental Protection Agency (EPA), paper and paperboard recycling totaled 18.4 million tons in 1988, a recovery rate of 25.6 percent. This compares to a recovery rate of 16.7 percent in 1970.[73]

Recycling reduces the energy used in the paper production process and also in the harvesting and transport of the timber. However, these energy savings are offset somewhat by the energy needed to collect, transport, and de-ink the waste paper.

[72] Eric D. Larson, ''Prospects for Biomass-Gasifier Gas Turbine Cogeneration in the Forest Products Industry: A Scoping Study, ' Princeton University, Center for Energy and Environmental Studies Working Paper No. 113.

[73] U.S. Environmental Protection Agency, *Characterization of Municipal Solid Wrote in the United States: 1990 Update*, EPA/530-SW-90-042, June 1990, pp. ES-7, 11.

Table 3-9—Estimated Energy Used To Produce Virgin and Recycled Paper and Paperboard Products
(million Btu/ton produced)

Product	From 100% virgin wood Energy use	From mixed recycled paper Minimum virgin fiber content (percentage)	Energy use	Change due to recycling (percentage)
Paper products				
Newsprint. 44.33	0	34.76	-21.6
Printing paper. 67.72	16	43.43	-35.9
Packaging paper. 47.07	70	43.48	-7.6
Tissue paper. 68.52	0	29.46	-57.0
Paperboard products				
Liner board. 14.46	75	*36.28*	+1 50.9
Corrugated board. 37.22	0	*36.28*	-2.5
Box board. 25.97	0	*36.25*	+39.6
Food service board. 29.19	100	NA	—
Other paper board. 17.65	0	36.32	+1 05.8
Construction board. , ... 31.71	*65*	32.24	+1.7

SOURCE: T. Gunn and B. Hannon, "'Energy Conservation and Recycling in the Paper Industry," *Resources and Energy 5:243-260, 1983.*

Estimates of energy used to produce paper and paperboard products from virgin wood and recycled paper are shown in table 3-9. Paper and paperboard mills are the major consumers of secondary fiber.

MATERIALS PRODUCTION

■ Steel

Steel products are produced from iron ore and iron scrap using a variety of pyrometallurgical, electrolytic, and mechanical processes. Integrated mills rely mostly on ore-based processes, the most common of which involves reducing pelletized iron ore into pig iron using coke (in a blast furnace); refining the iron into steel (in a basic oxygen furnace); and casting, forming, and treating the steel into sheet, bars, beams, and other products. The major steps are: ore preparation, cokemaking, ironmaking, steelmaking, primary casting, secondary finishing, and heat treating. Minimills usually produce steel from scrap, not iron, in an electric arc furnace. This method is also employed at some integrated mills. The process does not include ore preparation, cokemaking, and ironmaking, but does involve many of the same casting and forming steps. Over the last several decades, scrap-based steelmaking capacity has grown relative to ore-based capacity. However, in recent years, the U.S. industry's production has been relatively stable at 63 percent ore-based and 37 percent scrap-based.

The most energy-intensive steps are ironmaking and electric steelmaking. Reductions in energy intensity can result from shifts in the mix of processes, improvements in the efficiency of the processes, and improvements in yields. Currently, about 22 million Btu are used on average to produce a ton of finished steel (based on 1990 and 1991 data) .74 Energetic and the International

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[74] The U.S. steel industry used **27.4** million tons of metallurgical coal (733 trillion Btu), 1.3 million tons Of steam coal (28 trillion Btu), 5.2 million tons of purchased coke (127 trillion Btu), 35.2 billion kWh of electricity (370 trillion Btu based on a conversion factor of 10,500 Btu/kWh), 244 million gallons of fuel oil (35 trillion Btu), and 368 billion cubic feet of natural gas (380 trillion Btu) to produce 78.9 million tons of steel products in 1991. The technology mix was 60.0 percent basic oxygen furnace (BOF), 38.4 percent electric arc furnace (EAF), and the remainder open hearth furnace (OH). The American Iron and Steel Institute, *Annual Statistical Report,* (Washington, DC: 1991).

Iron and Steel Institute (IISI) have estimated the energy intensity of state-of-the-art operations for the major production methods:

Energy intensity (million Btu per ton of finished steel)	Energetics75 estimate	IISI76 estimate
Basic oxygen furnace method (BOF)	16.1	19.077
Electric arc furnace method (EAF)	10.2	8.0
Average based on a 60:40 ratio of BOF and EAF production	13.8	14.6

Details of the Energetic estimates are shown in tables 3-10 and 3-11. Widespread adoption of state-of-the-art technologies can reduce energy consumption by about 34 to 38 percent from current average practices. Advanced technologies, not yet commercialized, could possibly reduce energy use an additional 13 percent.

ORE PREPARATION

Iron ore is prepared by being crushed and ground and then agglomerated (via pelletizing or sintering) into marble sized pieces that can be fed into a blast furnace. Ore preparation uses about 0.7 million Btu/ton of pellets or sinter produced. Use of state-of-the-art technologies, such as organic or cold bonding for pelletizing, can reduce energy use by about 18 percent from current average practices. If direct ironmaking and/or steelmaking, which are advanced technologies, become commercially available, the pelletizing and sintering operation may possibly not be needed.

COKEMAKING

Coke is produced by heating high-grade (metallurgical) coal to temperatures of 1,650 to 2,0000F for 12 to 18 hours. This boils off volatile compounds and leaves an 80 to 90 percent pure carbon product. Traditionally the chemical reactions in the coke ovens were stopped by quenching the coke with water and venting the steam into the atmosphere. A much more efficient technique is dry coke quenching, in which a nonoxidizing gas is circulated through the ovens to stop the chemical reactions and, at the same time, capture the heat from the coke to generate steam or electric power. This process also improves coke quality and reduces environmental emissions.[78]

The efficiency of converting coal to coke has improved substantially in recent years. The average amount of energy used to produce a ton of coke declined from 6.1 million Btu in 1980 to 3.5 million Btu by 1989.[79] State-of-the-art technologies, such as dry quenching and oven-gas heat recovery can lower this by about 14 percent. If direct ironmaking and/or steelmaking are commercialized, the coking operation will no longer be needed.

The high costs of environmental compliance have made coke ovens expensive to operate. The Clean Air Act of 1990 may force the closure of many U.S. coke facilities. In the short term, this will probably lead to greater importation of coke and more scrap-based steelmaking. In the longer term, coke may be rendered unnecessary by direct ironmaking and/or direct steelmaking. Indeed, the costs and environmental problems of cokemaking are a major force behind the efforts to develop direct ironmaking and steelmaking technologies.

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75 Energetics, Inc., *Industry Profiles: Steel*, prepared for the U.S. Department of Energy, Office of Industrial Technologies, Report No. DE-AC01-87CIM0762, December 1990.

76 International Iron and Steel Institute, *Energy and the Steel Industry, Brussels*, 1982.

77 This is Case A, commercially proven technologies, rather than the IISI base case.

78 Jonathan p, Hicks, "The Search for a Cleaner Way to Make Steel, ' *The New York Times, Mar. 21, 1990*, p. D7.

79 Energetic, Inc., In&m-y *profiles: Steel*, op. cit., footnote 75.

Table 3-10--Energy Use by Steel Production Technologies

Process	Process mix Current (1989)	State-of-the-art (2010)	Advanced (2010)	Tons input per ton output or percent	Energy use Current (1983)	State-of-the-art (2010)	Advanced (2010)	Product
Agglomeration								
Pelletizing	1.11	1.11	1.11	Pellets/pig iron	0.4	0.2	0.2	Pellets
Sintering	0.38	0.38	0.38	Sinter/pig iron	1.5	1.2	1.2	Sinter
Cokemaking	0.54	0.54	0.54	Coke/pig iron	6.0	3.0	3.0	
Ironmaking	0.85	0.85	0,85	Pig iron/BOF steel	13.9	10,2	10.2	iron
	0.66	—	—	Pig iron/OH steel	13.9	—	—	Iron
Steelmaking								
Basic oxygen furnace (BOF)	59.6	62.0	31.0	percent	0.5	-0.1	-0.1	BOF steel
Open hearth (OH)	4.5	—	—	percent	3.3	—	—	OH steel
Electric arc furnace (EAF)	35.9	38.0	38.0	percent	6.3	5.0	5.0	EAF steel
Direct steelmaking	—	—	31.0	percent	—	·	9.9	Direct steel
Raw steel production, subtotal								
Ore/coke/iron/BOF route	—	—	—	—	15.9	10.5	10.5	BOF steel
Ore/coke/iron/OH route	—	—	—	—	15.2	—	—	OH steel
Scrap/electric furnace route	—	—	—	—	6.3	5.0	5.0	EAF steel
Direct steelmaking route	—	—	—	—	—	—	9.9	Direct steel
Average	1.00	1.00	1.00	Ton of raw steel	12.4	8.4	8.2	Raw steel
Primary casting								
ingot casting	35.1	5.0	5.0	percent	2.7	0.7	0.7	Cast steel
Continuous casting	64.8	95.0	27.0	percent	1.0	0.2	0.2	Cast steel
Strip casting		—	68.0	percent	—	·	b	Cast steel
Average	0.91	0.94	0.94	Cast steel/raw steel	1.6	0.3	0.1	Cast steel
Forming, finishing, heat treating, and annealing								
Sheet/strip: hot rolled	21.1	21.1	—	percent	2.5	1.5	—	Finished steel
Sheet/strip: cold roiled	37.9	37.9	—	percent	6.2	3.8	—	Finished steel
Heavy plate	9.0	9.0	—	percent	3.2	2.4	—	Finished steel
Sheet/strip: hot rolled (strip cast)	—	—	21.1	percent	—	—	0.7	Finished steel
Sheet/strip: cold rolled (strip cast)	—	—	37.9	percent	—	—	1.6	Finished steel
Heavy plate (strip cast)	—	—	9.0	percent	—	—	1.0	finished steel
Shapes and rails	6.7	6.7	6.7	percent	4.4	1.9	1.9	Finished steel
Bars/wire rods	25.3	25.3	25.3	percent	5.0	2.7	2.7	Finished steel
Average	0.91	0.94	0.94	Finished steel/raw steel	4.7	2.8	1.7	Finished steel
Unallocated energyc	—	—	—		1.9	1,8	1.6	Raw steel
Total	—	—	—		20.1	13.1	11.5	Raw steel
					22.2	13.9	12.2	Finished steel

a Average of currently implemented technologies.
b All energy use for direct strip is charged. appropriate forming and finishing processes; hot and cold rolled sheet/strip and heavy plate.

ᶜIncludes galvanizing, electrolytic tinning, fuel-fired boiler operations, power generation services, and other miscellaneous services.

KEY: BOF ▬ basic oxygen furnace; OH - open hearth furnace; EAF ▬ electric arc furnace.

NOTE: Purchased electricity is counted at 10,500 Btu/kWh; generation and transmission losses are included. Estimated losses in 1989 were approximately 3.0 million Btu/ton of raw steel.

SOURCES: Sayed A. Azimi and Howard E. Lowitt, Energetic, Inc., *The U.S. Steel Industry: An Energy Perspective,* prepared for the U.S. Department of Energy, Office of Industrial Programs, Report No. DOE/RL/01830-T55 (Springfield, VA: National Technical Information Service, January 1988). Energetic Inc., *Industry Profiles: Steel,* prepared for the U.S. Department of Energy, Office of Industrial Technologies, Report No. DE-AC01-87CE40762, December 1990. F.T. Sparrow, Argonne National Laboratory, *Energy and Materials Flows in the Iron and Steel Industry,* Report No. ANL/CNSV-41 (Springfield, VA: National Technical Information Service, June 1983). J.B.Darby, Jr. and R.M.Arons, Argonne National Laboratory, *Energy and Materials Flows in the Fabrication of Iron and Steel Semifinished Products,* Report No. ANL/CNSV-8 (Springfield, VA: National Technical Information Service, August 1979). Some data modified by the office of Technology Assessment.

Table 3-1 I—Major Energy Saving Features of Improved Steel Production

Process	State-of-the-art	Advanced
Agglomeration		Stage discontinued, made obsolete by direct steelmaking.
Pellitizing	Peridur organic bonding process. (S) Cold bonding processes. (S)	
Sintering	Combustion air preheat. (M) Raw materials preheat. (M) Steam or power generation using sinter cooler offgases. (M)	
Cokemaking	Dry quenching. (S) Coke oven gas heat recovery. (S)	Stage discontinued, made obsolete by direct steelmaking.
Ironmaking		Stage discontinued, made obsolete by direct steelmaking.
Blast furnace	Top gas pressure recovery. (S) Hot stove waste heat recovery. (M) Wurth charging top; improves distribution of ore, coke, and limestone.	
External desulfurization	Added process between the blast furnace and the steelmaking stage. Decreases coke consumption by reducing the sulfur removal function of the blast furnace. (S)	
Steelmaking		
Open hearth (OH)	Discontinued use of open hearth steel furnace.	
Basic oxygen furnace (BOF)	In-process control of temperature and carbon content. (S) BOF offgas heat recovery. (M) Combined top and bottom oxygen blowing. (M)	Replacement of BOF steelmaking with direct steelmaking.
Electric arc furnace (EAF)	Scrap preheating. (S) Ultra high power transformers. (M) Bottom tap furnaces. (M) Water cooled furnace panels and top. (M)	
Secondary refining	Ladle metallurgy techniques, including: vacuum arc decarburization, argon stirring, and injection systems for desulfurization. (s) Specialty and stainless steel processes, including: electroslag remelting, argon-oxygen decarburization, vacuum induction melting, electron beam melting, and vacuum arc remelting. (S)	
Auxiliary processes	Ladle drying and preheating. (S)	

Primary casting	**Greater use of continuous casting.**	**Replacement of continuous casting by direct thin strip casting for hot and cold rolled sheet/strip and heavy plate products; combines primary casting and finishing and. forming stages.**
Continuous casting	**Modern casters. (S)** **Slab heat recovery. (S)**	
Ingot casting	**Soaking pit utilization and pit vacant time. (M)**	
Forming and finishing		
Reheating	**Direct roiling of sheet/strip; eliminates need for reheat furnace. (S)** **Reheat furnace waste heat recovery. (S)** **Reheat furnace insulation improvements. (M)** **Hot charging of products into reheat furnace. (M)**	**Replacement of continuous casting by direct thin strip casting for hot and cold rolled sheet/strip and heavy plate products; combines primary casting and finishing and forming stages.**
Pickling	**Insulated floats for steam savings. (M)**	
Annealing	**Continuous annealing. (S)** **Batch annealing air preheat. (M)**	
Cold rolling	**Continuous cold rolling. (S)**	
General	**Computerized** process control. **Increased combustion efficiency.** **(5 percent improvement over current practice).**	**Computerized process control.** **Increased combustion efficiency.** **(15 percent improvement over current practice).**

KEY: (S) = significant savings, impact on total operation greater than 200,000 Btu/ton; (M) = moderate savings, impact on total operation less than 200,000 Btu/ton.

SOURCE: SayedA. Azimi and Howard E. Lowitt, Energetic, Inc., *The U.S. Steel Industry:An Energy Perspective,* **prepared for the U.S. Department of Energy, Office of Industrial Programs, Report No. DOE/RI/O1830-T55 (Springfield, VA: National Technical Information Service, January 1988).**

IRONMAKING

Blast furnaces are the most common technology used to convert iron ore into iron.[80] Pelletized or sintered ore are fed into the top of the blast furnace together with coke and limestone and/or dolomite. Heated air (sometimes combined with natural gas or fuel oil) is blown into the blast furnace from the bottom. The burning coke heats, chemically reduces, and melts the iron ore.[81] The limestone and dolomite combines with impurities in the iron to form a slag that is removed at the end of the process. The pig iron produced by blast furnaces varies in composition depending on the ore and coke used, but typically consists of iron (92 percent), carbon (4 percent), manganese (2

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[80] An alternative technique is the direct reduction of iron ore to metallic iron using natural gas. Direct reduced iron (DRI), also called sponge iron, is suitable for steelmaking using electric arc furnaces. This technology is used extensively in areas such as Venezuela, Mexico, and Indonesia, where natural gas is abundant and inexpensive, but is relatively rare in the United States.

[81] The coke serves three purposes in the ironmaking stage: as a reducing agent to convert the ore (iron oxide) into pig iron; as fuel to heat and melt the ore/iron; and to physically support the ore within the blast furnace. To meet these needs, coke must have a low impurity and ash content and be physically strong. Coke is produced from a higher grade coal than is used for steam and electricity generation applications.

percent), silicon (1 percent), and small amounts of other elements.

Ironmaking currently uses on average about 13.9 million Btu/ton of iron ore produced. It accounts for about half of the energy used in an average integrated mill, using the basic oxygen steelmaking process. State-of-the-art technologies such as top gas pressure recovery and external desulfurization can reduce the energy use of this stage by 27 percent from current average practices. Top gas pressure recovery turbines can be used to generate 8 to 15 MW of power using the pressure and heat from the blast furnace. External desulfurization of pig iron is an added process between the blast furnace and the steelmaking stage. It lowers coke consumption by decreasing coke's role in removing sulfur from the melt in the blast furnace. If direct steelmaking is commercialized, the ironmaking operation will no longer be needed.

There are several direct ironmaking technologies under development that could decrease energy consumption at this stage. One of the primary goals of these development efforts is to produce iron with coal, rather than with coke.[82] By eliminating the coke ovens and agglomeration facilities, mills based on these new technologies would have substantially lower capital costs than similarly-sized conventional plants. The U.S. Department of Energy, as part of its Metals Initiative, is conducting research into an advanced ironmaking technology that has such benefits, plus it is tailored to domestic taconite (iron ore) supplies. Among the new ironmaking technologies are the plasmared, Korf Reduction, plasmasmelt, inred, and elred processes. Energy requirements for these systems range from about 11.4 million Btu/ton of hot metal for three-stage systems to as much as 25.8 million Btu/ton for single-stage systems. The low end of these energy requirements is about 10-percent better than what typical conventional blast furnaces achieve and about 5 percent better than what the best cost effective blast furnace technology available today achieves. The high end of the direct ironmaking energy requirements is however, much higher than conventional best practice technologies achieve today .[83] The potential capital savings and other advantages may push direct coal-based processes into a dominant role in the steel industry of the future.

STEELMAKING

Steelmaking refines the pig iron, scrap, or, in some cases, direct reduced iron (DRI). The purpose of the process is to remove most of the impurities such as carbon, phosphorus, sulfur, and silicon from the melt, and to add the necessary alloying elements such as manganese, molybdenum, chromium, and nickel.

Two types of furnaces are commonly used to produce steel: the basic oxygen furnace (BOF) and the electric arc furnace (EAF).[84] Basic oxygen furnaces are used in plants that produce finished steel from iron ore. The iron is refined into steel by blowing oxygen into the furnace. The oxygen reacts with the carbon in the iron melt to produce carbon monoxide. The evolving gas removes carbon from the melt and vigorously boils the melt to accelerate other refining reactions. The oxygen also reacts with silicon and various other elements in the melt to form a slag, which is later separated from the steel.

The carbon-oxygen reaction is exothermic (produces heat) and theoretically needs no external energy to run. To absorb excess heat produced by the reaction, about 30 percent of the iron charge to a BOF is scrap, which contains little

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[82] U.S. Congress, Office of Technology Assessment, *Fueling Development: Energy Technologies for Developing Countries,* op. cit., footnote 12.

[83] R.B. Smith and M.J. Corbett, ''Coal-Based Ironmaking,'' *Ironmaking and Steelmaking, vol. 14, No. 2, 1987,* pp. 49-75.

[84] A third technology, the open hearth furnace, was made obsolete by the basic oxygen furnace. The last open hearth facility in the United States was closed in 1991.

carbon to react with oxygen. In practice, BOFs consume 0.5 million Btu/ton of raw steel produced. State-of-the-art BOFs equipped with in-process control of temperature and carbon content, offgas heat recovery, and combined top and bottom blowing generate about 0.1 million Btu of excess energy for each ton of raw steel produced.

Electric arc furnaces are used primarily to refine recycled steel scrap and to a lesser extent, DRI. EAF-based processes are economic at smaller scales than integrated processes using basic oxygen furnaces, and are thus less capital-intensive. They are also less energy-intensive (if the energy embodied in scrap is not included). All minimills use EAFs, and some integrated producers augment their processes with EAFs. Until recently, minimills were limited in the set of products that they were capable of producing. Now, with control of residual elements and use of thin slab casting, minimills can produce nearly all the products available from integrated mills.

EAFs use 6.3 million Btu, on average, to in the produce of a ton of steel. State-of-the-art technologies such as scrap preheating, ultrahigh power (UHP) transformers, bottom tap furnaces, and water-cooled furnace panels and tops can reduce energy use by 20 percent from current average practices. The scrap would be preheated with waste heat from the furnace. UHP transformers would give furnaces shorter cycle times and correspondingly better productivity, thus reducing energy use because of the shorter period at high temperature.[85]

Secondary refining processes such as ladle refining are important auxiliaries to steelmaking furnaces. By carrying out part of the refining in vessels other than the furnace, these processes increase the productivity of the furnace and shorten the period each ton of steel spends at the very high temperatures.

Efforts are underway to develop an advanced direct steelmaking process. Direct steelmaking would replace the coke oven and blast furnace steps with one continuous process. Another advantage is that direct steelmaking can either use iron ore or scrap. The key to the success of this process is effectively transferring heat from postcombustion to the bath. The Oak Ridge National Laboratory (ORNL) estimates that direct steelmaking can reduce energy use by 20 to 30 percent and achieve production rates that are two to three times higher than those of a blast furnace.[86]

Another advanced technology that is under development is the ore-to-powder steelmaking process, which eliminates the ore melting process with magnetic separation and chemical leaching. ORNL estimates that this method may reduce energy use by 40 percent and also decrease capital costs. The need for highly-refined magnetic separation may be a technical barrier to using this method.[87]

After the steelmaking step, the ore-based and scrap-based production routes converge, so this is an appropriate juncture to compare the energy intensities of these two basic production methods. Up through the steelmaking stage, the ore-coke-blast furnace-BOF route uses on average 15.9 million Btu/ton of raw steel. The scrap-EAF route uses on average 6.3 million Btu/ton, 60 percent less than the ore-based method. About 60 percent of U.S. steel is produced in BOFs and 36 percent is produced in EAFs (1989), resulting in an average of 12.4 million Btu of energy for each ton of raw steel produced (up through the steelmaking stage). State-of-the-art technologies are estimated to be capable of using 10.5 million Btu/ton of raw

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[85] Sven Eketorpe, ''Electrotechnologies and Steelma.king,'' Thomas B. Johansson, Birgit Bodlund, and Robert H. Williams (eds.), *Electricity: Efficient End-Use and New Generation Technologies and Their Planning Implications* (Lund, Sweden: Lund University Press, 1989), pp. 261-296.

[86] Oak Ridge National Laboratory, Energy *Technology R&D: What Could Make a Difference?* op. cit., footnote 40.

[87] Ibid.

A slab being torch cut after emerging from a continuous slab caster.

steel in the ore-coke-blast furnace-BOF route and 5.0 million Btu/ton of raw steel in the scrap-EAF route. The estimate for an advanced direct steel-making process is 9.9 million Btu/ton. Direct steelmaking may hold many cost and environ-mental advantages, but the energy consumption advantages (compared with state-of-the-art con-ventional steelmaking processes) are not large.

PRIMARY FINISHING

Primary finishing includes the casting and initial rolling of steel into slabs (for flat sheets) and blooms and billets (for structural shapes and bars). Ingot casting involves pouring the liquid

steel into molds to form ingots, which are later stripped, reheated, and rolled. Continuous casting pours the liquid steel directly into its semifinished shape.

Continuous casting eliminates the need for the stripper, reheating (soaking pit), and primary rolling mill associated with ingot casting. Contin-uous casting reduces energy use by about 50 percent, as compared with ingot casting. Also, continuous casting has a greater yield (95 percent) than ingot casting (82 percent), so less scrap metal must be returned to the steelmaking process in the form of waste and unfilled ingot molds. In addition, the product is often higher quality, and there are reduced emissions problems.[88] Because of these advantages, continuous casting has rapidly come to dominate the steel industry. In 1980, 20 percent of steel was continuously cast, and in 1989, 65 percent was cast this way.

A major breakthough in continuous casting, called thin slab casting, has been recently com-mercialized at the NUCOR, Inc. plant in Craw-fordsville, Indiana.89 This innovative process has the potential to reduce energy use and production time considerably. For example, producing one-tenth of an inch thick slabs can be done in only 3 hours with a thin slab caster, but may take as long as a week with conventional procedures. Thin slab casting is enabling minimills to Compete with integrated mills for the first time in the high-value sheet and strip product lines. The process could be used in integrated mills and minimills throughout the industry.

There are other advanced casting technologies (at various stages of development) that offer even greater potential capital and energy savings, and productivity improvements. These include: thin strip casting, net shape casting, and spray steel.

Primary finishing uses on average about 1.6 million Btu/ton of finished steel cast. State-of-the-

88 Sayed A. Azimi and Howard E. Lowitt, Energetic, Inc., *The U.S. Steel Industry: An Energy Perspective,* prepared for the U.S. Department of Energy, Office of Industrial Programs, Report No. DOE/RL/01830-T55 (Springfield, VA: National Technical Information Service, January 1988).

89 Jonathan p. Hicks, "Making Steel Faster and Cheaper, *The New York Times,* Business Technology, Feb. 27, 1991, pp. D-6 and 7.

art modern casters with slab heat recovery can reduce the energy use of this stage by an estimated 80 percent from current average practices.

FORMING AND HEAT TREATING

Forming, or secondary finishing, operations transform the steel slabs, blooms, and billets into their final shapes. Depending on the product, the process may involve, reheating, hot rolling, pickling, annealing, and cold rolling. Many of the forming operations are very electricity-intensive. Hot rolling, cold reduction, and finishing operations each consume about 125 kWh/ton. Hot rolling thin cast strip to cold-rolled gages in an inert atmosphere could eliminate a series of scale removal, cleaning, and annealing steps and ultimately save 50 to 100 kWh/ton.[90] State-of-the-art technologies include direct rolling of sheet and strip, which eliminates need for reheat furnace, reheat furnace waste heat recovery, and continuous cold rolling.

After forming, the steel is reheated and then allowed to cool slowIy in order to relieve the stresses built up within the steel by the rolling processes, This improves the strength and ductility of the final product. Heat treatment has experienced considerable efficiency gains in recent years. In the United States, energy consumption of heating and annealing furnaces dropped by nearly one-third between 1980 and 1989.[91]

Aluminum[92]

Aluminum is the second most widely used metal after steel. Its light weight, corrosion resistance, ease of recycling, and high electrical and thermal conductivity make it useful in a variety of applications in the container, packaging, transportation, building, and construction markets.

Aluminum can be recovered from many minerals (e.g., clays, anorthosite, nepheline syenite, and alunite), but is produced most economically from bauxite, an impure form of alumina (Al_2O_3). To extract the aluminum, the bauxite ore is refined into alumina and then smelted into aluminum.

Electric power accounts for about 26 percent of the aluminum industry's production costs, other energy sources account for an additional 1 percent (based on 1990 data) .[93] As a consequence, aluminum production capacity is located in areas of abundant, inexpensive electricity. In the United States, smelter capacity is located roughly one-third in the Pacific Northwest, one-third in the Ohio Valley, and the rest in the Carolinas, New York, and Texas. Because of rising electricity prices, very little aluminum smelting capacity has been built in the United States in the recent past and none is expected to be built in the future .[94] Most new capacity, is being located in Australia, Canada, Brazil, and Venezuela.

ALUMINA REFINING: BAYER PROCESS

The Bayer refining process produces pure alumina from bauxite. The bauxite is crushed and ground, then digested in hot (280 to 450F) caustic soda (NaOH) solution. The alumina minerals in the ore react with the caustic soda and dissolve as sodium-aluminate. Most of the impu-

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90 Electric *power* Research Institute, *power Utilization in Flat Processing of* Steel, Report No. *EM-5996* (Palo Alto, CA: Electric Power Research Institute, January 1989).

91 Energetics, Inc., *Industry Profiles: Steel*, op. cit., footnote 75.

92 U.S. Congress, office of Technology Assessment, *Nonferrous Metals: Industry Structure,* OTA-BP-E-62 (Washington, DC: U.S. Government Printing Office, September 1990), ''Aluminum,'' *McGraw-Hill Encyclopedia on Science and Technology (New York,* NY: McGraw-Hill, 1987). Energetic, Inc., Industry *Profiles: Aluminum,* prepared for the U.S. Department of Energy, Office of Industrial Technologies, Report No. DE-AC01-87CE40762, December 1990.

93 U.S. Department of Commerce, Bureau of the Census, 1990 *Annual Survey of Manufactures: Statistics for Industry Groups and Industries,* op. cit., footnote *24.*

94 During *the 1980s, 10* aluminum smelters closed and capacity declined by 16 percent. The last new smelter in the United States opened in 1980.

Table 3-12—Energy Use by Aluminum Production Technologies

| | Energy use (mIllIon Btu/ton of aluminum) | | |
| | Current | State-of-the-art | Advanced |
Process	(1980)	(2010)	(2010)
Alumina refining: Bayer process.	**35.5**	**27.0**	**27.0**
Aluminum smelting: Hall-Heroult process			
Electrolysis (kWh per lb of aluminum).	**49.5 (7.3)**	**42.3 (6.2)**	
Fume recycling and other electricity..	3.4 (0.5)	2.7 (0.4)	
Anode production: heat and energy. 5.4		3.3	
Anode production: raw materials.	14.6	12,5	
Fluoride prduction. . . . ., . . 2.0		0.4	
Subtotal.	74.9	61.2	49.0b
Ho/ding, casting, melting, alloying, and scrap remelting. 9.5		9.5	9.5
*Total **end use energy***			
Based on domestic alumina refining. 119.8		97.7	85.4
Based on imported alumina.	84.3	70.7	58.4
Electricity tosses c	75.6	64.2	51.7
Total ~. 177.7		148.4	123.6

a Average of currently implemented technologies.
b Based on estimated 20 percent improvement in smelting energy efficiency.
c Assumes that 65 percent of electricity is produced from thermal sources (68 percent losses) and 35 percent is produced from hydro sources (1 O percent losses).
d Assumes that half of the alumina is refined domestically and half is imported.

NOTE: Purchased electricty is counted at 10,500 Btu/kWh; generation and transmission losses are included.

SOURCES: S.Y. Shen, Argonne National Laboratory, *Energy and Materials Flows in the Production of Primary Aluminum,* Report No. ANL/CNSV-21 (Springfield, VA: National Technical Information Service, October 1981).R.M. Arons and A.M. Wolsky, Argonne National Laboratory, *Energy and Materials Flows in the fabrication of Aluminum Products,* Report No. ANL/CNSV-3 (Springfield, VA: National Technical Information Service, August 1978). Energetic Inc., *industry Profiles: Aluminum,* prepared for the U.S. Department of Energy, Office of Industrial Technologies, Report No. DE-AC01-87CE40762, December 1990.

rities in the ore precipitate out as ''red mud, ' which is removed by countercurrent recantation and filtration. The solution is then seeded with starter crystals and agitated to crystallize out alumina hydrate. This material is then calcined in kilns (to remove the water) and the result is pure alumina.

Alumina refining accounts on average for about 27 percent of the energy used in aluminum production (based on 1980 data). State-of-the-art technologies can reduce energy use in alumina production by 24 percent (tables 3-12 and 3-13). However, these savings do not apply to all aluminum production, because about half of U.S. alumina supplies are imported instead of refined domestically.

ALUMINUM SMELTING: HALL-HEROULT PROCESS

The Hall-Heroult smelting process reduces the alumina to aluminum. Alumina is dissolved in a molten cryolite (Na_3AlF_6) bath contained in carbon-Lined steel cells (pots). In each pot, a direct current is passed through the bath (between a carbon anode and the carbon bottom of the cell) to reduce the dissolved alumina into aluminum. Molten aluminum collects at the bottom of the pots and is siphoned off into large crucibles. The aluminum (averaging about 99.8 percent purity) is poured directly into molds to produce foundry ingot or further refined and/or alloyed to make fabricating ingot. Scrap aluminum may be added to the melt either at this last stage or when the ingot is remelted at the foundry or fabricating

Table 3-1 3—Major Energy Saving Features of Improved Aluminum Production

Process	State-of-the-art	Advanced
Aluminum smelting (Hall-Heroult process)		
Electrolysis	**More efficient rectifiers and computer control of amperage flow.** **Design changes in carbon anodes.** **Improvements in the chemical bath.** **Low-current density design cells.** **Increased furnace insulation.**	*Retrofit* **Closer anode-cathode spacing.** **Highly conductive electrolyte.** **Bipolar anode-cathode assemblies.** **Soderberg conversion.** *Replacement* **Pora composite anode.** **Advanced technology reduction cell, with bipolar electrode with 3, 4, and 5 bipolar plates.** **Alcoa aluminum chloride smelting process.** **Inert anode.** **Carbothermic reduction process.** **Advanced technology reduction cell.** **MonoPolar electrode.**
Anode production		*Retrofit* **Composite anodes.** **Oxygen resistant, high electrical conductivity material for anodes.** **Solvent refined coal or lignite liquids.** *Replacement* **Inert anode, cathode, and sidewalls.** **Carbothermic reduction process.**

SOURCE: Energetic, Inc., *Industry Profiles: Aluminum,* prepared for the U.S. Department of Energy, Office of Industrial Technologies, Report No. DE-AC01-87CE40762, December 1990.

facility. The carbon anodes, which are consumed in the process, are produced at the smelter by baking petroleum coke and coal tar pitch at 1,800 F.

The smelting process is continuous. Alumina is added, anodes are replaced, and molten aluminum is siphoned off without interrupting current in the cells. A potline may consist of 50 to 200 cells with a total line voltage of up to 1,000 volts at current loads of 50,000 to 225,000 amps.

Smelting accounts on average for 65 percent of the energy used in aluminum production (based on 1980 data). Most of this energy is electricity. Electricity use in the electrolysis section of smelters currently averages about 7.3 kWh/lb of aluminum.[95] Modern, state-of-the-art smelters use 6.0 to 6.5 kWh/lb.

Energy use in the Hall-Heroult process is determined by the design and operation of the electrolysis cell. About 45 percent power of the energy input is used to reduce the alumina to aluminum, and the remainder is lost as heat. The primary cause of this low efficiency is the spacing (typically 1.75 inches) between the anodes and cathodes. Narrower electrode spacings give lower power consumption and improved energy efficiency. However, there are limits to how close the electrodes can be spaced. Undulation in the metal

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[95] Though the basic process Of aluminum smelting is over 100-years-old, the technology has improved steadily. Just after World War II, about 12 kWh of electricity was required to produce a pound of aluminum.

bath (caused by magnetic fields interacting with metal pad currents and gases from the deteriorating anodes) can periodically short out the circuit if the electrodes are spaced too closely. It is estimated that reducing anode-cathode spacing from 1.75 to .75 inches could reduce electrolysis electricity use by 23 percent, and that reducing the spacing to .25 inches would result in energy savings of 33 percent. Realizing these potential savings would require developments in cell design, electrode and lining materials, and electrolyte composition.[96]

RECYCLING

Scrap recycling reduces significantly the energy used to produce aluminum products. Recycling requires only about 5 percent of the energy needed to produce primary aluminum from bauxite. In recent years, recycling has accounted for about one-third of total aluminum production in the United States.[97]

SUMMARY

Most improvements in aluminum production are expected to be marginal over the next 20 years. Full implementation of state-of-the-art technologies, such as more efficient rectifiers and computer control of amperage flow, would lower energy use by an estimated 16 percent from current average practices .[98] If breakthroughs were made in the development of advanced technologies, such as the Pora composite anode, the inert anode, or carbothermic reduction process, energy use may be reduced by an additional 17 percent.

1 Cement[99]

Cement is the bonding agent that holds particles of aggregate together to form concrete. Cement production is very energy-intensive, but the final concrete is one of the least energy-intensive construction materials.

The raw materials for Portland cement, the most commonly used cement, are limestone (calcium carbonate), silica sand, alumina, iron ore, and small quantities of other materials. These materials are quarried, crushed, ground, and mixed together, and then burned at 2,700 to 2,9000F in large rotary kilns. This sinters and partially fuses the materials into marble-sized pellets known as clinker. The clinker is then cooled, ground into a fine powder, and mixed with gypsum for use as cement. The main processes involved in cement manufacture are raw materials preparation, clinker production, and finish grinding.

There are two principal categories of cement production, the wet process and the dry process. In the wet process, water is added to the process stream at the grinding stage and later the materials are fed into the kiln as a slurry. In the dry process, the raw materials are ground without water, then preheated or precalcined, and finally fed into the kiln as a dry meal that contains less than 7 percent moisture. The preheat and precalcine stage uses waste heat from the kiln. In some plants, this intermediate stage is skipped and the dry ground materials are fed directly into the kiln.

The choice of whether to process wet or dry depends on the initial moisture content of the raw materials. Materials with greater than 15 percent

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96 *Energetic,* Inc., *Industry Profiles: Aluminum,* op. **cit.,** footnote 92.

97 Patricia A. Plunkert and Errol D. Sehnke, "Aluminum, Bauxite, and Alumina," *Minerals Yearbook, vol. I,* 1990 ed. (Washington, DC: U.S. Department of the Interior, Bureau of Mines, 1993).

98 This assumes that one-half of the U.S. alumina supply continues to be imported.

99 "Cement," Th. *Academic American Encyclopedia, online edition* (Danbury, CT: Grolier Electronic Publishing, 1991). U.S. Congress, Office of Technology Assessment, *Fueling Development: Energy Technologies for Developing Countries,* op. cit., footnote **12.** Energetic, Inc., *Industry Profiles: Cement,* prepared for the U.S. Department of Energy, Office of Industrial Technologies, Report No. DE-AC01-87CE40762, December 1990.

moisture are wet processed, because there is insufficient waste heat from the kiln to reduce their moisture content to levels low enough for dry processing. The dry process is the most popular of the two production methods and its use has been growing because of its greater energy efficiency.

The energy sources of the wet and dry processes differ considerably, with the dry process using somewhat more electrical energy and substantially less thermal energy. In recent years, electricity use in cement manufacture has increased because of the shift to the dry process, greater environmental controls, and more extensive use of preheater that require large fan systems. In addition, greater production of more finely ground, higher strength cements has also increased electricity use.[100] This is partially offset because less cement is needed when higher strength types are used.

RAW MATERIALS PREPARATION

This step, which includes the crushing, proportioning, drying, grinding, and blending of the various minerals, accounts for about 8 percent of the energy used in cement manufacturing (tables 3-14 and 3-15). The grinding stage, which consumes the most energy, is done either wet or dry. The wet process requires less energy at the grinding stage, but much more energy in clinker production. Grinding is particularly inefficient, with an estimated 2 to 5 percent of the input energy going to breaking materials apart, and the remainder going into heat and vibration. Full use of state-of-the-art technologies such as the dry process, with additional drying in the mills and improved classification schemes, are estimated to reduce energy use in raw materials preparation by about 19 percent from current average practices. Technologies, not yet commercialized, such as advanced sensors and instrumentation, modeling and controls for grinding circuits, and differential grinding, may be able to reduce the energy use an additional 23 percent.

CLINKER PRODUCTION

Sintering and fusing the ground materials into clinker is the most energy-intensive stage of the process. It accounts for approximately 80 percent of the energy used in cement production. The dry process with precalcining or preheating uses the least energy, the wet process uses the most. Advances in the preheater and precalciner processes have led to significant improvements in the overall energy efficiency of cement production in recent years.

State-of-the-art technologies, such as the dry process with either preheat or precalcine and improvements in kiln refractories, kiln combustion, and improved clinker cooling techniques, are estimated to reduce energy use in clinker production by about 26 percent from current average practices. Advanced technologies such as catalysts to lower calcination temperatures, advanced kiln control based on artificial intelligence, and modifications to alkali specifications may be able to reduce the energy use an additional 17 percent.

FINISH GRINDING

Grinding the clinker into a fine powder and mixing it with gypsum accounts for about 11 percent of the energy use of cement production. The same low (2 to 5 percent) grinding efficiencies that exist in the raw materials stage exist here

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[100] Stewart W. Tresouthick and Alex Mishulovich, "Energy and Environment Considerations for the Cement Industry, " paper presented at the Energy and the Environment in the 21st Century conference. Massachusetts Institute of Technology, Cambridge, MA, Mar. 26-28, 1990.

Table 3-14—Energy Use by Cement Production Technologies

Process	Process mix (fraction of clinker processed, except where noted)			Energy use (thousand Btu/ton of clinker)		
	Current	State-of-the-art	Advanced	Current	State-of-the-art	Advanced
	(1988)	(2010)	(2010)	(1988)	(2010)	(2010)
Raw materials preparation						
Primary crushing.	1.00	1.00	1.00	26	24	42
Secondary crushing. , ...	1.00	1.00	—	32	28	b
Proportioning.	1.00	1.00	1.00	21	19	19
Drying.	0.16	—	—	270	—	—
Raw grinding (wet).	0.34	—	—	275	—	—
Raw grinding (dry). ., ...	0.66	1.00	1.00	312	270	203
Blending.	1.00	1.00	1.00	2	2	2
Subtotal.				425	343	266
Clinker production						
Long kiln (wet).	0.34	—	—	4,932	—	—
Long kiln (dry), no preheat/precalcine.	0.16	—	—	4,294	—	—
Short kiln (dry), with preheat.	0.20	0.20	—	3,469	3,000	—
Short kiln (dry), with precalcine. ... , .	0.30	0.80	0.80	3,332	3,000	2,500
Stationary clinkering, with precalcine.	—	—	0.20	—	—	2,360
Clinker cooling.	1.00	1.00	1.00	63	57	57
Subtotal.				4,121	3,057	2,529
Finish grinding						
Ball milling.	0.95	—	—	525	—	—
Ball milling, with pregrinding.	0.05	0.99	0.70	473	378	321
Roller milling.	—	0.01	0.20	—	420	315
Nonmechanical grinding.	—	—	0.10	—	—	300
SubtotaL				522	378	318
Total						
From domestic clinker.	97%	93%	7470	5,067	3,778	3,112
From imported clinker.	30/0	7%	6%	522	378	318
From secondary materials.	—	—	20%	—	—	—
Weighted average.				4,925	3,528	2,325

a Average of currently implemented technologies.

b Included in primary crushing.

NOTE: Purchased electricity is counted at 10,500 Btu per kWh; generation and transmission losses are included. Estimated losses in 1988 were approximately 944 thousand Btu per ton of cement.

SOURCES: S.R. Venkateswaren and Howard E. Lowitt, Energetic, Inc., *The U.S. Cement Industry: An Energy Perspective,* prepared for the U.S. Department of Energy, Office of Industrial Programs, Report No. DOE/RL/01830-T58 (Springfield, VA: National Technical Information Service, May 1988). Energetic Inc., *Industry Profiles: Cement,* prepared for the U.S. Department of Energy, Office of Industrial Technologies, Report No. DE-AC01-87CE40762, December 1990.

as well. Addition of a pregrinding stage saves about 10 percent of the energy used in grinding. Currently, only about 5 percent of clinker is preground.

State-of-the-art technologies, such as pregrinding and improvements in the grinding media and classification techniques, are estimated to reduce energy use in finish grinding by about 28 percent from current average practices. Partial use of advanced technologies such as roller milling and nonmechanical comminution might be able to reduce energy use an additional 16 percent.

Table 3-15—Major Energy Saving Features of Improved Cement Production

Process	State-of-the-art	Advanced
Raw material preparation	Wet process slurry dewatering with filter presses and slurry thinners. Waste heat drying using preheater exit gases/ cooler heat in roller or air-swept ball mills. High-efficiency classifiers in closed-circuit grinding plants. Roller mills. Improved grinding media and wear resistant linings.	Fluidized-bed drying with low-grade fuels. Advanced sensors for particle size, fineness, and mass flow measurements and automatic computer control of grinding circuits. Differential grinding: limestone and clay raw materials ground separately. Nonmechanical comminution, based on ultra-sound, lasers, thermal shock, electrical shock, or cryogenics.
Clinker production	Dry precalciner kilns. Dry suspension preheater kilns. Use of waste fuels, including: coke, municipal wastes, rice hulls, wood wastes, rubber tires, hazardous wastes, waste oil, pot liners, sewage sludge, etc. Optimized heat transfer conditions in the clinker cooler through better distribution of clinker and air. Improved insulating refractories and seals to reduce kiln shell heat loss. Kiln combustionimprovements, including semi-direct/ indirect coal firing, optimal oxygen levels, and advanced burners matched to the kiln/coler design. Material recirculation in flash precalciners to improve calcination efficiency. Cogeneration using exhaust heat from kiln and/ or coler. Kiln internal heat transfer enhancement: chains, lifters, and trefoils. Low pressure-drop cyclones for suspension preheater. High-temperature ceramic filters for kiln exhaust.	All electric kilns and hybrid fossil-electric kilns. Stationary clinkering systems, including fluidized-bed kilns and trough kilns. Sensors and online analysis of kiln exhaust, temperature and clinker quality, and high level computer-based kiln control. Alkali specification modification.
Finish grinding	Roller mills. High-efficiency classifiers in closed circuit plants. High-pressure roller press for clinker pre-grinding. Improved grinding media and wear resistant linings. Modified bail mill configuration and operation. Particle size distribution control. Grinding aids.	Blended cements: Portland cements with fly ash, kiln dust, blast furnace slag, and natural pozzolana. High-pressure roller press as an autonomous grinding unit. Modified fineness specification. Advanced sensors for particle size, fineness, and mass flow measurements and automatic computer control of grinding circuits. Nonmechanical comminution, based on ultra-sound, lasers, thermal shock, electrical shock, or cryogenics.

I Glass 101

Glass is produced by melting silica, limestone, and soda ash, in a furnace and allowing them to cool to an amorphous (noncrystalline) state.102 Other elements may be added to alter the color or other properties. While still molten, the glass is formed into a variety of products including: windows, mirrors, bottles, jars, light bulbs, tableware, and fiberglass. The principal processing steps are batch preparation, melting and refining, forming, and postforming.

The energy used to manufacture glass varies significantly among the major categories of glass products: flat, containers, pressed and blown, and fibrous. Currently, between 15 and 27 million Btu are used on average to produce a ton of glass, depending on the product (based on 1985 data). For the industry as a whole, widespread adoption of state-of-the-art technologies can reduce energy consumption by an estimated 21 percent (tables 3-16 and 3-17) from current average practices. The estimated reductions are greatest for flat glass and smallest for fibrous glass. Advanced technologies, not yet commercialized, could possibly reduce energy use an additional 30 percent.

BATCH PREPARATION

Glassmaking begins with raw materials weighing and mixing. Recycled material (cullet) is crushed and added to the process at this stage. Batch preparation accounts for an average of 4 percent of the energy used in glass production. Computer control for the weighing, mixing, and charging saves about 10 percent of the energy used in batch preparation.

MELTING AND REFINING

The raw materials are batch charged or continuously charged to the melting furnace, where they are heated to between 2,400 to 2,900°F. After melting, the glass passes to the refining section of the furnace where it stays long enough for the bubbles to escape. Glass is produced in various types of melters including regenerative, recuperative, electric, and pot furnace or day furnaces. Most furnaces are freed by gas or oil, but electricity is becoming more widely used.

Regenerative furnaces are used in large continuous melting operations and account for approximately 90 percent of U.S. capacity. The charge is melted by a flame that plays over the glass surface. Fuel and preheated air are fired at one end of the furnace and the hot combustion exhaust gases pass through an open brick lattice (checker) at the opposite end. After 15 minutes, the flow is reversed. The air is preheated by passing through the hot checker and the exhaust gases from the combustion heat the checker at the other end for the next cycle. Recuperative furnaces are similar, except that they were originally built without checkers and have since been retrofitted with heat recovery units. Fossil-fueled, regenerative furnaces are 40 to 55 percent efficient in terms of end-use energy.

Electric melters heat the glass by passing current between electrodes embedded in the charge. These melters are approximately 60 to 75 percent efficient in terms of end-use energy. Among the advantages of electric melting are: reduced pollution; improved glass quality (more uniformity and fewer stones); better control of operations; faster furnace rebuilds; and small

101 "Glass and Glass Products," *McGraw-Hill Encyclopedia on Science and Technology (New York,* NY: McGraw-Hill, 1987). "Glass," *The Academic American Encyclopedia, online edition* (Danbury, CT: Grolier Electronic Publishing, 1991). E. Babcock, A. Elaahi, and H.J.?. Lowitt, Energetic, Inc., *The U.S. Glass Industry: An Energy Perspective,* prepared for the U.S. Department of Energy, Office of Industrial Programs, Report No. DOE/RL/O1830-T60 (Springfield, VA: National Technical Information Service, September 1988).

102 GINS can be produced without silica, but most commercial glass products are based on it.

Table 3-16—Energy Use by Glass Production Technologies

Process	Process mix (tons of product/ton of finished glass)			Energy use (million Btu/ton of product)			Product
	Current (1985)	State-of-the-art (2010)	Advanced (2010)	Current* (1985)	State-of-the-art (2010)	Advanced (20˙0)	
Batch preparation	32	.32	26	0.27	0.24	0.24	Batch processed glass
Melting and refining							
Large fossil fuel melter	.26	.26	—	8.10	5.10	—	Melted glass
Advanced melter with batch preheat	—	—	1.20	—	5.10	3.00	Melted glass
Subtotal	.26	.26	1.20	8.10	5.10	3.00	Melted glass
Forming	.26	.26	.26	.45	1.30	.17	Formed glass
Post-forming							
Annealing	1.20	1.20	—	0.42	0.27	—	Postformed glass
Tempering	0.60	0.60	—	3.03	2.14	—	Postformed glass
Laminating/autoclaving	0.40	0.40	—	0.82	0.75	—	Postformed glass
Advanced	—	—	1.20	—	—	1.36	Postformed glass
Subtotal	1.20	1.20	1.20	2.20	.59	1.36	Postformed glass
Total	1.00	0 0	.00	15.03	10.28	6.93	Finished glass
Container glass							
Batch preparation	1.32	.32	.24	0.53	0.48	0.48	Batch processed glass
Melting and refining							
Large fossil fuel melter	1.01	1.0˙	—	5.50	3.90	—	Melted glass
Small fossil fuel melter	0.19	0.19	—	9.42	8.35	—	Melted glass
Small electric melter	0.06	0.06	—	10.50	8.90	—	Melted glass
Advanced melter with batch preheat	—	—	1.19	—	—	3.00	Melted glass
Subtotal	1.26	1.26	1.19	6.34	4.82	3.00	Melted glass
Forming	1.20	.20	1.˙3	4.0˙	3.20	2.88	Formed glass
Post-forming							
Annealing	1.13	1.13	—	1.84	1.40	—	Postformed glass
Advanced	—	—	1.13	—	—	1.33	Postformed glass
Subtotal	1.13	1.13	1.13	.84	1.40	1.33	Postformed glass
Total	1.00	1.00	1.00	15.59	2.14	8.9˙	Finished glass

Table 3-16-Energy Use by Glass Production Technologies-(Continued)

Process	Process mix (tons of production of finished glass)			Energy use (million Btu/ton of product)			Product
	Current (1985)	State-of-the-art (2010)	Advanced (2010)	Cur rent" (1985)	State-of-the-art (2010)	Advanced (2010)	
Pressed and blown glass							
Batch preparation. 1.51	1.51	1.51	0.76	0.68	0.68		Batch processed glass
Melting and refining							
Small fossil fueled melter. 1.30	1.30	—	10.10	8.00	—		Melted glass
Small electric melter. 0.14	0.14	—	9.90	8.90	—		Melted glass
Advanced melter with batch preheat. . —	—	1.30	—	—	3.00		Melted glass
Moly-lined electric melter. . . . . —	—	0.14	—	—	6.70		Melted glass
Subtotal. 1.44	1.44	1,44	10.08	8.09	3.37		Melted glass
Forming. 1.37	1.37	1.37	5.31	4.50	4.05		Formed glass
Post-forming							
Fire polishing. 1.37	1.37	—	1.20	1.10	—		Postformed glass
Annealing. 1.37	1.37	—	2.04	1.79	—		Postformed glass
Advanced. . . . . —	—	1.37	—	—	2.74		Postformed glass
Subtotal. 1.37	1.37	1.37	3.24	2.89	2.74		Postformed glass
Total 1.00	1.00	1.00	27.37	22.80	15.18		Finished glass
Fibrous glass							
Batch preparation. 1.30	1.30	1.30	1.15	1.04	1.04		Batch processed glass
Melting and refining							
Small fossil-fueled melter. 1.11	1.11	—	9.89	9.08	—		Melted glass
Small electric melter. 0.12	0.12	—	9.90	8.90	—		Melted glass
Advanced melter with batch preheat. . —	—	1.11	—	—	3.00		Melted glass
Moly-lined electric melter. . . . . —	—	0.12	—	—	6.70		Melted glass
SubtotaL 1.24	1.24	1.24	9.89	9.06	3.37		Melted glass
Forming. ... , ... 1.11	1.11	1.11	7.24	6.00	5.40		Formed glass
Post-forming							
Curing. 1.00	1.00	—	1.10	0.94	—		Postformed glass
Drying. 1.00	1.00	—	1.64	1.40	—		Postformed glass
Advanced. . . . . —	—	1.11	—	—	2.22		Postformed glass
Subtotal. 1.00	1.00	1.11	2.74	2.34	2.22		Postformed glass
Tofal. 1.00	1.00	1.00	24.51	21.56	13.98		Finished glass

a Average of currently implemented technologies.

NOTE: Purchased electricity is counted at 10,500 Btu/kWh; generation and transmission losses are included. Estimated losses in 1985 *were* approximately 2.6 million Btu/ton of flat glass; 4.4 million Btu/ton of container glass; 9.2 million Btu/ton of pressed and blown glass; and 7.6 million Btu/ton of fibrous glass.
SOURCES: E. Babcock, E. Elaahi, and Howard E. Lowitt, Energetic, Inc., *The U.S. Glass Industry: An Energy Perspective,* prepared for the U.S. Department of Energy, Office of Industrial Programs, Report No. DOE/RL/01830-T60 (Springfield, VA: National Technical Information Service, September 1988). Energetic Inc., *Industry Profiles:* Glass, prepared for the U.S. Department of Energy, Office of Industrial Technologies, Report No. DE-AC01-87CE40762, December 1990.

Tables 3-17—Major Energy Saving Features of Improved Glass Production

Process	State-of-the-art	Advanced
Batch preparation	Computer controlled weighing and mixing and charging.	Batch preheating. Cullet preheating. Raw material purification.
Melting and refining Gas/oil-fired melters	Oxygen-enriched combustion air. Electric boosting. Dual-depth melter. Regenerator flow controller (process control). Chimney block regenerator refractories. Chemical boosting. Oxygen monitoring (process control). Sealed-in burner systems. Reduction of regenerator air leakage.	Submerged burner combustion. Batch liquefaction. Advanced glass melter. Thermochemical recuperator. Ultrasonic agitation and refining. Pressure swing absorption oxygen generator. Excess heat extraction from generators. Improved furnace insulation.
Electric melters	Automatic tap changing transformers for electric melters. Dual-depth melter.	Molybdenum lined electric melter.
Coal-fired melters		Direct coal firing (substitution of coal for gas or oil). Coal-fired hot gas generation (COHOGG)(substitution of coal for gas or oil).
Chemical process		Sol-gel process.
Forming	Computerized inspection.	Improved productivity, resulting from greater production of lighter weight containers and tempered flat glass products. Improved mold design. Improved mold cooling systems. Automatic gob control.
Post-forming	Computerized inspection.	Improved productivity, resulting from greater production of lighter weight containers and tempered flat glass products. Improved glass strengthening techniques. Improved protective coating for glass.

SOURCES: E, Babcock, A. Elaashi and Howard E. Lowitt, Energetic, Inc., *The U.S.* Glass *Industry:An Energy Perspective,* prepared for the U.S. Department of Energy, Office of Industrial Programs, Report No, DOE/RL/01830-T60 (Springfield, VA: National Technical Information Service, September 1988). Energetic, Inc., *Industry Profiles:* Glass, prepared for the U.S. Department of Energy, Office of Industrial Technologies, Report No. DE-ACO1-87CE40762, December 1990.

space requirements. [103] However, there are also major drawbacks, including: electricity costs, reduced refractory life, more frequent furnace rebuilds, capacity limitations, and the inability melt glasses that are oxidizing or that contain metals that attack the molybdenum electrodes.

Melting and refining account for 50 to 68 percent of the energy used in glass production and are the focus of energy conservation efforts in the industry. State-of-the-art technologies such as oxygen-enriched combustion air, electric boosting, improved process control, and better refracto-

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[103] E. Babcock, A. Elaahi, and H.E. Lowitt, Energetic, Inc., op. cit., footnote 101.

ries can reduce the energy use of this stage by an estimated 8 to 37 percent from current average practices. Advanced technologies could possibly reduce energy use an additional 38 to 63 percent.

FORMING

Once refined, the molten glass flows to the forehearth section of the furnace where it is homogenized and heat conditioned to establish and maintain temperature uniformity. Overall, the melt is cooled to the proper working temperature, where its viscosity is suitable for shearing and gob formation. However, it must also be heated periodically to eliminate temperature gradients within the glass. The cooling function interferes with the heating function, making the forehearth a larger energy user.

Molten glass is drawn from the forehearth when it is ready to be formed. The forming stage differs greatly depending on the product being produced.

Flat products such as windows are formed primarily by the float glass process developed in the 1950s. In the float process, a continuous strip of glass from the melting furnace floats onto the surface of a molten metal, usually tin, at a carefully controlled temperature. The flat surface of the molten metal gives the glass a smooth, undistorted surface as it cools. After sufficient cooling the glass becomes rigid and can be handled on rollers without damaging the surface finish. The glass can be formed at high speeds and is much less expensive to produce than similar quality glass made by grinding and polishing methods.

Containers are formed by blowing or suction techniques. To form a jar or bottle, a gob of hot glass is blown or sucked into a mold on a continuous machine. Light bulbs are produced by a similar technique, except that the glass is fed into the forming machine as a ribbon, rather than individual gobs of glass, and a special nozzle blows glass from the ribbon into the molds. A high-speed ribbon machine produces light bulbs at a rate of more than one every 2 seconds.

Products such as tableware, cooking utensils, and laboratory equipment are produced by blowing and pressing techniques. A gob of hot glass is placed in a metallic mold, and a metallic plunger is forced into the mold to form the glass into the desired shape. Patterns in the mold surface are pressed onto the glass.

Fiberglass is formed by one of four techniques: rotary fiberization, steam or air blowing, mechanical drawing, and flame blowing. In the rotary process, glass is extruded from holes on the periphery of a spinning mold. After extrusion, the diameter of the fibers is reduced (attenuated) by a blast of hot air or gas. The other processes all extrude the glass through holes in a stationary platinum mold, but differ in their attenuation techniques.

Forming accounts for 12 to 33 percent of the energy used in glass production. State-of-the-art forehearth technologies can reduce the energy use of this stage by an estimated 10 to 20 percent from current average practices. Advanced technologies could possibly reduce energy use an additional 10 percent.

POSTFORMING

Postforming operations are used to adjust the strength and other properties of the formed product. Like the forming stage, these processes vary according to the product being made. Flat products are annealed and cut, and then either tempered and quenched or laminated and autoclaved. Sometimes they are also coated. Containers and pressed and blown products are annealed, coated, and finished. Pressed and blown products are sometimes cut and fire polished. Fiber glass is either dried or cured.

Postforming accounts for about 11 to 18 percent of the energy used in glass production, State-of-the-art technologies can save an estimated 11 to 28 percent of this energy from current average practices. Advanced technologies could possibly reduce energy use an additional 5 to 14 percent.

103 E. Babcock, A. Elaahi, and H.E. Lowitt, Energetic, Inc., op. cit., footnote 101.