Energy Efficiency and Use in the Chemical Industry

Tracy Carole, Energetics, Inc.
Paul Scheihing, U.S. Department of Energy
Lou Sousa, U.S. Department of Energy

ABSTRACT

The chemical industry is energy-intensive, using about 6.282 quadrillion Btu (includes feedstock and processing energy) in 1997. The energy used is in the form of heat and power supply for manufacturing processes as well as energy feedstocks (e.g., natural gas, petroleum) used to produce petrochemicals, plastics, and synthetic fibers. In some processes, energy for heat, power, and feedstocks can account for up to 85% of production costs, making energy efficiency an important issue.

In May 2000, the U.S. Department of Energy's Office of Industrial Technologies (OIT) published an *Energy and Environmental Profile of the U.S. Chemical Industry (Industry Profile).* The profile examines energy and environmental impacts of the six most energy-intensive chemical chains: ethylene, propylene, benzene-toluene-xylene, agricultural chemicals, butadiene, and caustics. Together these chains account for approximately 51% of the industry's process energy use. Data is provided on typical process flows, feedstock and process energy consumption, air emissions of pollutants and carbon dioxide, and hazardous waste streams. The profile also provides a review of theoretical minimum energy versus actual energy use based on published studies. This paper will present a synopsis of the industry profile, focusing on the six energy-intensive chemicals.[1]

Introduction

The chemical industry is one of the oldest U.S. industries. Often called the cornerstone of the manufacturing sector, the chemical industry produces over 70,000 diverse products, of which nearly a third serve as raw materials for other manufacturing industries.

Over the past decade, U.S. chemical production has grown steadily, reaching record shipments of $392 billion in 1997. The industry's gross investment in new plants and equipment has risen to meet the challenge of increased global competition from developing countries with lower energy costs and less stringent environmental regulations. Chemical manufacturers have responded by shifting the focus towards the high technology areas (e.g., pharmaceuticals, biotechnologies, advanced materials) and taking advantage of their advanced technology. This diversification has placed greater emphasis on research and development (R&D), reflected by an increase in R&D funding from $9.5 billion in 1987 to $18.7 billion in 1997.

Despite the increased global competition, the U.S. is the world's largest chemical producer, responsible for about 25 percent of the $1.5 trillion international chemicals market. The U.S. is also the second largest exporter of chemicals (behind Germany), securing almost 15 percent of the total world exports in 1997.

---

[1] Data for butadiene is incomplete and therefore the groups will sometimes be referred to as the five chains.

Industry Focuses on Energy Efficiency

Chemical production is energy-intensive and consumed 6.282 quadrillion Btu in 1997. In 1994, the industry accounted for 7 percent of all domestic energy use, and approximately 25 percent of all U.S. manufacturing use. Manufacturers have utilized energy management and housekeeping programs, process and equipment design improvements, cogeneration, and on-site recovery of waste heat and energy to improve energy efficiency. However, most of the low-cost, high-return investments have been made and future improvements in energy efficiency will require more dramatic and costly changes in process design and innovative R&D.

Potential Targets for Improved Energy and Resource Efficiency

The chemical industry is a large, complex industry and out of the scope of the *Industry Profile*. Instead, the top 50 chemicals were ranked in the following categories to determine the best targets for improved energy and resource efficiency: energy consumed for production, potential energy savings based on the difference between the minimum theoretical energy required and the energy consumed in practice, and the potential energy savings through improved catalytic processes. The chemicals that were ranked highly in two or more categories (e.g., ethylene, ammonia, propylene, sodium hydroxide, and chlorine) and/or were feedstock for other chemicals that were in the top 15 in at least one category were selected.

These chemical products were organized into six groups[2] based on their major constituent or chemical chain: ethylene, propylene, butadiene, benzene-toluene-xylene (BTX), agricultural chemicals, and caustics. Approximately 70-80 percent of the products of the chains account for 51% of the chemical industry's process energy consumption. This report will summarize the *Industry Profile* and focus on the chemical chains.

Market Trends and Statistics

In 1997, U.S. production of the six chemical chain groups was over 530 billion pounds. Agricultural chemicals had the largest production followed by ethylene and its derivatives. Table 1 shows the U.S. production for each group (DOE 2000).

Overall, the markets for these six chemical groups have increased, though some at a faster rate than others. The demand for ethylene and its derivatives has almost doubled in the past 15 years and much of the increased demand can be traced to the Asia-Pacific region. Although the recent Asian financial crisis has weakened this demand, growth in ethylene production is expected to remain at more than 5 percent.

Demand for propylene has risen steadily over the last 10 years, primarily in Southeast Asia, the Middle East, Africa, and Latin America. Increased demand for plastics such as polyethylene, polypropylene, and polyvinyl chloride (PVC) has supported the markets for BTX and chlorine (caustics group), but over-capacity and lower demand in Asia may have a negative impact on growth for the polypropylene, BTX, and caustics markets in the future. The U.S. agricultural chemicals sector has already experienced a 20-30% drop in production due to the growing capacity for manufacturing fertilizers in Asia, Mexico, and India.

---

[2] Data for butadiene is incomplete and therefore the groups will sometimes be referred to as the five chains.

Chlorine and sodium hydroxide (caustics group) are also faced with challenges beyond over-capacity and lower demand. Environmental regulations restricting the production or disposal of products that require large amounts of chlorine such as PVC have had a negative impact on the chlorine market. However, until a non-chlorine replacement for PVC is developed, demand will remain strong. To avoid a sodium hydroxide shortage, users are looking to reduce the amount consumed in manufacturing by implementing cost-effective ways to recycle sodium hydroxide or by switching to soda ash. Currently, all of the recycling methods are not cost-competitive with purchasing sodium hydroxide and although soda ash is naturally abundant in the United States, it is more expensive to mine it than to produce sodium hydroxide. These alternatives will only impact sodium hydroxide demand when they become economically viable.

Table 1. U.S. Production of the Six Chemical Chains

Chemical Group[3] (% of products represented in U.S. production)	U.S. Production (billion pounds)
Ethylene (80%)	128.2
Propylene (73%)	52.1
Butadiene (50%)	8.0
BTX (87%)	96.0
Agricultural Chemicals (75%)	173.7
Caustics (100%)	72.4
Total Production	530.4

Energy and Materials Consumption

In this report, the term "energy" includes the fossil fuels (e.g., oil, natural gas, coal) used to supply heat and power for the manufacturing processes (processing energy) as well as feedstocks used to produce petrochemicals, plastics, and synthetic fibers (feedstock energy). As shown in Table 2, six chemical chains account for about 51% of the process energy consumed by the chemical industry (DOE 2000).

The caustics group is the most energy-intensive chemical chain. Chlorine and sodium hydroxide are co-produced using the electrolysis process that is mainly powered by electricity. The electrical requirements for electrolysis cells are high and large energy losses are incurred in the generation and transmission of electricity.

The ethylene chain is close behind the caustics and accounts for approximately 25% of the processing energy represented by the six chains. Manufacture of ethylene, which requires heating the petroleum feedstock to temperatures between 1400°F and 1600°F, consumes almost half of the process energy attributed to the ethylene chain.

The agricultural chemicals chain has the third greatest process energy consumption. Most of this energy is used in the production of ammonia, an inefficient, low-yield process. Second to ammonia production in energy consumption is the production of phosphoric acid by the wet process. Figures 1, 2, and 3 show the chemical chains, their main products, 1997 production, and processing energy intensity[4] in Btu per pound (DOE 2000).

[3] Data are not available for all derivatives in every chain.

[4] Processing energy includes electricity losses through electricity generation and transmission and excludes energy exported.

Table 2. Summary of Process Energy Use for Six Chemical Chains

Chemical Chain (% of Products Represented by Process Energy Use)	Estimated Process Energy Use (Trillion Btu/year)[5]
Ethylene (80%)	529
Propylene (73%)	96
Butadiene (50%)	45
BTX (87%)	388
Agricultural Chemicals (75%)	492
Caustics (100%)	559
TOTAL ESTIMATED ENERGY USE FOR SIX CHAINS	2109
Process Energy Use by the Chemical Industry in 1997	4166
Percentage of Chemical Industry Use in 1997	~ 51 %

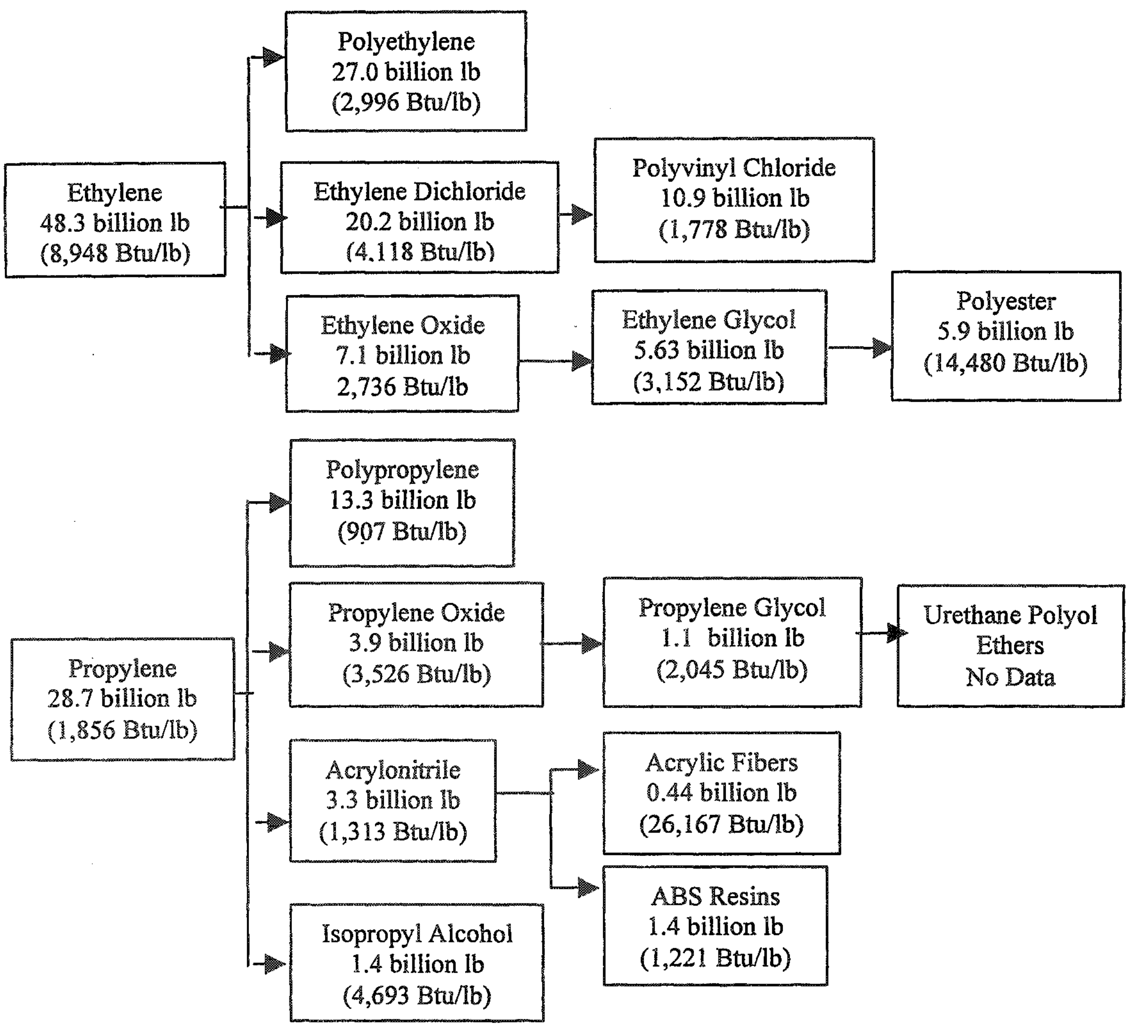

Figure 1. Production and Processing Energy of Ethylene and Propylene

[5] Includes losses incurred during electricity generation and transmission.

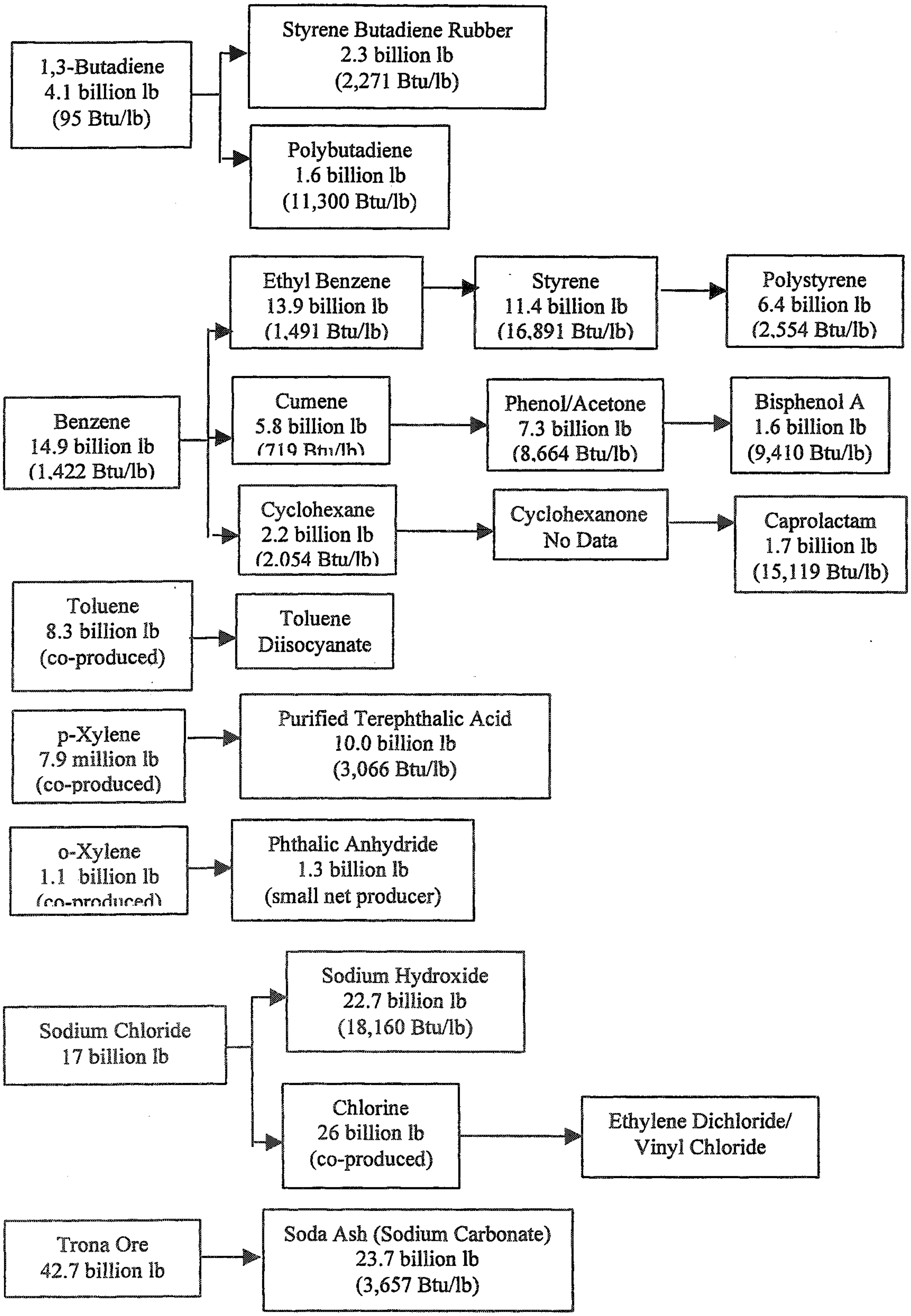

Figure 2. Production and Processing Energy of Butadiene, BTX, and Caustics Chains

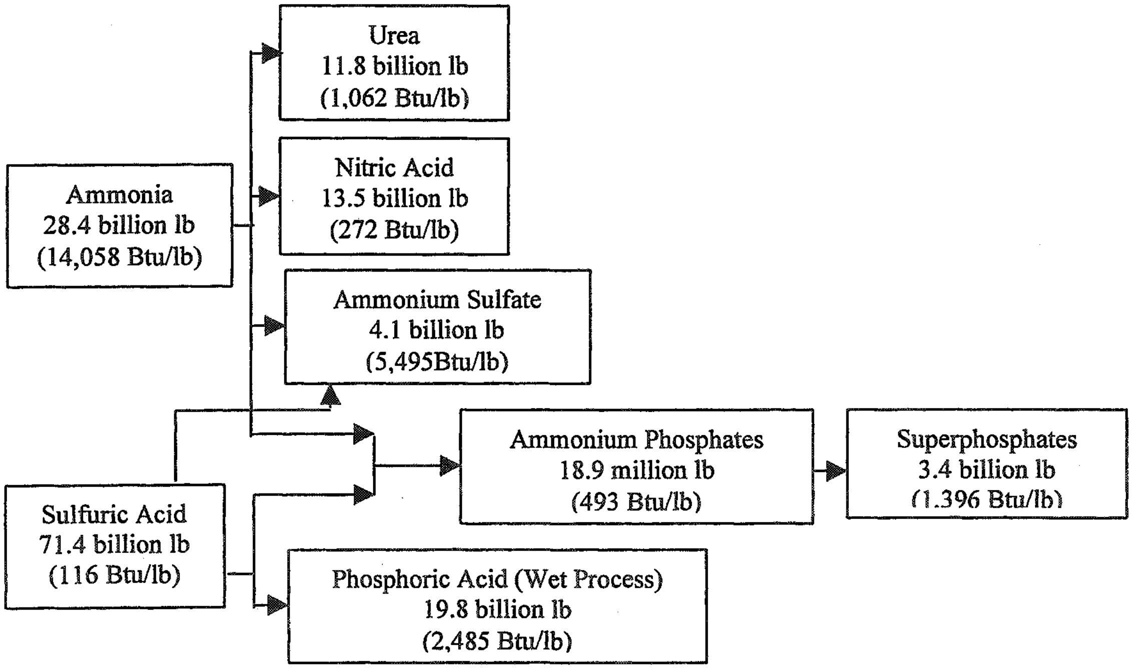

Figure 3. Production and Processing Energy of Agricultural Chemicals

Feedstock and Fuel Sources Vary Among Chemical Chains

The six chemical chains can be consolidated into two larger groups based on the raw materials used to manufacture them: organic chemicals and inorganic chemicals. Organic chemicals are derived from raw materials such as crude oil derivatives, natural gas, and coal that contain hydrocarbons. The production of ethylene, propylene, butadiene, benzene, toluene, and xylene requires a substantial amount of petroleum-based feedstocks—gas oil, naphtha, propane, or ethane—and plants manufacturing these chemicals are often located near petroleum refineries to ensure a sufficient supply.

Chemicals that do not contain organic carbon (obtained from hydrocarbons) are classified as inorganic chemicals. Based on this definition, the caustic and agricultural chemical chains are considered inorganic chemicals (despite the use of natural gas as the feedstock for ammonia production, the organic carbon is not present in the end-product). Inorganic chemicals such as sulfuric acid and phosphoric acid are made from mineral ores taken from the earth.

The chemical industry uses a variety of fuel sources such as fuel oil, liquid petroleum gas (LPG), natural gas, coal, coke, and electricity for its processing energy needs. Figure 4 shows the breakdown of processing fuel use by chemical chain (butadiene data is unavailable) (DOE 2000).

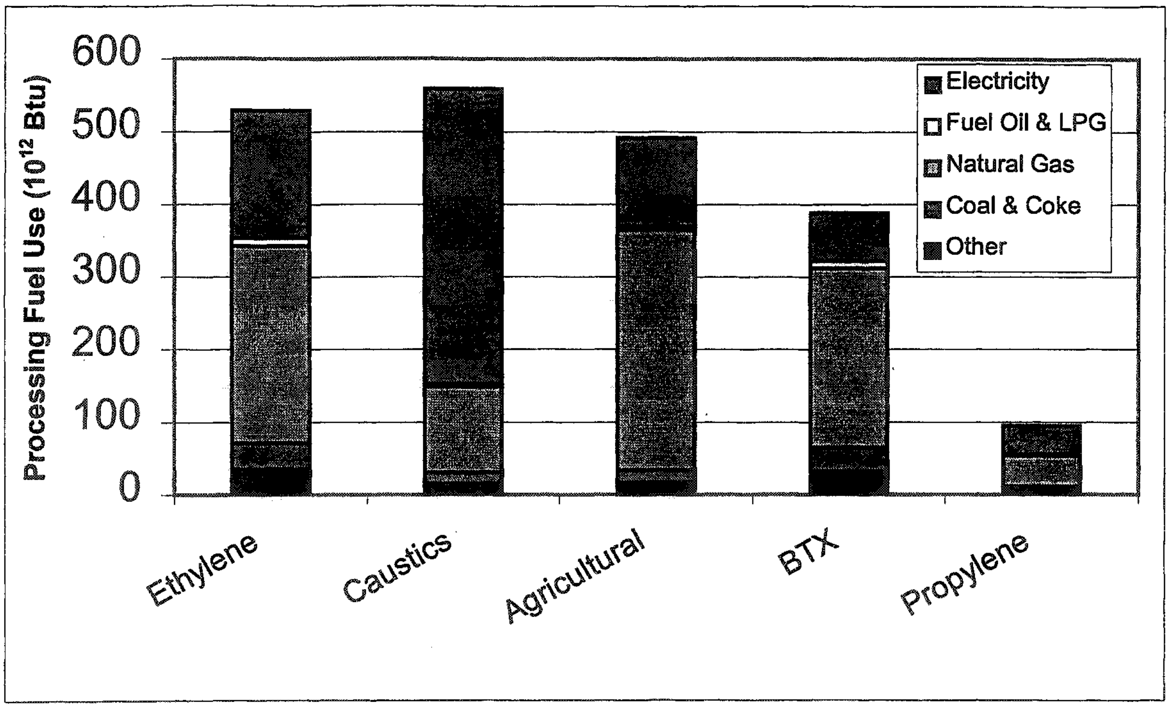

Figure 4. Processing Fuel Use by Chemical Chain

Improvements in Energy Efficiency Have Leveled Off

In the last two decades, the U.S. chemical industry has made significant improvements in energy efficiency. Between 1974 and 1995, energy consumed for heat and power per unit of output decreased by more than 39 percent, a trend that began with the oil crises of 1973. Since then, improvements in energy efficiency have leveled off due to the availability of inexpensive energy for heat, power, and feedstocks. When energy prices are low, there is less incentive to choose investments that will improve energy efficiency over those that increase market share. Figure 5 shows the relative intensity trends for energy consumed for heat and power (DOE 2000). [6]

Improved energy efficiency in the chemical industry over the last 30 years is the result of aggressive energy management and housekeeping programs begun in the early 1970s, use of cogeneration or direct generation of electricity, and improvements in process and equipment design. Many of the housekeeping improvements have centered around steam generation and distribution and operating practices for fueled reactors and fired heaters.

Almost every process in a chemical plant requires process heat from fired heaters and steam (about 75% of process energy use). Heaters are used to supply heat to raise the temperature of feed streams to a level necessary for chemical reaction or distillation. Steam is used in direct contact operations (distillation) and where indirect heating is needed (drying, evaporation). Although the potential for energy recovery is high, much of the available waste heat is not recovered or only partially recovered resulting in annual heat losses in the

[6] Electricity includes losses incurred during the generation and transmission of electricity.

range of two quadrillion Btu. Table 3 presents the potential energy content of waste heat streams in selected chemical sectors (PNNL 1984).

Figure 5. Energy Intensity Trends Related to Heat and Power in the U.S. Chemical Industry, 1974-1997

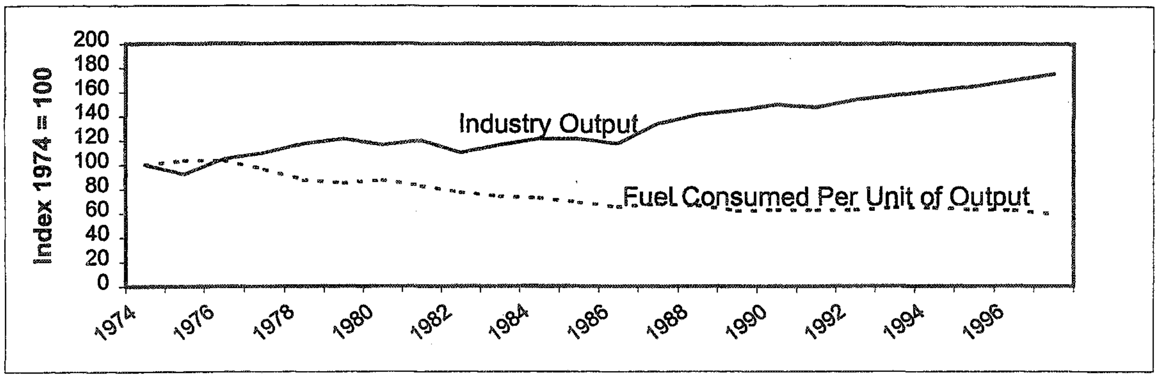

Table 3. Characteristics of Waste Heat Streams in Selected Chemical Sectors

Chemical Process	Million Btu/Ton of Product (Temperature in °F)[7]		
	Flue Gases	**Cooling Water**	**Other**
Sodium Hydroxide	4.5 (120)	0.4 (180)	0.1
Chlorine	--	0.24 (190)	2.2
Soda Ash	1.22 (400 to 500)	0.16	0.3
Styrene	0.6-0.7 (400 to 500)	29 (100 to 120)	--
Ethylene	1.9 (400)	--	--
Ammonia	2.4 (400)	0.5 (100 to 120)	0.43

Some of the recent gains in energy and material efficiency are the result of waste minimization initiatives aimed at decreasing the cost of environmental compliance (end-of-the-pipe waste treatment and disposal options often carry a heavy energy burden). However, the largest percentage of funds continues to be invested in non-productive, end-of-the-pipe controls to avoid the penalties of non-compliance. In 1999, nearly $10 billion was spent on end-of-the-pipe controls (ACC 2000).[8] To meet the challenges of increasingly stringent environmental regulations, changing product configurations, and growing competition from resource-rich developing countries the chemical industry must investigate means to improve efficiency and yield (e.g., innovative processing routes, improved waste heat recovery).

DOE's BestPractices Program Offers Improvements in Plant-Wide Energy Efficiency

The Department of Energy's BestPractices program provides resources, tools, information, cost-sharing, and technical and business advice to manufacturers, industrial service and equipment providers, and industry trade associations and other organizations interested in improving plant-wide energy efficiency. Cost-shared, plant-wide energy assessments are available to give manufacturers an overall picture of energy use throughout the plant. Plants that have undergone an energy assessment, installed energy-efficient

[7] Temperatures for some waste heat streams are unavailable.
[8] Costs of environmental compliance controls other than end-of-the-pipe are unavailable.

process technologies and improved systems, and received an independent third-party validation of technology performance and costs, are eligible to host a showcase demonstration. Showcase demonstrations are events that allow others to view the benefits of energy efficiency and resource productivity and help publicize and promote energy-saving technologies and practices (DOE 2001).

Software programs are available that target increasing energy efficiency by identifying potential improvements in process heating, process cooling and refrigeration, machine drive, and pumping systems. These software programs include:

- **MotorMaster+ 3.0:** aids in selecting energy-efficient motors and energy and cost savings analyses
- **Pump System Assessment Tool (PSAT):** assesses the efficiency of pumping systems
- **ASDMaster:** determines the economic feasibility of an adjustable speed drive (ASD) application and estimates the electricity saved using ASD
- **Steam System Scoping Tool:** evaluates the steam system and compares it to identified best practices
- **AirMaster+:** maximizes the efficiency and performance of compressed air systems
- **3E Plus:** optimizes boiler systems through the insulation of boiler steam lines

BestPractices hosts workshops where participants learn how to use the software programs and other tools to optimize their plant operations.

In addition, DOE's OIT is developing a user-friendly software program to evaluate new technologies that will impact the six chemical chains and their major derivatives. Users will select the chemical chain and major derivative(s) to be affected by the technology and input their projections of market penetration and feedstock and process energy reductions. Based on their input, the program will calculate the energy and environmental impacts of the technologies. This program will provide consistency in the evaluation and comparison of new technologies.

REFERENCES

[DOE] U.S. Department of Energy. 2000. Energy and Environmental Profile of the U.S. Chemical Industry. Washington, D.C.: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Office of Industrial Technologies.

[PNNL] Pacific Northwest National Laboratory. 1984. Characterization of Industrial Process Waste Heat and Input Heat Streams. PNL-4912.

[ACC] American Chemistry Council. 2000. Guide to the Business of Chemistry. Arlington, V.A.: American Chemistry Council.

[DOE] U.S. Department of Energy. 2001. BestPractices Program Brochure. Washington, D.C.: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Office of Industrial Technologies.