Energy and Environmental Profile of the U.S. Chemical Industry

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Prepared by

ENERGETICS
Incorporated
Columbia, Maryland

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This report was written by Joan L. Pellegrino of Energetics, Inc. in Columbia, MD. It was prepared under the general direction of Lou Sousa, Office of Industrial Technologies (OIT), U.S. Department of Energy, in cooperation with Hank Kenchington, OIT's Chemical Team Leader. This report represents the first attempt to take a comprehensive look at the industry and identify energy use for a wide number of individual processes. The report was reviewed by several experts in the chemical industry and community. However, due to the great complexity of the industry and its products, we acknowledge that we may not have the best or most up-to-date information available in every instance. We welcome comments that would add to the substance of the report. Comments can be forwarded to:

Lou Sousa, U.S. Department of Energy
Forrestal Building, EE-20, Room 5F-043
1000 Independence Ave. S.W.
Washington, DC 20585

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Harry Burney
Dow Chemical Company

Richard Alvarado
Dow Chemical Company

Edward J. Swain
Consultant

Bill Doumas
Consultant

Tom Manuel
Air Products & Chemicals

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FOREWORD

In 1996, the U.S. Department of Energy's Office of Industrial Technologies (DOE/OIT) began work on a series of reports in support of DOE/OIT's Industries of the Future strategy. Under this industry-led strategy, DOE/OIT works with U.S. industry to develop technology partnerships and support collaborative RD&D projects that enhance energy efficiency, competitiveness and environmental performance.

Though the profiles are intended primarily to better inform collaborative industry-DOE R&D planning, they provide a valuable resource that can be widely used by many others who are not directly involved in these efforts. Through these profiles, research managers, policymakers, industry analysts and others can gain a general perspective of energy use and environmental characteristics of the industry. The profiles do not attempt to recreate sources that already exist; rather, they provide a "snap-shot" of the industry and an excellent source of references on the topic.

The profiles synthesize into a single document information that is available in many different forms and sources. Aggregated data for the entire industry as well as data at the process level is presented according to the major unit operations of each industry. Data is obtained from the most currently available published sources, industry experts, and government reports. Prior to publication, profiles are reviewed by those working in the industry, trade associations, and experts in government and the national laboratories.

To date, energy and environmental profiles have been published for the aluminum, steel, metalcasting, petroleum refining, and chemical industries. Development of profiles for the glass, mining, and forest products industries is currently underway, and a similar report is planned for the renewable bioproducts area of agriculture.

1 Overview

1.1 Chemicals: A Huge, Complex, and Highly Diverse Industry

The Industry Produces Over 70,000 Products

The chemical industry is an integral component of the U.S. economy, converting various raw materials (e.g, metals, minerals, coal, oil, natural gas, air, water) into more than 70,000 diverse products. Many of its contributions are not highly visible, however, because most chemical companies are not directly involved in the production of consumer products. The industry itself consumes a large portion of the chemicals it produces–about 24 percent. Since very few goods can be manufactured without some input from the chemical industry, many of the industry's products become essential raw materials for the rest of the manufacturing sector, which purchases about 30 percent of these products. Manufacturers who use large amounts of chemicals represent rubber and plastic products, textiles, apparel, petroleum, paper and allied products, and primary metals. Non-manufacturing sectors also require chemical products, and large purchasers represent the agriculture, construction, and service industries (such as health care), as well as consumer goods (CMA 1998).

The industry creates its diverse slate of products using materials in two forms: organic and inorganic. Organic raw materials (oil, natural gas) are comprised of hydrocarbons that form the building blocks for final organic products. Inorganic chemicals are made from

Examples of Products Created with Chemical Industry Inputs

Paints
Food Packaging
Pharmaceuticals
Detergents
Adhesives
Cleaners
Waste Bags
Packaging Film
Toys
Plastic Bottles
Antifreeze
Printing Inks
Clothing
Carpets
Insulation
Auto Parts
Solvents
Paper

The U.S. Department of Energy and the Chemical Industry of the Future

The U.S. Department of Energy's (DOE's) Office of Industrial Technologies has formed a partnership with the U.S. chemical industry to accelerate the development of technologies and processes that will improve the industry's energy efficiency and environmental performance. This report is intended to support the DOE/chemical industry partnership.

ores or elements taken from the earth (e.g., phosphate, sulfur, potash), air (e.g., nitrogen, oxygen) and water (e.g., chlorine).

In the 1930s, the chemical industry was divided into various categories that were coded under the Standard Industrial Classification (SIC) System, based on the type of chemical processing used and the final products generated (OMB 1987). In 1997, the Office of Management and Budget (OMB) reclassified all U.S. industries under a new coding system, the North American Industry Classification System (or NAICS) (OMB 1997). NAICS recognizes new technologies and industries, and creates a uniform system for the three North American countries. These new classifications will be used in the next census of manufactures conducted by the Department of Commerce, and by other Federal agencies that collect data from industry. At present, however, all industry data is still classified under SIC codes. Appendix A contains an abbreviated list of the new classifications. The individual segments of the SIC code that will be examined in this study are shown in Table 1-1 (the NAICS codes are shown in parentheses).

Table 1-1. Major U.S. Chemical Industry SIC (and NAICS) Codes and Their Corresponding Products

SIC	Major Products
281 Industrial Inorganic Chemicals ***(32518 Other Basic Inorganic Chemical Manufacturing)*** [b]	
2812 Alkalies and Chlorine *(325181 Alkalies and Chlorine Manufacturing)* [b]	Caustic soda (sodium hydroxide), chlorine, soda ash, potassium, and sodium carbonates
2813 Industrial Gases *(32512 Industrial Gas Manufacturing)* [b]	Inorganic and organic gases (acetylene, hydrogen, nitrogen, oxygen)
2819 Industrial Inorganic Chemicals, nec[a] *(325188 Other Basic Inorganic Chemicals Manufacturing)*[b]	Compounds of aluminum, ammonium, chromium, magnesium, potassium, sodium, sulfur, and numerous other minerals; inorganic acids.
282 Plastics and Rubbers ***(32521 Resin and Synthetic Rubber Manufacturing)*** [b]	
2821 Plastics Materials and Resins *(325211 Plastics Material and Resin Manufacturing)* [b]	Synthetic resins, plastics, and elastomers (acrylic, polyamide, vinyl, polystyrene, polyester, nylon, polyethylene)
2822 Synthetic Rubber *(325212 Synthetic Rubber Manufacturing)* [b]	Vulcanizable rubbers (acrylic, butadiene, neoprene, silicone)
286 Industrial Organic Chemicals ***(32511 Petrochemical Manufacturing)*** [b]	
2865 Cyclic Crudes and Intermediates *(325192 Cyclic Crude and Intermediate Manufacturing and 325110 Petrochemical Manufacturing)* [b]	Distilling coal tars; cyclic intermediates, i.e., hydrocarbons, aromatics (benzene, aniline, toluene, xylenes); and organic dyes and pigments. (Note: in the NAICS codes, aromatics have been moved to petrochemical manufacturing.)
2869 Industrial Organic Chemicals, nec[a] *(325110 Petrochemical Manufacturing)* [b]	Aliphatic/acyclic organics (ethylene, butylene, organic acids); solvents (alcohols, ethers, acetone, chlorinated solvents); perfumes and flavorings; rubber processors and plasticizers. (The NAICS codes include aromatics here.)
287 Agricultural Chemicals ***(32531 Fertilizer Manufacturing)*** [b]	
2873 Nitrogenous Chemicals *(325311 Nitrogeneous Fertilizer Manufacturing)* [b]	Ammonia fertilizer compounds, anhydrous ammonia, nitric acid, urea and natural organic fertilizers.
2874 Phosphatic Chemicals *(325312 Phosphatic Fertilizer Manufacturing)* [b]	Phosphatic materials, phosphatic fertilizers

[a] nec means “not otherwise classified”; [b] NAICS codes are shown in parentheses.
Sources: OMB 1987, 1997.

The nine industrial segments represented by the four-digit SICs shown in Table 1-1 account for about 90 percent of the energy consumed and nearly 80 percent of the toxic waste generated by the chemical industry. Industry segments that are not covered in this report are primarily small energy users and/or represent a relatively small share of chemical product shipments. The exception is SIC 283, Drugs, a segment that is a small energy user but one producing very high-value products. It is not included primarily because energy data for this segment is not readily available. Energy data is also not available for SIC 284, Soap, Detergents, Cosmetics, and SIC 285, Paints, Varnishes, Lacquers and Enamels.

1.2 Industry Performance and Market Trends

Industry Has Experienced Substantial Growth

The chemical industry is one of the oldest U.S. industries, with roots going back to 1635. It is a dynamic, internationally competitive industry that invests billions of dollars annually in research and development (R&D), and relies on advanced technologies and innovative products to capture and maintain market share. The industry's composition has changed over the last decade to reflect more diversification into high technology areas (e.g., pharmaceuticals, biotechnologies, advanced materials). Along with this diversification has come an increased emphasis on R&D spending.

The industry accounts for about 5 percent of U.S. gross domestic product (GDP), and about 11.8 percent of the value added to GDP by all U.S. manufacturing. The industry has grown steadily over the last 10 years, and in 1997 achieved record shipments of over $392 billion. Capacity utilization over the same period has risen only slightly (less than 1 percent). The industry's gross investment in new plants and equipment has risen steadily along with R&D funding, a direct result of industry growth and record profits. Table 1-2 summarizes the trends in shipments, investments, and employment for the U.S. chemical industry during the past decade.

The chemical industry is the largest employer in the manufacturing sector, with more than a million workers on its payroll. The complex nature of the industry requires a large number of technically skilled production workers, as well as chemists, chemical and other types of engineers, and professionals from a variety of other technical disciplines (e.g., agronomists, toxicologists, biologists). About 4 of every 10 employees in the chemical industry are in R&D, administration, sales, technical servicing, and clerical positions. Nearly 89,000 scientists and engineers are involved just in R&D–or nearly 14 percent of all those employed in R&D in the entire U.S. manufacturing sector (CMA 1998).

Along with more emphasis on R&D, this highly technical and rapidly changing industry is also increasing its technical services and the amount of automation in its production processes. This has led to a slight decrease in production workers over the last few years, although the remaining labor pool has steadily increased its productivity. Because of the technical nature of the production workforce and its increasing productivity, these workers receive average hourly wages that are about 27 percent higher than those of manufacturing workers as a whole.

Organics Lead the Industry in Shipments

In terms of the value of shipments, SIC 2869, Industrial Organic Chemicals, is ranked first among the four-digit SICs examined for this study (see Figure 1-1). Combined shipments for SIC 2865, Cyclic Crudes, and SIC 2869, Industrial Organic Chemicals (which comprise most of organic chemicals manufacture), were valued at nearly $76 billion in 1996. SIC 2821, Plastic Materials and Resins, which relies heavily on the organic chemical segment for raw materials and intermediates, ranked second with shipments of about $40 billion in 1996. Several segments not covered in this study are shown in Figure 1-1 for comparison, notably pharmaceuticals, soaps and cleaners, and paints.

Together, SIC 2869, 2865, and 2821 accounted for a total of nearly $44 billion in "value added by manufacturing" (DOC 1994). The *value added* by manufacturing essentially represents

Table 1-2. U.S. Chemical Industry Trends in Shipments, Investments, and Employment (SIC 28)

	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
Value of Shipments ($billion)	230	261	283	293	299	305	314	334	362	373	392
Investment in Plant & Equipment ($billion)	9.8	12.4	15.4	17.5	18.5	18.4	18.0	17.8	23.1	23.4	n/a
R&D Spending ($billion)	9.5	10.8	11.5	13.2	14.4	15.1	16.7	16.7	17.3	17.7	18.7
Capacity Utilization (%)	81.3	84.0	83.7	83.0	80.1	80.2	78.6	78.8	78.9	78.4	79.1
Employment (1000s)	1025	1057	1074	1086	1076	1084	1081	1057	1038	1034	1034
Average Hourly Wages $/Hour (Production)	12.36	12.71	13.09	13.54	14.04	14.51	14.82	15.12	15.62	16.17	16.58

Source: CMA 1998.

the value of shipments minus the cost of materials, supplies, containers, fuels, purchased electricity, and other costs encountered during production. It is considered to be the best measure of value available for comparing the relative economic importance of manufacturing and other industries.

Another commonly used chemical industry indicator is "production of the top 50 chemicals." The list of the top 50 chemicals is compiled based on the annual production of selected chemicals throughout all segments of the chemical industry. Although about 30 of the chemicals have been on this list for decades, significant increases or decreases have been noted as changes occurred in consumer demands or external markets (e.g., the production of MTBE, a gasoline additive, increased as the Federal Government changed requirements for transportation fuels). The current top 50 chemicals according to 1997 data are shown in Table 1-3. It should be noted that many of the chemicals on this list are co-produced or are used almost entirely as intermediates in the production of other chemicals on the list.

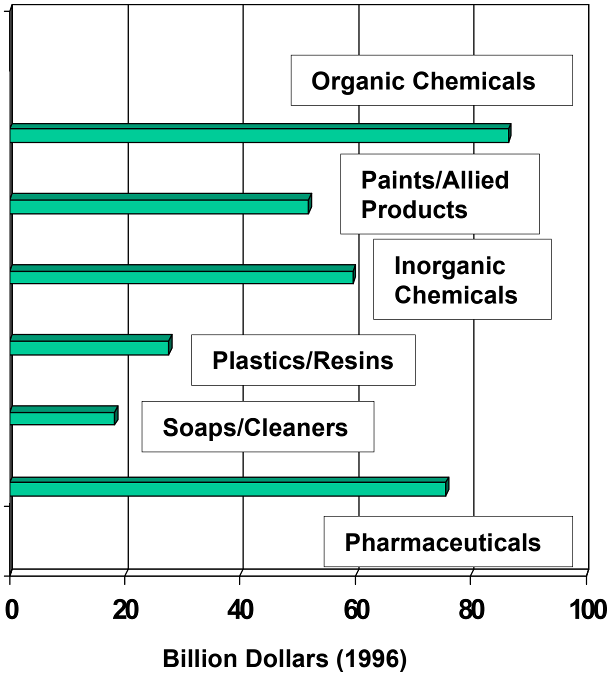


Figure 1-1. 1996 Shipments in Selected Chemical Segments

Examples are oxygen and nitrogen, which are derived from one process, air separation, and ethylbenzene, which is used almost entirely to produce styrene, often in the same plant.

Table 1-3. U.S. Production of Top 50 Chemicals, 1997 (1000 short tons)

Rank	Chemical	Production	Rank	Chemical	Production
1	Nitrogen	47,708	26	p-Xylene	3,963
2	Sulfuric Acid	35,707	27	Ethylene Oxide	3,550
3	Oxygen	30,068	28	Cumene	2,913
4	Ethylene	24,125	29	Ethylene Glycol	2,813
5	Lime	21,175	30	Acetic Acid	2,425
6	Propylene	14,350	31	Phenol	2,175
7	Ammonia	14,204	32	Ammonium Sulfate	2,045
8	Chlorine	12,997	33	Butadiene (1,3-)	2,038
9	Sodium Carbonate (Soda Ash)	11,838	34	Propylene Oxide	1,963
10	Caustic Soda (Sodium Hydroxide)	11,371	35	Carbon Black	1,750
11	Ethylene Dichloride	10,088	36	Acrylonitrile	1,663
12	Phosphoric Acid	9,909	37	Vinyl Acetate	1,500
13	MTBE	9,038	38	Titanium Dioxide	1,478
14	Vinyl Chloride	8,763	39	Acetone	1,463
15	Benzene	7,463	30	Aluminum Sulfate	1,181
16	Ethylbenzene	6,950	41	Sodium Silicate	1,155
17	Nitric Acid	6,765	42	Cyclohexane	1,100
18	Ammonium Nitrate	6,147	43	Bisphenol A	863
19	Methanol	6,013	44	Caprolactam	825
20	Urea	5,918	45	Aniline	713
21	Styrene	5,700	46	Isopropyl Alcohol	700
22	Terephthalic Acid	5,000	47	Sodium Sulfate	639
23	Hydrochloric Acid	4,219	48	Methyl Chloride	563
24	Formaldehyde	4,188	49	Propylene Glycol	538
25	Toluene	4,138	50	Methyl Methacrylate	313
TOTAL PRODUCTION, 1997: 364, 171,000 tons					

Source: CMA 1998.

Plastics Are a Billion-Dollar Industry

Many of the commodity organic chemicals are used as feedstocks in the production of plastics (e.g., polymers). The properties and use of plastics are highly diverse, and they are found in tens of thousands of consumer products. The estimated annual trade in plastics and plastic products is about $274 billion (SPI 1998).

Plastics (i.e., polymers) can be **thermoplastic** or t**hermosetting**. Thermoplastic polymers can be heated and remolded, and are therefore recyclable. Major thermoplastics include polyethylene, polypropylene, acrylonitrile-butadiene-styrene (ABS), polystyrene, nylon, and poly vinyl chloride (PVC).

Thermosetting plastics degrade upon heating and cannot be remolded. Major thermosets include resins of unsaturated polyester, urea, melamine, and phenol.

Engineering resins include fluoropolymers, polycarbonate, thermoplastic polyester, polyamide, and numerous others. These can be thermoplastic or thermosetting.

Recent data on U.S. plastics production is summarized in Table 1-4. About 92 billion pounds of polymeric materials were produced in the United States in 1998. Of this, more than 71 billion pounds were thermoplastics, while a much smaller quantity were thermosets (about 9 billion pounds). About 11 billion pounds of engineering resins and other plastics were also produced (SPI 1998).

Table 1-4. U.S. Plastics Production, 1997–1998 (millions of pounds, dry weight basis)

Plastic	1998	1997	% Change 98/97
Thermosets (TOTAL)	9,163	8,647	6.0
Epoxy	639	654	-2.3
Polyester (Unsaturated)	1,713	1,621	5.7
Urea	2,581	2,335	10.5
Melamine	290	303	-4.3
Phenolic Resins	3,940	3,734	5.5
Thermoplastics (TOTAL)	71,209	78,142	2.9
Low Density Polyethylene (PE)	7,578	7,691	-1.5
Linear Low Density PE	7,227	6,888	4.9
High Density PE	12,924	12,557	2.9
Polyproplyene (PP)	13,825	13,320	3.8
Acrylonitrile-Butadiene-Styrene (ABS)	1,432	1,374	4.2
Styrene-Acrylonitrile Rubber	122	96	27.1
Other Styrenics	1,654	1,623	1.9
Polystyrebe (PS)	6,237	6,380	-2.2
Nylon	1,285	1,222	5.2
Poly Vinyl Chloride	14,502	14,084	3.0
Thermoplastic Polyester	4,423	4,260	3.8
Engineering Resins	2,766	2,619	5.6
All Other Plastics	8,547	8,045	6.2
GRAND TOTAL	91,685	88,806	3.2

Source: SPI 1998.

The plastics industry has increasingly become globalized, and is primarily comprised of large, vertically integrated, multi-national chemical companies. Considerable consolidation has occurred in the industry, with the major products manufactured by fewer than five large companies. With globalization has come a shift in the production of many of the basic commodity resins to Saudi Arabia, China, South Korea, and other countries. The more highly industrialized countries such as the United States, Western Europe, and Japan have responded to this competition by increasing their production of specialty and higher-value-added products and adjusting their production capacity to improve profitability. By taking advantage of their advanced technology and research, highly developed producers can reduce the impacts of market cycles (DOC 1999).

Mature producers of plastics are increasing their exports to fast-growing parts of the world such as Mexico, South America, and Asia. Economic trends in these countries in turn can have a significant impact on future exports from the United States (as seen during the recent economic downturn and currency crisis in Asia). It is expected, however, that U.S. producers will continue to find opportunities for growth in these markets, despite economic fluctuations in the areas (DOC 1999).

The largest change in polymer chemistry in this decade has been the development and commercialization of **metallocene catalysts**, which make it possible to refine and even design the structure of polymers. Since these catalysts were first discovered in the 1980s, as much as $3 billion has been spent on research to modify, improve, and extend them (C&E 1995). Metallocene-based polymers demonstrate increased impact strength and toughness, better melt characteristics, and improved film clarity compared to earlier polymers.

Polymers made with metallocene catalysts have been available commercially since 1991 when Exxon first used its Exxpol catalysts to produce them. At the present time, Exxon Chemical and Dow Plastics are the major producers of these polymers in the United States, with over 1 billion pounds of capacity on-line (see Table 1-5 for a summary of the worldwide capacity for producing metallocenc-based polymers).

Metallocene catalysts are being used to produce improved polymers as well as entirely new kinds of polymers. Some compete with conventional polymers for use in packaging, medical equipment, and other applications. In other cases, new polymers are being produced that have unique densities and that will compete in entirely different markets than those where conventional plastics have been used.

The manufacture of metallocene-catalyzed thermoplastics has been growing at a rapid pace, both in the United States and globally. It remains, however, a small portion of total resin production. Market share is expected to rise worldwide as new technical advances are made and prices for the products fall (DOC 1999).

U.S. Is the World's Largest Chemical Producer and Second Largest Exporter

U.S. industry is now the largest producer of chemicals worldwide, accounting for about 25 percent of the $1.5-trillion global chemicals market. Japan, Germany, and France rank next in total production. The U.S. chemical industry's share of the global market is increasingly focused on specialty chemical products, particularly those where the industry has developed a technological advantage.

The U.S. chemical industry began exporting goods in the 18th century, when it established a limited export trade in potash and naval stores with the United Kingdom. The industry has historically maintained large trade surpluses, even during the late 1980s when the nation as a whole experienced huge trade deficits that were often over $100 billion. In 1997 the U.S. trade surplus in chemicals was $19.2 billion.

The United States is currently the second largest exporter of chemicals (after Germany), capturing about 15 percent of total world exports in 1997. Canada is the single largest market for U.S. chemical exports, followed by Japan. Exports to developing countries (e.g., Mexico, Latin America, Asia) are large in number and growing. Exports of U.S.

Table 1-5. Global Capacity for Metallocene-Based Polymers

Company	Location	Capacity[a] (millions of lbs per year)
Polyethylenes		
Dow Plastics	U.S.	250
Dow Plastics	Spain	125
Exxon Chemical	U.S.	253
Mitsubishi	Japan	220
Nippon Petrochemicals	Japan	110
Ube Industries	Japan	44
Total		**1,002**
Polypropylenes		
BASF	Germany	26
Chisso	Japan	44
Exxon Chemical	U.S.	220
Hoechst	Germany	220
Mitsui Toatsu	Japan	165
Total		**675**
EPDM[b]		
Dow/DuPont	U.S.	198
Cyclic Olefins		
Dow Plastics	U.S.	Pilot
Hoechst	Germany	Pilot
Mitsui Petrochemical	Japan	7
Polystyrene		
Idemitsu Petrochemical	Japan	22
TOTAL WORLDWIDE		**1,904**

[a] Forecasted by 1996

[b] Ethylene-propylene-diene monomer rubber

Source: C&E 1995.

chemicals to Mexico grew 196 percent between 1989 and 1997. Overall, exports of U.S. chemicals have grown at a rate of more than10 percent annually over the last 10 years (CMA 1998).

Despite U.S. Productivity, All Industry Sectors Face Increased Competition

U.S. imports of chemicals have also risen steadily during this period. This was particularly true for organic chemicals, where imports increased by nearly 14 percent from 1996 to 1997. Nearly $25 billion worth of products were imported into the United States in 1997, the majority from Western Europe. The global trade in organic chemicals is among the most competitive in the industry. While developed countries (United States, Western Europe, Japan) have traditionally dominated this sector of the industry, developing regions are also experiencing rapid growth rates. Countries increasing their chemical trading include Asia, the Middle East, and Latin America (DOC 1999). Figure 1-2 summarizes the value of the U.S. chemical trade over the last 10 years.

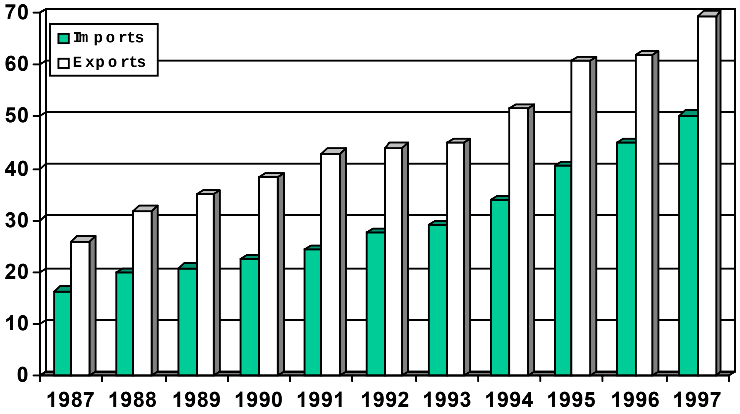


Figure 1-2. Value of U.S. Chemical Trade (CMA 1998)

Worldwide, the United States is the largest producer of phosphate fertilizers and the second largest producer of nitrogen fertilizers. Other countries, however, have large phosphate rock resources, and are expected to increase production of these products. Morocco, for example, has over 50 percent of the world's phosphate rock reserves, and is the largest phosphate rock exporter, primarily to European markets. A significant amount of phosphate fertilizer is also produced in China, India, and the former Soviet Union.

Figure 1-3 shows U.S. exports and imports of chemicals in 1997 according to Standard International Trade Classification categories (CMA 1998). A list of these categories can be found in Appendix A and they correlate fairly well with U.S. SIC/NAICS codes.

Despite a growing demand for petrochemicals worldwide, there is increasing competition in the export market for these raw materials also. It is anticipated that products from the Gulf Cooperation Council and Pacific Rim countries, including China and Korea, will begin to compete with U.S. products in current export markets as new facilities become operational in these developing areas.

Globalization has also become a key element in the inorganic chemicals sector. About one-third of the inorganic chemicals produced in the United States are exported, primarily to Canada, Japan, Mexico and Asia. About one-third of these total exports go to Asia, although they have been affected recently by economic slowdowns in the region (DOC 1999).

Foreign trade is an important aspect of the agricultural chemicals sector, representing about a third of shipments from U.S. manufacturers. China is the largest importer of U.S. fertilizers (30 percent), followed by the Asian Pacific markets (33 percent) and Latin America (25 percent). Despite their fluctuating economies, the developing countries, particularly Asia and Latin America, are high-growth markets for U.S. fertilizers (DOC 1999).

The North American Free Trade Agreement (NAFTA) and the Uruguay Round of the General Agreement on Tariffs and Trade (GATT) have reduced trade barriers and helped contribute to increased competition. U.S. firms are adapting by increasing their emphasis on specialty chemicals and higher value-added products (EPA 1995b).

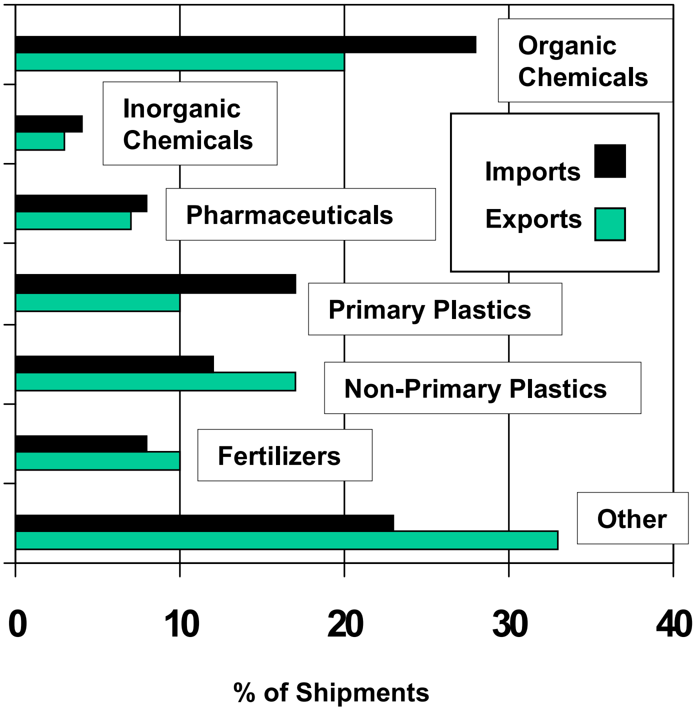


Figure 1-3. U.S. Exports and Imports of Chemicals by Product Area, 19997 (CMA 1998**)**

1.3 Energy and Materials Consumption

Energy Is Used Both as Fuel and Feedstock

In this report, the term “energy”will include energy used to supply heat and power for manufacturing processes as well as energy feedstocks such as natural gas and petroleum used as raw materials to produce a range of petrochemicals, plastics, and synthetic fibers. Moreover, certain chemical, physical, and biological separation and synthesis processes are required to transform these (and other) raw materials into salable products. These in turn consume large amounts of energy in the form of heating, cooling, or electrical power.

According to the most recent Manufacturing Energy Consumption Survey (MECs) conducted by the Energy Information Administration of the U.S. Department of Energy, the U.S. chemical industry consumed 5.051 quads (quadrillion Btu, or 10^{15} Btu) of energy (excluding electricity generating and transmission losses) in 1994 (EIA 1997). This represents about 7 percent of all domestic energy use that year, and approximately 25 percent of all U.S. manufacturing energy use.

The Chemical Manufacturers Association (CMA) also estimates and publishes energy data on the industry, and its most recent study indicates that the chemical industry’s energy consumption was 6.283 quads in 1997 (CMA 1998). Historical data on energy consumption from both CMA and MECs is shown in Tables 1-6 and 1-7 respectively. The discrepancy between these sets of data is attributed to differences in the methods used to collect and estimate the data.

The industry uses a diversity of fuel sources for its energy needs (e.g., electricity, natural gas, coal, crude oil, and derivatives), with nearly 50 percent of the total used as feedstocks. The chemical industry is the largest consumer of natural gas in the United States, requiring more than 10 percent of the total amount used domestically, and accounts for nearly 7 percent of all U.S. petroleum products consumed (equivalent to about 1.5 million barrels of oil per day). Table 1-8 provides a breakdown of the chemical industry’s energy use by fuel type and feedstock category for 1997.

Although they vary widely from product to product, energy expenditures can represent a significant portion of manufacturing costs in the chemical industry. For some products, energy for heat, power, and feedstocks can consume up to 85 percent of total production costs. In 1997 the industry spent about $29 billion on energy for all purposes, including feedstocks. These energy expenditures, however, represent only 9 percent of the value of chemical shipments. Purchases of fuels and electric energy across the industry for heat and power are shown in Figure 1-4, based on data from the Bureau of the Census (DOC 1998).

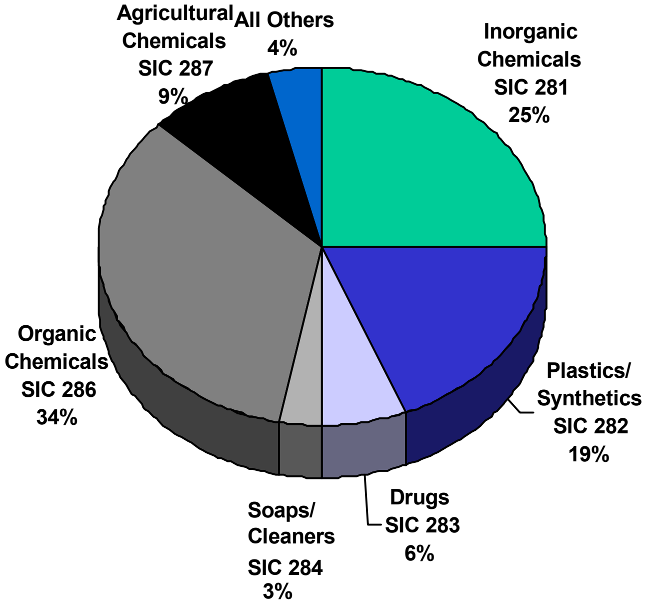


Figure 1-4. Purchases of Fuel and Electric Power in the U.S. Chemical Industry (SIC 28), by Industry Segment - 1996 (DOC 1998)

Table 1-6. U.S. Chemical Industry (SIC 28) Energy Use 1987–1997; CMA Estimates (Trillion Btu)

Year	Fuels	Purchased Electricity	Feedstocks	Net Energy Use	Electricity Losses[a]	TOTAL ENERGY USE
1987	2,014	409	2,215	4,638	850	5,488
1988	2,124	423	2,332	4,879	879	5,758
1989	2,153	444	2,290	4,887	922	5,809
1990	2,214	454	2,488	5,156	943	6,099
1991	2,200	474	2,610	5,284	985	6,269
1992	2,264	488	2,689	5,441	1014	6,455
1993	2,337	498	2,740	5,575	1035	6,610
1994	2,367	522	2,899	5,788	1084	6,872
1995	2,465	515	2,852	5,832	1070	6,902
1996	2,499	540	3,042	6,081	1122	7,203
1997	2,489	545	3,248	6,282	1132	7,414

[a] Electricity losses incurred during the generation, transmission, and distribution of electricity are based on a conversion factor of 10,500 Btu/kilowatt-hour.
Source: CMA 1998.

Table 1-7. U.S. Chemical Industry (SIC 28) Energy Use, 1985, 1988, 1991, and 1994: MECS Estimates (Trillion Btu)

Year	Fuels	Purchased Electricity	Feedstocks	Net Energy Use	Electricity Losses[a]	TOTAL ENERGY USE
1985	1,781	432	1,354	3,567	897	4,464
1988	2,266	416	1,678	4,360	864	5,224
1991	2,253	440	2,358	5,051	914	5,965
1994	2,345	520	2,463	5,328	1,080	6,408

[a] Electricity losses incurred during the generation, transmission, and distribution of electricity are based on a conversion factor of 10,500 Btu/kilowatt-hour.
Sources: EIA 1988, 1991, 1994b, 1997.

Table 1-8. U.S. Chemical Industry (SIC 28) Energy Use by Fuel and Feedstock Category, 1997 (Trillion Btu)

Energy Used for Heat and Power		
Electricity (excludes losses)	545	18%
Natural Gas	1,927	64%
Coal and Coke	250	8%
Fuel Oil and LPG	61	2%
Other	251	8%
TOTAL	3,034	100%
Feedstock Energy		
Liquefied Gases	1,106	34%
Heavy Liquids	1,513	47%
Natural Gas	598	18%
Coal	32	1%
TOTAL	3,248	100%

Sources: EIA 1997, CMA 1998.

On-Site Cogeneration and Direct Generation Supply One-Fourth of Industry's Electricity for Manufacturing

Electricity for chemical manufacturing can be purchased from utilities and independent power producers, or it can be produced on-site by **cogeneration** or **direct generation**. Cogeneration is the co-production of electricity and process heat. Cogenerating systems use fossil fuels or other combustibles (e.g., wood, process wastes) to power a gas or steam turbine, which runs a generator to produce electricity. Waste heat that is otherwise discarded is captured to produce steam for process needs and to power steam turbines to generate additional electricity.

Chemical plants are second only to pulp and paper mills as the largest industrial cogenerators in the manufacturing sector. Electricity produced by cogeneration often provides a competitive advantage to purchased electricity, since efficient systems can operate at greater than 90 percent thermal efficiency compared to 30–35 percent efficiency for direct generation. If pertinent regulations allow, any excess electricity can be sold back to the utility, providing additional cost benefits to the chemical plants.

As illustrated in Figure 1-5, the cogeneration capacity in chemical plants more than doubled between 1985 and 1994, with the electricity supplied by cogeneration systems increasing an average of 14 percent per year. This has helped improve the chemical industry's efficiency and profitability (CE 1992a, EIA 1997).

Table 1-9 shows how the demand for electricity is currently met in six of the chemical segments that are significant cogenerators or direct generators of electricity. Most cogenerating capacity is found in four segments: Plastics Materials and Resins, Organic Chemicals, Inorganic Chemicals, and Fertilizers.

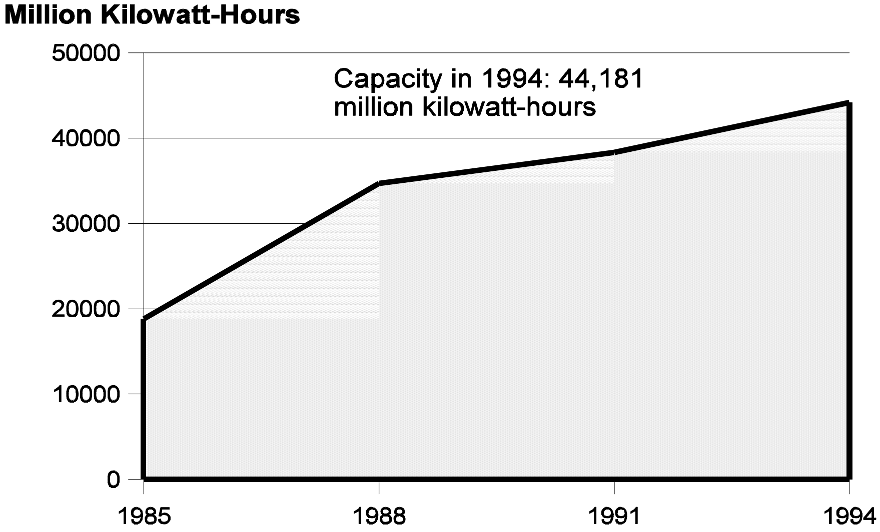


Figure 1-5. Trends in Cogeneration Capacity in the Chemical Industry
(CE 1992a, EIA 1997)

Table 1-9. Components of Electricity Use in the U.S. Chemical Industry, 1994: Selected Segments (Million Kilowatt-hours)					
Segment	**Purchased Electricity**	**Cogeneration**	**Direct Generation**	**Sales/Transfers Off-site**	**Total Demand**
SIC 2813 Industrial Gases	23,525	512	-	-	24037
SIC 2819 Industrial Inorganic Chemicals	42,861	2,794	283	622	45,315
SIC 2821 Plastics Materials and Resins	16,976	4,616	36	568	21,060
SIC 2865 Cyclic Crudes and Intermediates	4,794	817	1	5	5,607
SIC 2869 Industrial Organic Chemicals	22,537	23,522	2,072	3,751	44,380
SIC 2873 Nitrogenous Fertilizers	3,851	653	35	14	4,505
SIC 2874 Phosphatic Fertilizers	2,185	2,963	-	1,053	4,095

Source: EIA 1997.

Fuel and Feedstock Use Vary Considerably among Industry Segments

With thousands of processes used to produce the more than 70,000 products of the chemical industry, it is not surprising that manufacturing energy use varies significantly among different segments of the industry.

Within individual industry segments, energy use is closely tied to product configurations and whether fuels are used as a raw material (feedstock). Inorganic chemicals (alkalies and chlorine compounds, industrial gases, acids, salts of aluminum, bauxite, sodium, and other minerals) are not usually produced from energy feedstocks (with the exception of urea). Since they do not contain organic carbon, they are made primarily from mineral ores taken from the earth or through the liquefaction of air.

Organic chemicals, on the other hand, begin with raw materials that contain hydrocarbons, such as crude oil derivatives, natural gas, and coal. Large manufacturing plants producing primary olefins (e.g., ethylene, propylene, butadiene) require a substantial and reliable supply of petroleum-based feedstocks–gas oil, naphtha, propane, or ethane. These plants are often located near petroleum refineries to ensure an adequate supply of these materials.

Availability of feedstock is a primary concern for many chemical producers. The industry is highly susceptible to volatility in price and supply of energy feedstocks, a fact made evident during the oil embargo of 1973. The U.S. chemical industry posted a substantial trade surplus of more than $21 billion in 1995, but imports of large quantities of energy-based organic chemicals grew sharply in the last five years and this trend is continuing. To reduce the risk of interruptions in feedstock supply, chemical companies are examining ways to become more flexible in their choice of feedstocks, for example, by shifting from gas feeds to oil feeds. Some firms are also investigating the use of renewable resources such as biomass and processing wastes as alternative feedstocks.

Feedstock requirements can also be reduced by increasing conversion efficiencies and product yields. Some firms have accomplished this by implementing better process monitoring and control. For example, they choose to more accurately control the distillation process in order to decrease both feedstock and fuel requirements. This may also be achieved through new, more efficient production processes. A good example is the direct production of acetaldehyde from ethylene, rather than through a process that converted ethane to ethylene to ethanol and finally to acetaldehyde, as carried out prior to 1980. The direct process has resulted in a 15 percent improvement in the acetaldehyde-to-ethane yield ratio (EEA 1983).

Figure 1-6 compares the use of feedstock energy with the use of fuels for producing heat and power by the major segments of the chemical industry. It is clear that the segments producing organic chemicals depend on feedstock most heavily. Not all 4-digit SICs are represented in Figure 1-6, only those for which energy data is available or significant.

Figure 1-6 shows that the use of energy feedstocks was significant (between 25 and 55 percent) in three major chemical segments in 1994. Within these segments, primary energy feedstocks as well as intermediate products manufactured from primary energy feedstocks comprise a large portion of the raw materials used.

2821 Plastics Materials and Resins. Within this segment, natural gas, still gas (gas produced by distillation processes and comprised mostly of methane and other light gases), and a variety of organic intermediates derived from energy feedstocks are used as building blocks in the production of polymers, elastomers, and synthetic resins.

A breakdown of the primary raw materials used in this segment is shown in Table 1-10, based on the latest Census of Manufactures (1992). Major organic intermediates consumed include ethylene, propylene, and vinyl monomers (chloride and acetate). The use of energy-based intermediate feedstocks accounts for a substantial 73 percent of raw material costs in this segment.

SIC 2865 Cyclic Crudes and Intermediates. This segment consumes natural gas and other hydrocarbons as well as a number of organic and inorganic intermediates to produce aromatic organic chemicals (benzene, toluene, naphthalene), and organic dyes and pigments. The products from this segment are subsequently used in the production of a myriad of consumer products ranging from packaging to paints to pharmaceuticals.

As shown in Table 1-11, organic intermediates and hydrocarbon gases account for a large share of raw material costs (66 percent). Organic chemicals (benzol, xylenes, acetone, other cyclic crudes) account for the largest portion of energy-based feedstocks (about 54 percent).

SIC 2869 Industrial Organic Chemicals. This very diverse segment consumes large quantities of natural gas and other energy-based organic intermediates to manufacture high-volume commodity chemicals that are used as intermediates in many chemical processes. The most important products manufactured include ethylene, butylene, butadiene, alcohols and many other solvents, rubber processing chemicals, plasticizers, and organic acids.

As shown in Table 1-12, hydrocarbon gases account for a large share of energy-based raw materials used in this segment (37 percent).

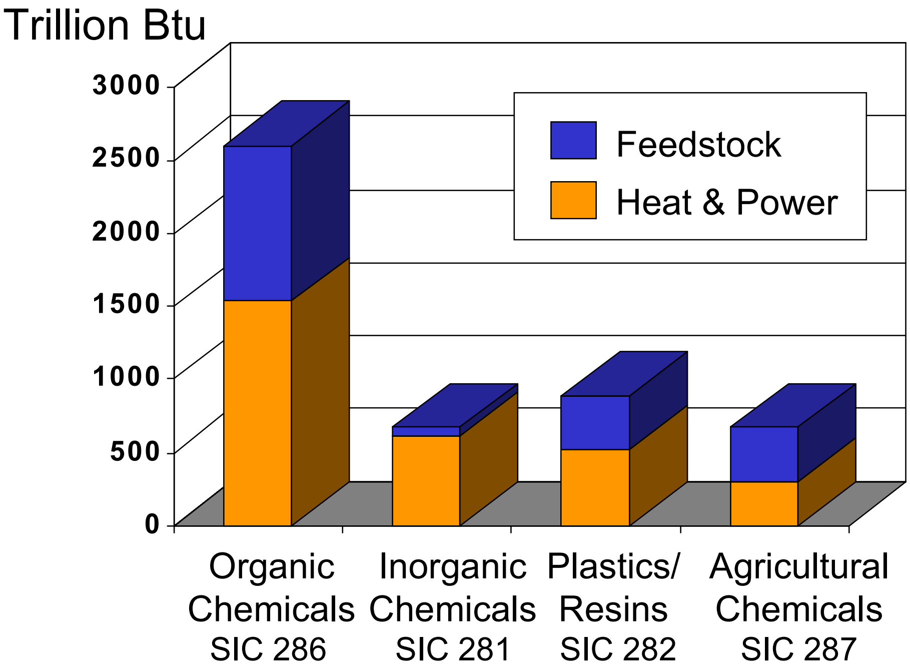


Figure 1-6. Fuel Versus Feedstock Consumption in Selected Chemical Industry Segments, 1994 (Source: EIA 1997)

Table 1-10. Feedstock and Materials Use in SIC 2821, Plastics Materials and Resins (1992)

Material	Delivered Cost ($millions)	% of Total Raw Materials Cost
Total Raw Materials and Supplies	**$16,946.8**	**100**
Hydrocarbons used as raw materials or feedstocks:		
Natural gas, ethane, ethylene, propane, propylene, butane, butylene, and others	4,867.5	29
Synthetic organic chemicals:		
Styrene	1,345.6	8
Other cyclic crudes and intermediates (phenol, benzene, others)	920.0	6
Alcohols	188.3	1
Organic dyes	22.8	<1
Acrylates and methacrylates, monomers	774.8	4
Vinyl chloride monomer	1,017.6	6
Vinyl acetate monomer	278.8	2
Rubber processing chemicals	194.5	1
Other organics (acrylonitrile, formaldehyde, etc)	1,986.3	12
Plastic resins (granules, pellets, powders)	620.1	4
Carbon Black	14.5	<1
TOTAL ENERGY-BASED RAW MATERIALS	**12,230.8**	**73**
Inorganic chemicals	412.6	2
Miscellaneous packaging	4303.4	26
TOTAL NON-ENERGY BASED RAW MATERIALS	**4,716.0**	**28**

Source: DOC 1995b, *Industry Series, Plastics Materials, Synthetic Rubber, and Manmade Fibers*.

Synthetic organic chemicals (alcohols, aromatics, other solvents) are also consumed in large quantities (24 percent of total raw materials). Overall, the use of energy-based raw materials represents about 61 percent of total raw material costs in this segment. In terms of Btus, this segment is the largest consumer of energy feedstocks and combustible energy for heat and power in the chemicals industry.

SIC 2873 Nitrogenous Fertilizers. The primary energy feedstock used in this segment is natural gas, which is necessary for the production of ammonia, a major component in nitrogenous fertilizers. This segment also relies on already-manufactured ammonia, which is purchased or is available from on-site inventories. As shown in Table 1-13, a substantial portion of the raw material costs for this segment–67 percent– is derived from the combined use of natural gas and manufactured ammonia. Inorganic materials including phosphate compounds, potassic compounds, inert fillers, sulfur, and sulfuric acids also comprise a portion of this segment's raw material costs.

Table 1-11. Feedstock and Materials Use in SIC 2865, Cyclic Crudes and Intermediates (1992)

Material	Delivered Cost ($millions)	% of Total Raw Materials Cost
Total Raw Materials and Supplies	**$5,604.1**	**100**
Hydrocarbons used as raw materials or feedstocks:		
Natural gas, ethane, ethylene, propane, propylene, butane, butylene, and others	673.5	12
Organic chemicals:		
Alcohols	54.2	1
Benzol	436.5	8
Tar, crude	131.3	2
Other cyclic crudes and intermediates	517.0	9
Other organics	760.8	14
Plastic Resins	7.7	<1
Other energy feedstocks, nec	455.2	8
TOTAL ENERGY-BASED RAW MATERIALS	**3,036.2**	**54**
Inorganic chemicals (acids, sulfur, chlorine)	350.9	6
Industrial gases	20.6	<1
Miscellaneous Materials	2,196.4	39
TOTAL NON-ENERGY-BASED RAW MATERIALS	**2,567.9**	**46**

Source: DOC 1995b, *Industry Series, Industrial Organic Chemicals.*

Table 1-12. Feedstock and Materials Use in SIC 2869, Industrial Organic Chemicals (1992)

Material	Delivered Cost ($millions)	% of Total Raw Materials Cost
Total Raw Materials and Supplies	**$26,535.5**	**100**
Hydrocarbons used as raw materials or feedstocks:		
Natural gas, ethane, ethylene, propane, propylene, butane, butylene, and others)	9,742.7	37
Organic chemicals:		
Alcohols	1,183.8	5
Toluene and xylenes	657.9	2
Benzol	573.8	2
Phenol	481.8	2
Other cyclic crudes and intermediates	698.2	3
Acetone	175.1	1
Other synthetic organic chemicals	2,382.3	9
TOTAL ENERGY-BASED RAW MATERIALS	**15,895.6**	**61**
Inorganic chemicals (acids, ammonia, chlorine, caustic soda)	1,780.4	6
Industrial gases	162.1	1
Miscellaneous Materials	8,697.3	32
TOTAL NON-ENERGY-BASED RAW MATERIALS	**10,639.8**	**39**

Source: DOC 1995b, *Industry Series, Industrial Organic Chemicals.*

Table 1-13. Feedstock and Materials Use in SIC 2873, Nitrogenous Fertilizers (1992)		
Material	Delivered Cost ($millions)	% of Total Raw Materials Cost
Total Raw Materials and Supplies	$1,189.4	100
Natural gas	514.2	43
Ammonia and ammonia compounds	287.0	24
TOTAL ENERGY-BASED RAW MATERIALS	**801.2**	**67**
Inorganic chemicals (phosphatic materials, potassic materials, sulfuric acid, sulfur, phosphate rock)	59.8	5
Miscellaneous Materials	328.4	28
TOTAL NON-ENERGY-BASED RAW MATERIALS	**388.2**	**33**

Source: DOC 1995a, *Industry Series, Agricultural Chemicals.*

Minerals Are Also Important Feedstocks in Chemicals Production

The chemical industry is one of the largest consumers of minerals in the United States, using about $6 billion worth of minerals as raw materials for a wide variety of chemical products in 1995. The actual quantities of minerals consumed in 1995 are shown in Table 1-14. Phosphate, salt, sulfur, potash, lime, and gypsum account for about 98 percent of the minerals used (CMA 1996)

Table 1-14. Chemical Industry (SIC 28) Minerals Use (1995)	
Mineral	**Quantity (1000 tons)**
Phosphate	52,645
Salt	21,850
Sulfur	13,405
Potash	9,970
Lime	4,935
Gypsum	3,340
Clay	1,455
Titanium	880
Fluorspar	435
Bauxite	280
Talc	235
Zinc	225
Magnesium	210
Diatomite	140
Bromine	75

Source: CMA 1996.

Improvements in Energy Efficiency Are Relatively Flat

The U.S. chemical industry has made significant improvements in energy efficiency over the last two decades. As shown in Figure 1-7, energy consumed for heat and power per unit of output declined by more than 39 percent between 1974 and 1995, a trend that was precipitated by the oil crises of 1973 (CMA 1996). Improvements in efficiency have remained relatively flat, however, since the late 1980s, primarily because of the availability of inexpensive energy for heat, power, and feedstocks. When energy prices are low, investments made to improve energy efficiency are far less attractive than investments made to increase market share (such as new product development). Figure 1-7 reflects trends in fuels purchased for heat and power, and does not reflect trends in feedstock consumption.

Much of the improved efficiency achieved over the last two decades has resulted from aggressive energy management and housekeeping programs instituted during the early 1970s, which are now an integral and established part of operations management at many firms. Many of these housekeeping improvements have focused on steam generation and distribution and operating practices for fueled reactors and fired heaters.

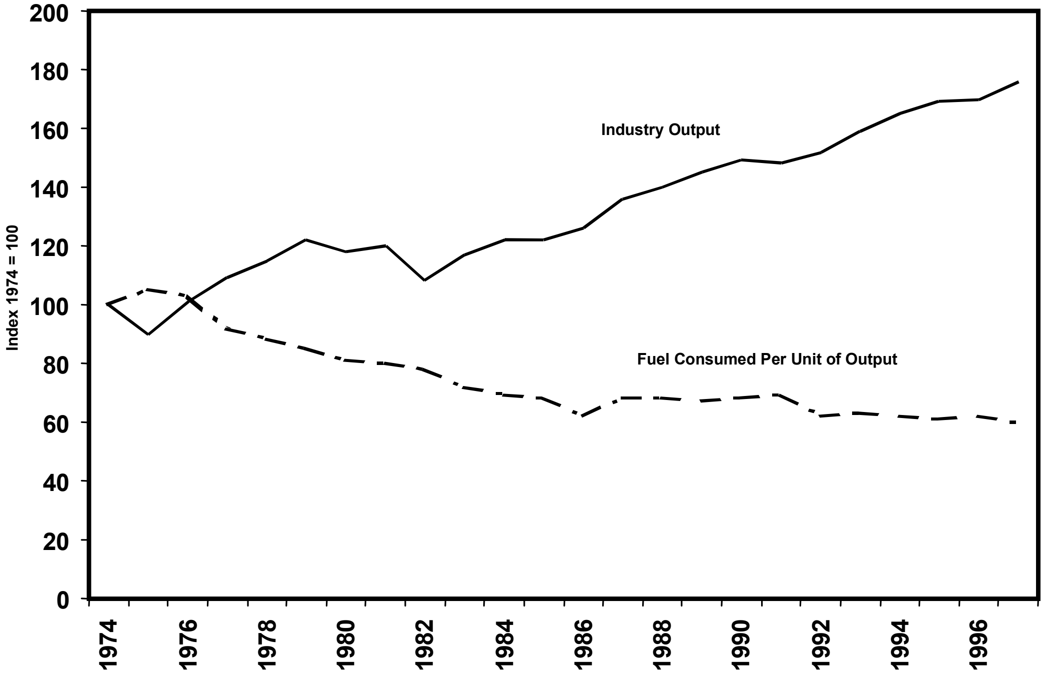


Figure 1-7. Energy Intensity Trends Related to Heat and Power in the U.S. Chemical Industry, 1974 - 1997 (Source: CMA 1998)

Improvements in process and equipment design have also contributed to gains in energy efficiency (e.g., more efficient designs for distillation, absorption, and other separation processes). The increased adoption of energy-efficient practices such as cogeneration and on-site recovery of waste heat and energy, including heat recovery from exothermic reactions, have also helped to reduce overall energy intensity.

More recent gains in energy and material efficiency have resulted from the realization that waste minimization could help decrease the cost of environmental compliance. (End-of-the-pipe waste treatment and disposal options often carry a heavy energy burden.) However, as regulations grow more stringent, the largest percentage of funds continues to be diverted toward non-productive investments on end-of-the-pipe controls to avoid the penalties of non-compliance.

Nonetheless, further efficiency gains could play an important role in the industry's ability to maintain its competitive edge in global markets. The increasing complexities of environmental compliance, changing product configurations, and growing competition from resource-rich developing countries are all challenges to the industry. These challenges can be met in part through improved efficiency, the use of innovative processing routes, and decreased dependence on petroleum-based feedstocks.

Many of the low-cost, high-return investments (e.g., housekeeping, improved operating practices) have already been made. Further gains may require more dramatic changes in process design and in innovative R&D.

Chemical Process Efficiency Is Limited by Thermodynamic and Other Constraints

The efficiency of any individual process used in chemicals manufacture is dependent on optimizing a number of process variables (e.g., temperature, pressure) that may be constrained by thermodynamic, kinetic, or transport limitations. Thermodynamic limitations, for example, dictate allowable conversions for catalytic reactions, requiring that several passes be made over the catalyst before an acceptable yield is obtained. These additional passes require energy for heating/cooling or separating the feedstocks, which increases energy intensity.

Thermodynamic constraints also place practical limits on many commonly used separation processes such as distillation. Some reactions are kinetically limited due to the production of unwanted byproducts. Transport limitations arise with some highly exothermic reactions as heat is generated at a faster rate than it can be effectively removed.

Chemical processing is further complicated by the fact that a series of unit operations is often required to reach the final end product. For example, ammonia is produced by the Haber process, which converts air and methane to ammonia and carbon dioxide. In this process, methane and air must first be passed through a steam reformer to yield hydrogen and nitrogen gas along with carbon dioxide. These gases must then be passed through a separator to remove the carbon dioxide.

Once this is accomplished, the hydrogen and nitrogen gases are sent to a catalytic reactor where they require about four passes over a catalyst to attain a yield of about 88 percent ammonia. The energy efficiency of this process depends on the combined efficiency of all these operations, as well as the operating conditions within individual plant sites.

Given these complexities, it is often difficult to accurately assess the overall efficiency of chemical processes. Typically, a range of energy intensities is reported in the literature based on actual operating experiences. While this can provide an average assessment of energy requirements, it gives little insight into potential efficiency gains. Theoretically, minimum energy requirements for producing any chemical can be determined based on the net chemical reaction used to produce the chemical. While this technique does not consider the individual unit operations and auxiliary equipment requirements, it may provide a simplistic gauge for evaluating the efficiency of actual operating practices.

A study done several years ago by Argonne National Laboratory (ANL 1991) compared the theoretical minimum energy requirements for producing 31 of the top 50 chemicals with published ranges of production energy intensity. In this study, theoretical minimum energy requirements were derived by determining the reversible work for the reaction, based on Gibbs free energy at ambient conditions. (See the sidebar on the next page for further explanation of minimum theoretical energy and Gibbs free energy.) The actual net production energy intensity (Btu/ton) was then compared with theoretical energy intensity to determine efficiency as a percent of the theoretical minimum requirements. For exothermic processes that produce energy, energy requirements were determined based on the percentage of available energy that was not recovered.

Figures 1-8 through 1-11 show the theoretical versus the actual energy requirements for producing various chemicals that were determined during this study (ANL 1991 and updates). These chemicals represent four different 4-digit SICs. These results illustrate that a range of efficiencies occurs within all chemical segments.

By calculating the difference between the minimum theoretical energy required and the energy consumed in practice, it is possible to estimate the potential energy savings if these chemicals were produced under “minimized” or ideal conditions. However, in commercial applications, it is unlikely that ideal conditions can be achieved. Moreover, energy beyond the theoretical minimum will be required to operate auxiliary equipment such as pumps, compressors, and fans, and to carry out other unit operations such as separations to recover the final product.

Finally, there are always some irreversibilities associated with chemical reactions as well as heat transfer operations that place practical and economic limitations on reaching the minimum theoretical energy use.

Keeping these limitations in mind, the results of this study still provide a preliminary analysis of the potential for improved energy efficiency and reduced energy consumption. Figure 1-12 compares theoretical and actual energy requirements using this methodology, broken out by 4-digit SIC codes. The graph shows there is considerable room for improvement in many chemical processes.

The largest potential for energy savings is evident in the organic chemicals segment, which relies heavily on energy-based feedstocks. This segment accounts for production of high volume chemicals (e.g., ethylene, propylene, benzene) that are important as intermediates in many other chemical processes. The difference between actual and theoretical energy requirements in this segment (for the selected chemicals reviewed in the study) is nearly 80 million Btu per ton of product.

The inorganic chemicals segment exhibits the next highest potential, primarily because sulfuric acid, nitrogen, oxygen, and lime are among the top five chemicals produced in the United States. Given their volume of production, energy inefficiencies in the processes used to produce these chemicals can have a significant impact on energy use. Energy dependence in these segments is on fuels used for heat and power rather than feedstock energy. The difference between actual and theoretical energy requirements in this segment (for the chemicals reviewed) is about 30 million Btu per ton of product.

The agricultural chemicals segment, which included some of the most inefficient chemical processes, such as production of ammonium

Minimum Theoretical Energy and Gibbs Free Energy

***Minimum theoretical energy** can be defined as the minimum energy required to synthesize a substance in its standard state from substances also in a standard state*. It can also be defined as the maximum work or available energy that can be attained when the substance is brought from its standard state to complete thermodynamic equilibrium. A system closed to heat and mass transfer is at thermal equilibrium if there are no temperature gradients in the system. A closed system is at thermal equilibrium if no pressure gradients exist. The closed system is in chemical equilibrium if it is in mechanical and thermal equilibrium, and no work can be derived at the given system temperature and pressure.*

*The concept of equilibrium is closed associated with the idea of spontaneity of a chemical reaction: when will a chemical reaction occur in a closed system without the addition of heat or work? For a long time it was believed that a chemical reaction was spontaneous if the reaction was exothermic (heat releasing) at a fixed temperature and pressure. In the 1870's J.W. Gibbs showed that this idea was not complete, since heat may be derived from a chemical reaction even though work may not be derived from that heat at the system temperature and pressure. Gibbs thus defined the **free energy** of a system at a fixed temperature and pressure as the work that was capable of being extracted (or the amount of work needed to bring the system to equilibrium).*

For a chemical reaction, minimum theoretical energy (or maximum work) can be calculated based on the change in Gibbs Free Energy (ΔG) occurring during the reaction, assuming both reactants and products are in their standard states (GIBBS 1961). In short, the equilibrium state of the chemical system is that state for which total Gibbs Free Energy is a minimum with respect to all possible changes at a given temperature and pressure. The following equations define the relationship between optimum work and Gibbs Free Energy:

$$\text{Work} = -(\Delta G_{\text{products}} - \Delta G_{\text{reactants}})$$
$$\text{and } \Delta G = \Delta H - T(\Delta S)$$

H = the heat of the reaction
S = the entropy of the system.

A negative result indicates that the chemical reaction requires work (energy); a positive result indicates that net work (energy) is produced by the chemical reaction.

**A standard state at ambient temperature and pressure is commonly used to calculate theoretical minima based on Gibbs Free Energy.*

nitrate and urea, scored low in terms of energy savings potential. This occurred because the agricultural chemicals are produced in less volume using comparatively lower energy-intensity processes, compared to chemicals in other segments. The difference between actual and theoretical energy requirements in this segment (for the chemicals reviewed) is about 26 million Btu per ton of product.

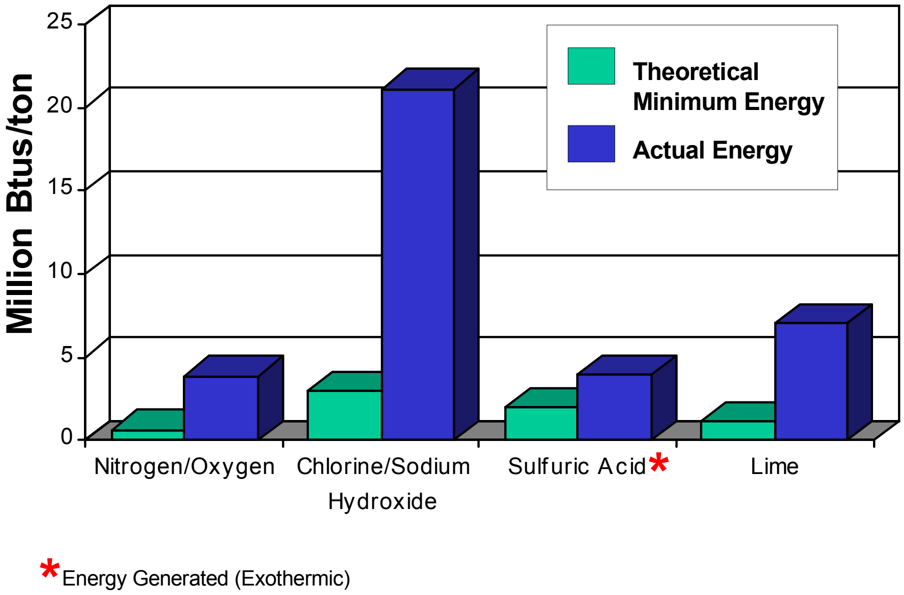


Figure 1-8. Theoretical vs. Actual Energy Requirements for SIC 281, Industrial Inorganic Chemicals (ANL 1991)

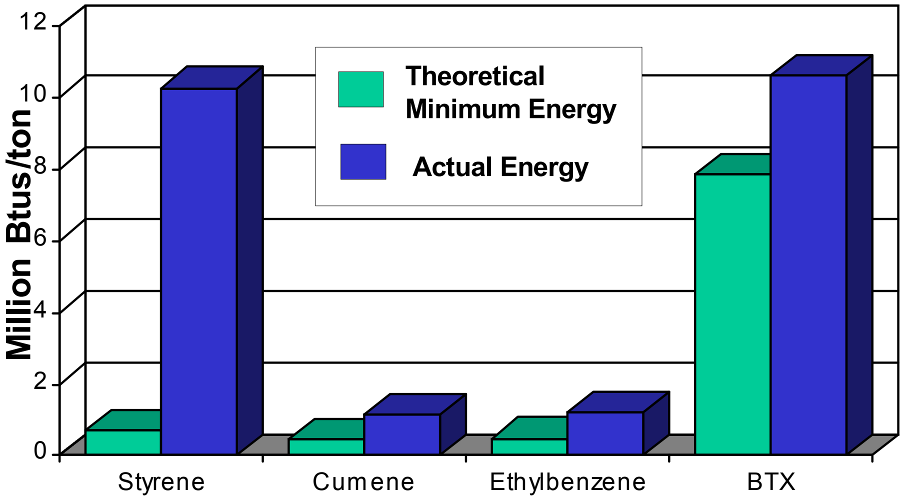


Figure 1-9. Theoretical vs. Actual Energy Requirements for SIC 2865,Cyclic Crudes and Intermediates (ANL 1991)

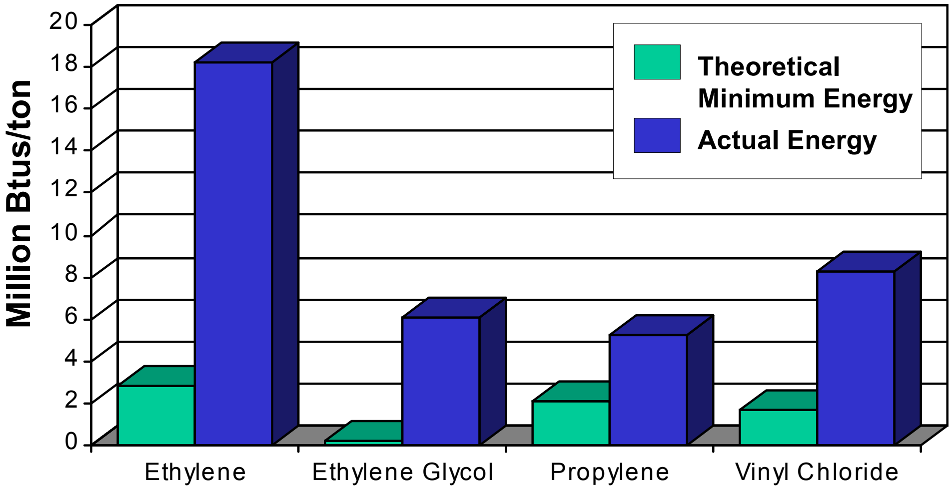


Figure 1-10. Theoretical vs. Actual Energy Requirements for SIC 2869, Industrial Organics (ANL 1991)

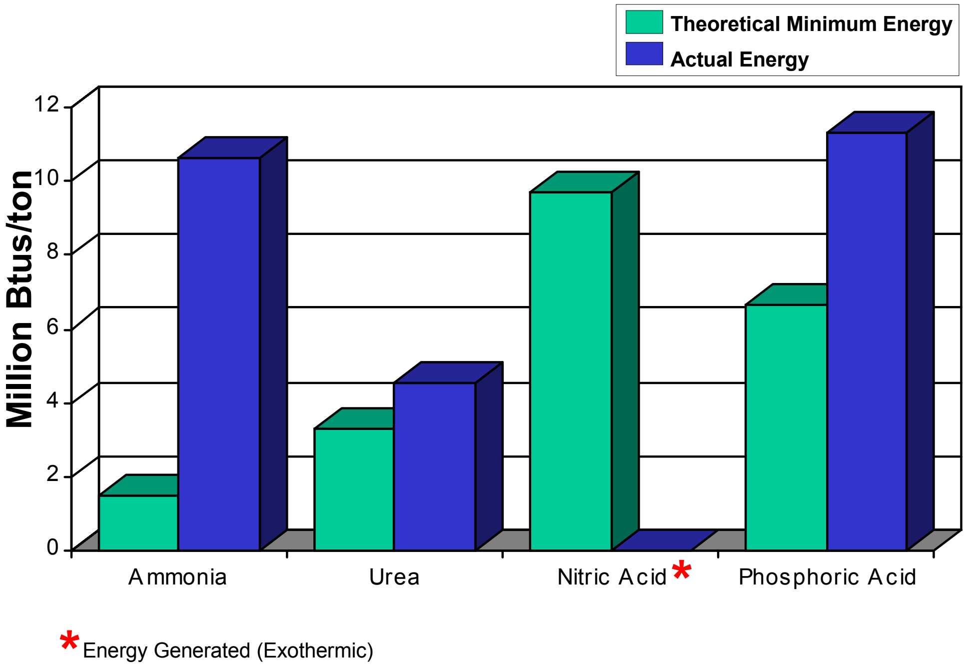


Figure 1-11. Theoretical vs. Actual Energy Requirements for SIC 287, Agricultural Chemicals (ANL 1991)

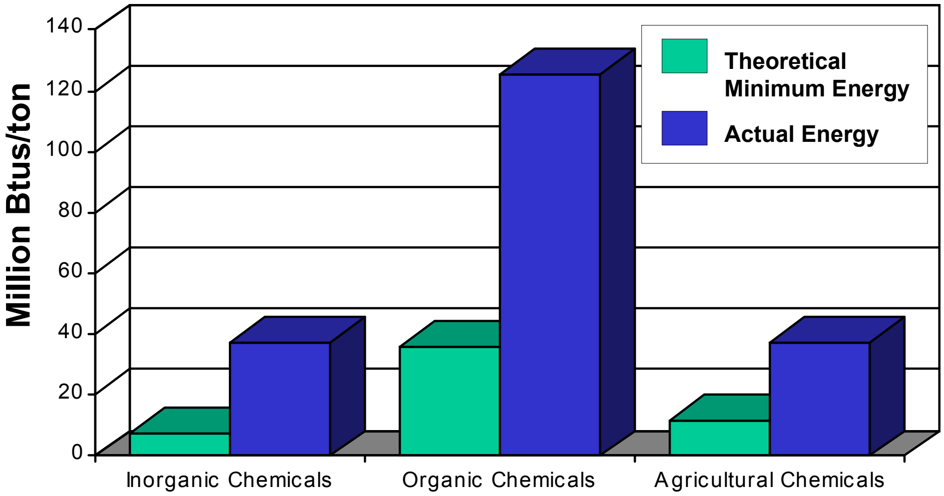


Figure 1-12. Potential Energy Savings - Theoretical Energy Minima Versus Operating Practice (ANL 1991)

Several other studies have also examined the potential for energy savings in production of the top 50 chemicals. One study by Pacific Northwest National Laboratory (PNNL), which ranked the top 50 chemicals by energy intensity, energy consumption, revenues, and other parameters, identified process inefficiencies in a number of areas (PNNL 1994). The top 20 chemicals ranked by the study in terms of total energy consumption are shown in Table 1-15.

It should be noted that the energy intensities used for this study were based on average process and feedstock energy requirements, not on the measured values for actual operations. In fact, in 1993, the total energy consumption for these 20 chemicals was higher than the estimated consumption value for the entire segment for that year, as reported by CMA. Part of the discrepancy can be attributed to PNNL's use of average energy intensity values, which do not account for differences between plant sites.

The study does, however, provide a means for ranking chemical production by the approximate level of energy consumed. A companion study (see Table 1-16) examined the potential for energy savings achievable through improved catalytic processes (PNNL 1995). This study identified the loss of 830 trillion Btu of energy due to process inefficiencies during the production of 30 major chemicals. The study also discovered that over $2 billion were spent to purchase feedstocks that were subsequently converted to waste.

Table 1-15. Energy Consumed in Production of Major Chemicals, PNNL Estimates (Trillion Btus)				
Chemical	**Rank**	**Energy for Heat and Power**	**Feedstock Energy**	**Total Energy**
Ethylene	1	400	1010	1410
Ammonia	2	290	460	750
Propylene	3	160	540	700
Benzene	4	10	420	430
Vinyl Chloride	5	100	300	400
Sodium Hydroxide	6	380	0	380
Styrene	7	50	280	330
Ethylbenzene	8	10	310	330
Ethylene Dichloride	9	30	290	320
Methy t-Butyl Ether	10	60	240	300
Urea	11	20	220	240
Chlorine	12	230	0	230
p-Xylene	13	60	140	200
Phosphoric Acid	14	150	50	200
Phenol	15	20	160	180
Ammonium Nitrate	16	30	150	180
Terephthalic Acid	17	30	140	170
Ethylene Oxide	18	0	160	160
Carbon Black	19	40	120	160
Butadiene	20	70	80	150
TOTAL ENERGY CONSUMED: 7,220 Trillion Btu				

Source: PNNL 1994.

Table 1-16. Potential Energy Savings through Improved Catalysts, PNNL Estimates (trillion Btus)

Chemical	Rank	Total Energy Savings
Ammonia	1	294
Propylene	2	98
p-Xylene	3	94
Butadiene	4	81
Vinyl Chloride	5	44
Methanol	6	37
Ethylene Oxide	7	29
Acrylonitrile	8	24
Adipic Acid	9	20
Styrene	10	20
Vinyl Acetate	11	16
Propylene Oxide	12	16
Phenol	13	12
Ethylene Dichloride	14	11
Acetone	15	8
Terephthalic Acid	16	8
Formaldehyde	17	6
Ethylbenzene	18	4
Cumene	19	3
Acetic Acid	20	2
Nitric Acid	21	1
MTBE	22	1
Caprolactam	23	1
Ethylene Glycol	24	1
Sulfuric Acid	25	1
Isobutylene	26	0.3
TOTAL ESTIMATED ENERGY SAVINGS: 832.2 Trillion Btu		

Source: PNNL 1995.

Six Chemical Chains Capture the Most Energy-Intensive Chemicals

The chemical reactions associated with six **chemical chains** account for a substantial share of the energy consumed in the chemical industry. These chains include ethylene, propylene, BTX (benzene-toluene-xylene), butadiene, agricultural chemicals, and caustics. As shown in Table 1-17, roughly 70-80 percent of the products of the chains account for about 54 percent of current energy consumption in the chemical industry. Tables 1-18 through 1-24 illustrate the major products within these chemical chains, and summarize the related energy use, production, and common manufacturing processes involved.

Production data for most chemicals was taken from current statistics published by the Chemical Manufacturers Association (CMA 1998). Data for polymers and a few chemicals was obtained from several other sources (SPI 1998, CHEMX 1999). Data on energy consumption and specific processes was obtained from a number of studies and literature describing licensed technologies (Sittig 1977, Boustead 1979, ANL 1980, BIO 1988, EEA 1983, PNNL 1994, Brown 1996, Enviro-Chem 1999a-d, HP 1999). The data represents estimated, approximate values, based on averages throughout the industry, and may not represent the most current and state-of-the art technologies available for production of these chemicals.

Tables 1-18 through 1-23 help to identify where the largest portion of process energy is consumed throughout the chemical chain, and the distribution of the primary feedstock to various end-products. As shown in Table 1-22, the chain accounting for the most energy consumed annually is **agricultural chemicals**. This is attributed to the large energy requirements for ammonia production, which is a largely inefficient, low-yield process. Other energy-intensive processes in this chain include production of phosphoric acid by the wet process. Overall this chain accounts for about 26 percent of energy use attributed to the six chemical chains.

Table 1-18 illustrates that nearly half of **ethylene** produced is used to manufacture polyethylene, one of the most highly consumed plastics. However, production of polyethylene requires the least processing energy among all of the products produced from ethylene, and accounts

Table 1-17. Summary of Process Energy Use for Six Chemical Chains

Chemical Chain (% of Products Represented)	Estimated Process Energy Use (Trillion Btu/year)
Ethylene (80%)	406
Propylene (73%)	80
BTX (87%)	400
Butadiene (50%)	45
Agricultural Fertilizers (75%)	424
Caustics (100%)	291
TOTAL ESTIMATED ENERGY USE FOR SIX CHAINS	1646
Process Energy Use by the Chemical Industry in 1997	3,034
Percentage of Chemical Industry Use in 1997: ~ 54%	

Sources: Sittig 1977, Boustead 1979, ANL 1980, BIO 1988, EEA 1983, PNNL 1994, Brown 1996, Enviro-Chem 1999a-d, HP 1999.

Table 1-18. Ethylene Chain Production, Processing Energy, and Associated Processes

	% of Ethylene	PRIMARY INTERMEDIATE Annual Production (Process Energy) Primary Process(es)	SECONDARY INTERMEDIATES Annual Production (Process Energy) Primary Process(es)	ESTIMATED ANNUAL PROCESS ENERGY (Trillion Btu)
Ethylene 48.3 billion lbs **(8,107 Btu/lb)** *- Steam Cracking* *- Catalytic Hydrogenation* *- Distillation* **Annual Energy Use:** **392 Trillion Btu** **Attributed to chemical industry:** **196 Trillion Btu**	45	Polyethylene (100%) 27.0 billion lbs **(1,178 Btu/lb)** *Addition Polymerization*	---	32
	15	Ethylene Dichloride 20.2 billion lbs **(3,410 Btu/lb)** *Catalytic Chlorination*	Poly Vinyl Chloride (100%) 10.9 billion lbs **(1,246 Btu/lb)** *Addition Polymerization*	83
	20	Ethylene Oxide 7.1 billion lbs **(1,711 Btu/lb)** *Catalytic Oxidation*	Ethylene Glycol (69%) 5.63 billion lbs **(2,045 Btu/lb)** *- Hydrolysis* *- Distillation* → Polyester (56%) 5.9 billion lbs **(12,128 Btu/lb)** *- Condensation Polymerization*	95
	TOTAL ENERGY USE (Including Ethylene)			**406**
	20	Other Products: Vinyl Acetate, Acetaldehyde, Ethanol, Ethylbenzene, Styrene/Polystyrene, Antifreeze		

Sources: Sittig 1977, Boustead 1979, ANL 1980, BIO 1988, EEA 1983, PNNL 1994, Brown 1996, Enviro-Chem 1999a-d, HP 1999.

Table 1-19. Propylene Chain Production, Processing Energy, and Associated Processes

	% of Propylene	PRIMARY INTERMEDIATE Annual Production (Process Energy) Primary Process(es)	SECONDARY INTERMEDIATES Annual Production (Process Energy) Primary Process(es)	ESTIMATED ANNUAL PROCESS ENERGY (Trillion Btu)
Propylene 28.7 billion lbs **(1,351 Btu/lb)** *- Steam Cracking* *- Distillation* **Annual Energy Use:** **39 Trillion Btu**	36	Polypropylene 13.3 billion lbs **(514 Btu/lb)** *Liquid Phase or Gas Phase Catalytic Polymerization*	---	7
	20	Propylene Oxide 3.9 billion lbs **(2,557 Btu/lb)** *Epoxidation Reactor*	Propylene Glycol (25%) → Urethane Polyol Ethers 1.1 billion lbs (60%) No Data **(2,045 Btu/lb)** *Direct Hydration, Evaporation, Distillation*	12
	13	Acrylonitrile 3.3 billion lbs **(956 Btu/lb)** *Catalytic Fluidized Bed Reactor*	Acrylic Fibers (42%) 0.44 billion lbs **(21,520 Btu/lb)** *Suspension Polymerization* ABS resins (19%) 1.4 billion lbs **(1,221 Btu/lb)** *Continuous Mass, Emulsion and Suspension Polymerization*	15
	4	Isopropyl Alcohol 1.4 billion lbs **(4,693 Btu/lb)** *Sulfuric Acid Oxidation*	Coating Processes (70%) Pharmaceuticals (15%) Miscellaneous Uses (15%)	7
	TOTAL ENERGY USE (including propylene)			**80**
	27	Other Products: Cumene (see BTX chain), Acrylic Acid & Acrylates, Butyraldehyde		

Sources: Sittig 1977, Boustead 1979, ANL 1980, BIO 1988, EEA 1983, PNNL 1994, Brown 1996, Enviro-Chem 1999a-d, HP 1999.

Table 1-20. BTX (Benzene-Toluene -Xylene) Chain Production, Processing Energy, and Associated Processes

	% of Benzene	PRIMARY INTERMEDIATE Annual Production (Process Energy) Primary Process(es)	SECONDARY INTERMEDIATES Annual Production (Process Energy) Primary Process(es)	ESTIMATED ANNUAL PROCESS ENERGY (Trillion Btu)
Benzene 14.9 billion lbs **(1,255 Btu/lb)** *- Steam Cracking* *- Distillation* **Annual Energy Use for BTX:** **40.4 Trillion Btu**	53	Ethyl Benzene 13.9 billion lbs **(1,404 Btu/lb)** *Acid Catalyzed Friedal Crafts Alkylation*	Styrene 11.4 billion lbs **(16,891 Btu/lb)** *Dehydrogenation, Vacuum Distillation* → Polystyrene (66%) 6.4 billion lbs **(2,264 Btu/lb)** *Bulk Polymerization*	228
	22	Cumene 5.8 billion lbs **(696 Btu/lb)** *Catalytic Alkylation*	Phenol/Acetone (100%) 7.3 billion lbs **(7,850 Btu/lb)** *Oxidation, Vacuum Separation* → Bisphenol A (35%) 1.6 billion lbs **(9,410 Btu/lb)**	76
	12	Cyclohexane 2.2 billion lbs **(1,743 Btu/lb)** *Catalytic Hydrogenation*	Cyclohexanone → Caprolactam (90%) 1.7 billion lbs **(13,185 Btu/lb)** *Oxime production*	26
	13	Dodecylbenzene, Maleic Anhydride		--
Toluene 8.3 billion lbs (co-produced)	8	Toluene Diisocyanate 0.93 billion lbs **(11,279 Btu/lb)** *Conversion to diamine, then reaction with phosgene*	Polyurethane (85%) 4.6 billion lbs **(138 Btu/lb)** *Continuous process*	11
	92	Benzene (57%), medicines, solvents, high octane gasoline, explosives		--
o-Xylene 1.1 billion lbs (co-produced)	~100	Phthalic Anhydride 1.3 billion lbs (small net producer)	Plasticizers (53%) Unsaturated Polyester Resins (21%)	--
p-Xylene 7.9 billion lbs	~100	Purified Terephthalic Acid (PTA) 10.0 billion lbs **(1,779) Btu/lb)**	Polyester (see ethylene chain)	18
TOTAL ENERGY USE (including BTX)				**400**

Sources: Sittig 1977, Boustead 1979, ANL 1980, BIO 1988, EEA 1983, PNNL 1994, Brown 1996, Enviro-Chem 1999a-d, HP 1999.

Table 1-21. Butadiene Chain Production, Processing Energy, and Associated Processes

1,3-Butadiene 4.1 billion lbs byproduct of ethylene production (95%) **(95 Btu/lb)** dehydrogenation of butane or butene (5%) **(14,500 Btu/lb)** **Annual Energy Use:** **22 Trillion Btu**	**% of Butadiene**	**PRIMARY INTERMEDIATE Annual Production (Process Energy) Primary Process(es)**	**SECONDARY INTERMEDIATES/PRODUCTS Annual Production (Process Energy) Primary Process(es)**	**ESTIMATED ANNUAL PROCESS ENERGY (Trillion Btu)**
	30	Styrene Butadiene Rubber (SBR) 2.3 billion lbs **(2,271 Btu/lb)** *Addition Polymerization*	Tires, footwear, coatings, adhesives, carpet backing	5
	20	Polybutadiene 1.6 billion lbs **(11,300 Btu/lb)** *Solution Polymerization*	Tires, blends with SBR	18
	50	Other products: adiponitrile, neoprene rubber, nitrile rubber,styrene butadiene latex		
TOTAL ENERGY USE (including butadiene)				**45**

Sources: Sittig 1977, Boustead 1979, ANL 1980, BIO 1988, EEA 1983, PNNL 1994, Brown 1996, Enviro-Chem 1999a-d, HP 1999.

Table 1-22. Agricultural Fertilizers Chain Production, Processing Energy, and Associated Processes

	% of Feedstock	PRIMARY INTERMEDIATE Annual Production (Process Energy) Primary Process(es)	SECONDARY INTERMEDIATES Annual Production (Process Energy) Primary Process(es)	ESTIMATED ANNUAL PROCESS ENERGY (Trillion Btu)
Ammonia 28.4 billion lbs **(12,150 Btu/lb)** *- Steam Reforming* **Annual Energy Use: 345 Trillion Btu**	50	Urea 11.8 billion lbs **(843 Btu/lb)** *Pressurized Reactor*	Fertilizer (84%)	10
	26	Nitric Acid 13.5 billion lbs **(267 Btu/lb)** *2-Stage Catalytic Oxidation of Ammonia*	Ammonium Nitrate (80%*) → Fertilizer 12.3 billion lbs **(341 Btu/lb)** *Non-catalyzed Reactor Crystallizer*	8
	4	Ammonium Sulfate 4.1 billion lbs **(4,000 Btu/lb)** *Byproduct of Caprolactam Production, Evaporation*	Fertilizer (90%)	16
	4	Ammonium Phosphates 18.9 million lbs **(323 Btu/lb)**	Fertilizer (98%)	6
	2	Superphosphates 3.4 billion lbs **(690 Btu/lb)**	Fertilizer (100%)	3
Sulfuric Acid 71.4 billion lbs **(-900 Btu/lb)** *- Catalytic Sulfur Oxidation* *- Absorption* **Net Energy Producer**	65	Phosphoric Acid Wet Process Fertilizer Grade 19.8 billion lbs **(4,300 Btu/lb)**	Fertilizer (92%)	36
	35	Petroleum Refining (5%) Ore Processing (5%) Other Uses (25%)		-
	TOTAL ENERGY USE (including ammonia and sulfuric acid)			**424**

Sources: Sittig 1977, Boustead 1979, ANL 1980, BIO 1988, EEA 1983, PNNL 1994, Brown 1996, Enviro-Chem 1999a-d, HP 1999.

Table 1-23. Chlor-Alkali/Caustics Chain Production, Processing Energy, and Associated Processes

	% of Feedstock	PRIMARY INTERMEDIATE Annual Production (Process Energy) Primary Process(es)	SECONDARY INTERMEDIATES Annual Production (Process Energy) Primary Process(es)	ESTIMATED ANNUAL PROCESS ENERGY (Trillion Btu)
Sodium Chloride (NaCl salt) 17 billion lbs	50	Sodium Hydroxide (Caustic Soda) 22.7 billion lbs **(3,765 Btu/lb)** *Electrolytic Cell*, *Steam Concentration*	Chemical manufacturing, pulp and paper production, soaps and detergents, textiles	86
	50	Chlorine 26 billion lbs **(4,800 Btu/lb)** *Electrolytic Cell*, *Drying and Compression*	Ethylene dichloride/vinyl chloride (38%), polyurethanes (14%), pulp and paper (6%), other uses	125
Trona Ore (sesqui-carbonate) 42.7 billion lbs	~100%	Sodium Carbonate (Soda Ash) 23.7 billion lbs **(3,393 Btu/lb)** Heating of Trona ore	Sodium silicate, sodium tripolyphosphate (for soaps and detergents) Flue gas desulfurization, water treatment, pulp and paper production	80
	TOTAL ENERGY USE (does not include salt or Trona ore mining/production)			**291**

Table 1-24. Comparison of Process Use among Various Chemical Production Chains

Chemical Chain	Processes							
	Distill-ation	Steam Cracking/ Reforming	Electro-lysis	Catalytic Oxidation	Other Catalytic Reactions	Evapor-ation/Hy-dration	Polymeri-zation Reactions	Hydroly-sis
Ethylene	●●	●		●	●●		●●●	●
Propylene	●●	●	●	●●●	●	●●	●●●●	
BTX	●●	●			●●		●●	
Butadiene		●			●		●	
Agricultural Chemicals		●		●●		●		
Caustics			●●					

Key: ● Indicates number of product lines where process is used.

Sources: Sittig 1977, Boustead 1979, ANL 1980, BIO 1988, EEA 1983, PNNL 1994, Brown 1996, Enviro-Chem 1999a-d, HP 1999.

for only about 8 percent of the energy use attributed to the ethylene chain. The ethylene chain accounts for nearly 25 percent of the processing energy represented by the six chains.

The **propylene chain**, on the other hand, accounts for a large amount of annual chemical production but relatively little energy consumption (see Table 1-19). With 73 percent of the chain's products analyzed, overall energy use attributed to this chain is 80 trillion Btu per year, or about 5 percent of total energy use for the six chains.

The **BTX chain**, whose primary products are benzene, toluene, and xylene, is the third largest energy consumer among the six chains, using about 24 percent of the total (see Table 1-20). The production of ethylbenzene and styrene accounts for the largest amount of the energy consumed within this chain, 228 trillion Btu per year. Most of this is attributed to the production of styrene, a very energy-intensive process.

The caustics chain is associated with co-production of **chlorine and sodium hydroxide** (see Table 1-23). This is also an energy-intensive process, and large quantities of these chemicals are produced each year, accounting for a significant portion of the total annual energy use for the six chains, about 13 percent. Production of **sodium carbonate** (soda ash) is less energy-intensive but still consumes a considerable amount of energy because nearly 24 billion pounds are produced annually. Overall the caustics chain accounts for about 18 percent of energy consumed by the six chains.

Over 95 percent of **butadiene** is produced as a co-product of ethylene. The butadiene chain consumes the least amount of energy among the six chains under discussion (see Table 1-21).

Among the chains, energy consumption is roughly split between chemicals that are organic in nature (ethylene, propylene, BTX, butadiene) and those that are inorganic (agricultural chemicals [see Table 1-22], caustics). Processes involving organic chemicals consume about 57 percent of the total energy use represented.

Table 1-24 examines the processes in which the six chemical chains are involved, including processes common to one or more of the chains. Distillation, steam cracking, catalytic oxidation and other catalytic reactions, and various polymerization reactions are common to 60 percent of the chains.
In general, these tables provide another means for identifying targets of opportunity for improving production and energy efficiency. The remainder of this study will examine in more detail the six chemical chains identified, with a focus on their most economically important and energy-intensive products.

1.4 Environmental Overview

The Chemical Industry's Pollutant Emissions Are Decreasing

In recent years the industry has made major advances in protecting the environment as well as the health and safety of its workers. The development of new technologies and investments in new equipment, processes, and practices have contributed in large part to these advances. The industry has also instituted initiatives like Responsible Care®, an industry-wide program that promotes continuous improvements in health, safety, and environmental performance. An additional contributing factor is the myriad of federal and state laws and regulations that have set environmentally strict standards for government, industry, and consumers.

The total amount of toxic releases from the chemical industry declined significantly between 1988 and 1994. The Chemical Manufacturers Association reports that toxic releases of over 300 pollutants by its member companies fell 55 percent between 1988 and 1996, while industrial production during the same period rose by more than 23 percent. Moreover, this improved environmental performance was not achieved by shipping larger quantities off-site for treatment; transfers to treatment facilities also fell 42 percent during the same time period (CMA 1998).

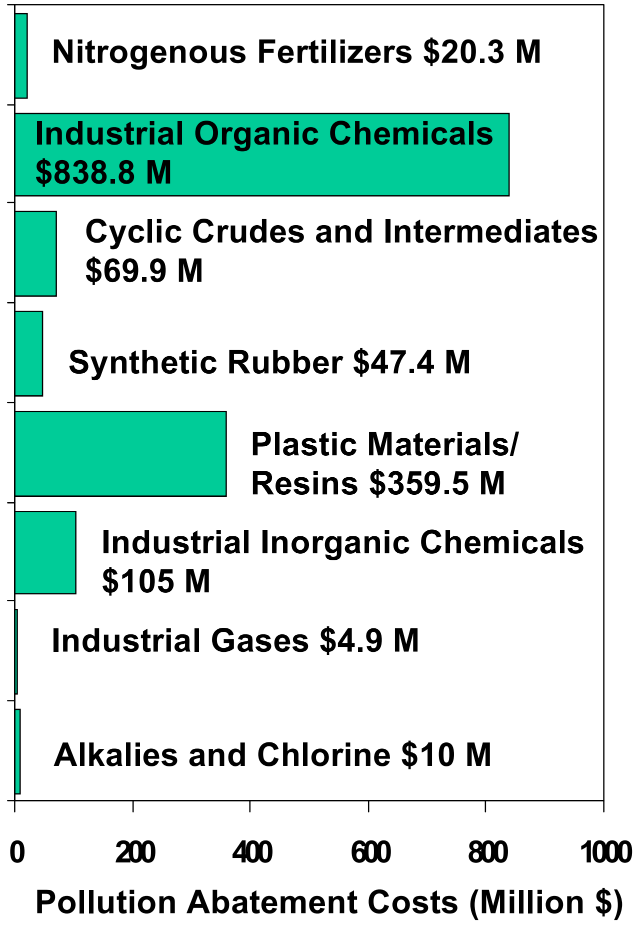
Many firms also participate in EPA's 33/50 Program, a voluntary effort targeting a reduction in emissions of 17 priority chemicals by 33 percent from 1988 to 1992, and by 50 percent by the end of 1995. CMA reports that its member companies met the 50 percent reduction goal in 1994, one year ahead of schedule (CMA 1996). Despite these gains in resource efficiency, however, the industry continues to face considerable challenges in the management of emissions.

The Industry Makes Substantial Investments in Pollution Control

Since 1973, the industry has acted to lessen the environmental impacts of chemical production by investing more than $25 billion in capital expenditures for pollution abatement and control. In 1997, the industry's pollution-related capital expenditures totaled about $2.1 billion, and were equivalent to about 1.1 percent of sales. These expenditures represent nearly 26 percent of total capital expenditures for pollution abatement and control by all U.S. manufacturers.

Operating costs for carrying out pollution abatement and control at chemical manufacturing facilities cover depreciation, labor, material and supplies, and services, and these costs are substantial. In 1997, these costs represented about 1.6 percent of sales, worth about $3.1 billion. Chemical companies also spend about $1.2 billion annually on Superfund and other hazardous waste site remediation (CMA 1998).

Overall, gross annual costs for pollution abatement and control in the chemical industry topped $5.4 billion in 1997, about 1.7 times the costs incurred in 1987 (CMA 1998). Four segments of the industry bear the bulk of expenditures for pollution abatement and control: SIC 2869, 2821, 2819, and 2865 (see Figure 1-13). Of these four, pollution abatement costs are greatest for SIC 2869, Industrial Organic Chemicals, nec, which is also the largest energy consumer (EPA 1995c).



Comprehensive Environmental Response Compensation and Liability Act of 1980 (CERCLA) and the Superfund Amendments and Reauthorization Act of 1986 (SARA) provide a mechanism for the cleanup of contaminated waste sites. To fund these activities, the legislation allowed specific taxes to be imposed on petroleum refineries and chemical facilities. The mandate to impose taxes expired several years ago, however, and the fund is expected to be depleted of cash sometime in early 2000.

Title III of SARA also established "right to know" standards that require chemical plants and other industries to provide information to the public about stored toxic substances and annual release of substances into the environment (known as the Toxic Release Inventory or TRI). EPA is preparing a proposal to add persistent, bioaccumulative, and toxic pollutants (PBTs) to the TRI, and to lower threshold reporting for these compounds.

Re-authorization of CERCLA is currently underway, although regulators are not optimistic about resolving the long-standing dispute about which parties should be exempt from Superfund liability. In addition, most Superfund clean-up activities are slated to be completed within five years (CHEMWK 1999).

The Industry Is Subject to a Growing Number of Environmental Laws

Industry operations are controlled by a growing number of **state and federal laws** regulating the effects of chemicals production on the environment (EPA 1995b, EPA 1995a, CMA 1998). Major legislation includes the following:

Toxic Substances Control Act (TSCA) of 1976 regulates any chemical substance whose manufacture, processing, distribution in commerce, use, or disposal may present an unreasonable risk of injury to health or the environment. Under TSCA, the EPA can prohibit, limit, or ban the manufacture and use of chemicals. For example, under TSCA, the EPA has banned most uses of asbestos.

Resource Conservation and Recovery Act (RCRA) of 1976 establishes standards and regulations for management of solid and hazardous wastes. The law also calls for the establishment of programs at individual companies to reduce the volume and toxicity of hazardous wastes. Efforts to re-authorize and amend RCRA began in 1990. These efforts have lost some momentum, however, since EPA's final regulation that exempts certain clean-up wastes from RCRA (December 1998). Although it appears the rule will result in faster and less-costly clean-ups, it does not meet industry's desire for broad delegation of authority to state regulators (CHEMWK 1999).

The Clean Air Act, first passed in 1970 and later amended in 1990, regulates criteria air pollutants from automobiles, electric power plants, and all industrial sources, including chemical plants. The 1990 amendments established emission standards for industrial sources of 41 air pollutants (air toxics) to be met by 1995, and for 148 other air toxics to be met by 2003. The Act promulgates maximum achievable control technology (MACT) standards for relevant chemical industry segments. It also contains a provision to phase out the use of ozone-depleting chemicals, such as chlorofluorocarbons (CFCs). This provision continues to significantly impact chemical segments that previously produced and used CFCs and other ozone depleters (CHEMWK 1999). Under the *Amendments of 1990,* several major rules have not yet been promulgated.

The Clean Water Act, first passed in 1972 and later amended in 1977 and 1987, regulates effluents from sewage treatment plants, chemical plants, and other industrial sites. Specific guidelines are included for individual segments of the chemical industry. The act sets "best available technology" (BAT) standards for direct and indirect discharges to publicly owned water treatment works (POWTs). There are currently proposals in Congress to re-authorize this act, but they face opposition from the current administration because of fears that restrictions on wetlands will be eased (CHEMWK 1999).

The Hazardous Materials Transportation Act (HMTA) authorizes the Department of Transportation (DOT) to regulate the movement of hazardous materials. Chemical manufacturers must comply with regulations governing all aspects of transportation, including shipping documentation and labeling, loading and unloading of cargoes, emergency and security planning, incident notification, and liability insurance. Substances covered by the act include RCRA hazardous wastes as well as those designated by the DOT as hazardous. Re-authorization of the HMTA is now underway.

Pollution Prevention Act establishes a national policy to reduce or eliminate the generation of waste at the source wherever feasible, and directs EPA to establish a comprehensive pollution-prevention program.

EPA Initiatives coming in the near future include a voluntary testing program for high volume chemicals (greater than 1 million lbs/year) that was negotiated by the Chemical Manufacturers Association, EPA, and the Environmental Defense Fund in November 1998. Chemical companies must also complete risk management plans for EPA, including worst-case scenarios, by June 1999. Under this program the plans will be shared with local communities and made available to the public (CHEMWK 1999).

Chemical Producers Manage Large Quantities of Hazardous and Toxic Wastes

The U.S. chemical industry generates considerable amounts of hazardous and non-hazardous wastes every year. One report (EPA 1993b) indicates that the industry produced about 450 million short tons of **hazardous waste** in 1989, which represents over 90 percent of the total amount of hazardous waste generated by the U.S. manufacturing segment. A survey of 627 chemical production facilities conducted in 1989 (CMA 1991) revealed that

Toxic Release Inventory Definitions

Toxic release - an on-site discharge of a toxic chemical to the environment. This includes emissions to the air, discharges to bodies of water, and releases at the facility to land and underground injection wells.

Point source air emissions - occur from controlled air streams, such as stacks, vents, ducts, or pipes.

Fugitive air emissions - equipment leaks, evaporative losses from surface impoundments, and releases from ventilation systems.

Releases to water - discharges to stream, rivers, lakes, oceans, and other bodies of water, including storm run-off.

Releases to land - occur within the boundaries of a facility, including disposal of chemicals in a landfill, land treatment, and surface impoundment.

Underground injection - disposal of waste fluids by subsurface placement in a well by injection.

Off-site transfers - transfer of toxic chemicals in wastes to a geographically or physically separated facility, for energy recovery, treatment, recycling, or disposal. Except for disposal, these quantities do not represent entry of the chemical into the environment.

Transfers to POTW - transfer of wastewater to publicly owned treatment works (POTW) for water treatment. Not all chemicals can be treated by a POTW ; those not removed are released to surface waters.

the vast majority of this hazardous waste, 97 percent, was contaminated wastewater. Hazardous waste generation is assigned to specific industry segments in Figure 1-14. Of the segments shown, Industrial Organic Chemicals accounts for the largest portion of hazardous waste generation.

Some hazardous waste is also considered "toxic," as defined by the **Toxic Chemical Release Inventory (TRI)** Reporting Program, which began collecting data on toxic releases in 1987 (see sidebar for TRI definitions). In 1996, the U.S. chemical industry reported about 10 billion pounds of production-related toxic chemical waste through the TRI Reporting Program (EPA 1998). Currently, this data is reported under the SIC code system. In 1996, five chemical segments accounted for the majority of toxic releases (see Figure 1-15). However, in many cases firms are conducting more than one type of chemical manufacturing. (i.e., manufacturing products that are classified in separate categories). For example, a facility may manufacture both inorganic chemicals and agricultural chemicals. Others may produce both organic chemicals and plastics. Toxic-containing production wastes from these multiple-product facilities account for nearly 50 percent of wastes reported (see Table 1-25).

The largest **multiple-code reporting** category is the combination of plastics and organic chemicals. An example of this would be a facility producing ethylene primarily as a feedstock for the production of polyethylene, a major plastic produced at the same facility. The second largest multiple-code reporting category is the combination of organic chemicals (ethylene, propylene) with cyclic crudes and intermediates (aromatics such as benzene, xylene), many of which are co-produced in the same process.

The combination of alkalies and chlorine with inorganic chemicals production is also common, primarily because chlorine and caustic soda are common inputs for the production of many inorganic chemicals. Agricultural chemicals and fertilizers are also often produced in the same facilities because byproducts can be recycled as inputs. This is true in general for many multiple-code facilities, where byproducts are utilized to make useful products on-site rather than being sold off-site.

Table 1-25. Top Ranked Multiple-Code Toxic Waste Generators - 1996 (ranked in order) (million lbs)

SIC Code Combination[a]	Number Facilities Reporting	Total On- and Off-Site Releases	Total Other On-Site Waste Management	Total Transfers Off-site for Further Waste Management	Total Production-Related Waste
2821, 2869	1,194	54	1,148	106	1,306
2865, 2869	809	38	1,060	85	1,183
2812, 2819	190	10	257	98	267
2873, 2879	521	105	153	3	262
2821, 2865, 2869, 2879	448	16	214	11	239
2812, 2813, 2842	190	2	177	118	179
2819, 2873	194	68	79	25	176

a SIC Codes: 2812 Alkalies & Chlorine, 2813 Industrial Gases, 2819 Industrial Inorganic Chemicals nec, 2821 Plastic Materials & Resins, 2842 Polishes & Sanitation Goods, 2865 Cyclic Crudes & Intermediates, SIC 2869 Industrial Organic Chemicals nec, SIC 2873 Nitrogenous Fertilizers, SIC 2879 Agricultural Chemicals nec; Source: EPA 1998.

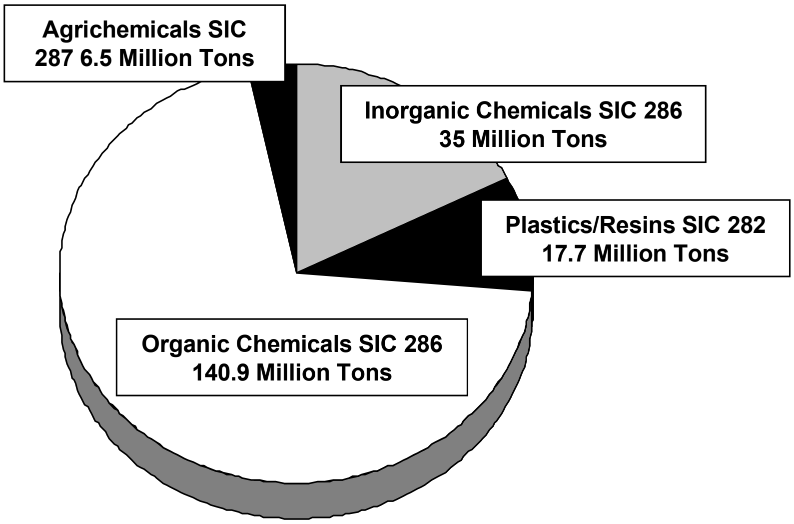


Figure 1-14. Hazardous Waste Generation in Selected Chemical Segments, 1989 (CMA 1991)

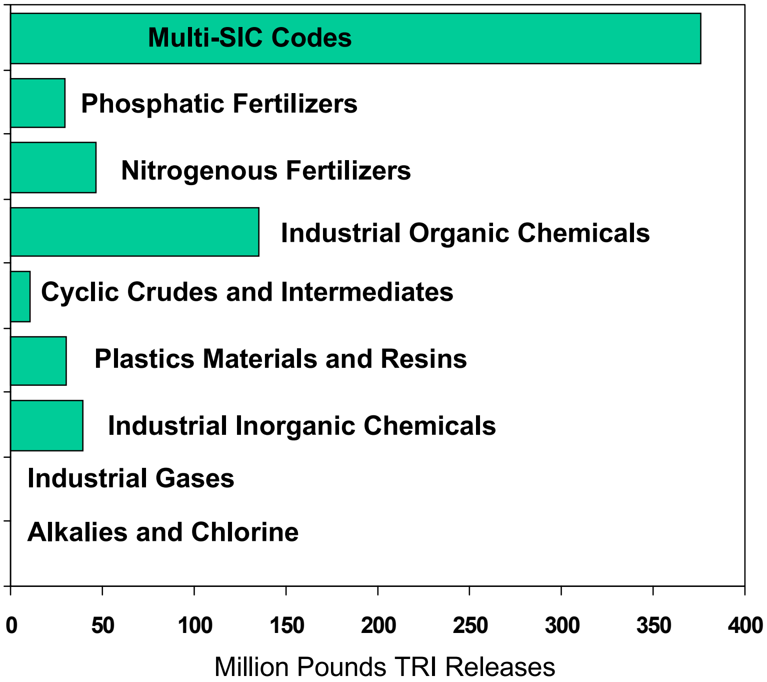


Figure 1-15. Toxic Releases in Selected Chemical Segments, 1996 (EPA 1998)

Table 1-26 summarizes the chemical industry's release and transfer activity for toxic wastes between 1995 and 1996. Total production of toxic wastes decreased by about 2 percent, and about 6 billion pounds were ultimately recovered through recycling or energy recovery (EPA 1998). On-site recycling increased by over 12 percent, while energy recovery increased by nearly 6 percent.

Table 1-26. Summary of Toxics Release and Transfer[a] Activity for SIC 28 - 1995-96 (million pounds)

Activity	1995	1996	Percent Change 95/96
RELEASES			
Releases and On-site Land Disposal	**814.6**	**754.3**	-7.4
Total Air	421.9	392.4	
Fugitive Air	98.6	93.4	
Point Air	323.3	299.1	
Water Discharges	88.2	90.4	
Underground Injection	235.1	200.5	
On-site Land Disposal	69.4	71.0	
ON-SITE WASTE MANAGEMENT			
Recycling	**3324.7**	**3731.3**	12.2
Energy Recovery	**1277.6**	**1348.4**	5.5
Treatment	**3829.4**	**3254.5**	-15
OFF-SITE TRANSFERS			
Transfers	**950.0**	**929.7**	-2.1
POTW Discharge	114.8	109.5	
Disposal	29.7	30.8	
Recycling	236.1	256.6	
Treatment	159.0	154.3	
Energy Recovery	410.3	378.4	
Other Transfers	0.1	0.1	
TOTAL	**10196.3**	**10018.2**	-1.8

[a] Releases are defined as an on-site discharger to the environment, including emissions to air, discharges to water, releases to land, and contained underground disposal. Transfers are defined as the transfer of the toxic chemical to a facility that is geographically or physically separate from the reporting facility, and do not necessarily represent entry of the chemical into the environment.

Source: EPA 1993a.

The 15 toxic chemicals released in greatest quantity by the chemical industry are shown in Table1-27 (EPA 1998). The “top two” chemicals in terms of amount released both originate in large part from the manufacture of agricultural chemicals.

The two largest generators of toxic waste (SIC 286, Industrial Organic Chemicals and SIC 281, Industrial Inorganic Chemicals) manage most of their wastes on-site through recycling, energy recovery, or treatment. The Pollution Prevention Act of 1990 requires facilities to report information about the management of TRI chemicals and efforts made to reduce or eliminate those chemicals. The data is useful for assessing trends in source reduction within industries and facilities.

Data collected for the organic chemical segment, for example, indicates that this industry managed about 2.3 billion pounds of production-related wastes in 1997, with about 90 percent of those managed on-site. The inorganic chemical segment managed about 2 billion pounds of production-related waste, with over 95 percent managed on-site.

The organic chemicals segment recycles about 25 percent of wastes. In the inorganic chemicals segment, the percentage of recycled wastes is much larger–close to 80 percent. Table 1-28 provides an accounting of waste management activities for these industrial segments in 1997 (EPA 1997c). Major toxic and hazardous pollutants from the processing of inorganic chemicals include chlorine gas emissions (both fugitive and point source), impurities removed from electrolytic cell effluents, and pollutants originating from electrolytic cell materials and other parts. The top five toxic chemicals in the amount released include the following:

- hydrochloric acid
- chromium and chromium compounds
- carbonyl sulfide
- manganese and manganese compounds
- ammonia

Major toxic and hazardous pollutants from organic chemicals processing include fugitive emissions, liquid wastes, solid wastes, and contamination in ground water. Fugitive emissions arise from pumps, valves, flanges, and other sources. Liquid wastes include wash solvents, surplus chemicals, product washes/purifications, scrubber blowdown, cooling water, steam jets, leaks, spills, and waste oils/lubricants.

Table 1-27. Releases and Transfers, Top 15 Toxic Chemicals (1994)

Chemical	**Toxic Releases by Chemical SICs (million lbs)**	**Major Chemical Manufacturing Sources**
Ammonia	108	Alkalies, chlorine, industrial gases, inorganic chemicals, plastics, rubber, cyclic crudes, organic chemicals, fertilizers
Nitrate Compounds	94	Fertilizers, chemicals manufacture
Methanol	65	Inorganic chemicals, plastics, medicinals, pharmaceuticals, cyclic crudes, organic chemicals
Carbon Disulfide	60	Plastics, cellulose fibers, carbon black
Phosphoric Acid	55	Inorganic chemicals, fertilizers
Ethylene	32	Plastics, organic chemicals
Acetonitrile	24	Organic chemicals
Chromium compounds	22	Catalysts, organic chemicals, inorganic pigments
Propylene	20	Plastics, organic chemicals
Nitric Acid	19	Fertilizers, inorganic chemicals
Toluene	16	Inorganic chemicals, plastics, rubbers, medicinals, pharmaceuticals, paints, varnishes, organic chemicals
Manganese Compounds	15	Inorganic pigments
Ethylene Glycol	13	Organic chemicals
Formic Acid	13	Organic chemicals
Hydrochloric Acid	12	Alkalies, chlorine, inorganic chemicals, organic chemicals

Source: EPA 1998.

Table 1-28. Source Reduction and Recycling Activity for Organic and Inorganic Chemicals, 1997

Segment	Quantity of Production Related Waste (million lbs)	% Of Waste Handled On-Site			% of Waste Handled Off-Site			
		% Recycled	% Energy Recovery	% Treated	% Recycled	% Dis-posed	% Energy Recovery	% Treated
Organic Chemicals SIC 286	2,342	24	27	35	1	6	4	3
Inorganic Chemicals SIC 281	2,008	79	0	17	0	3	0	0

Source: EPA 1997c.

Solid wastes typically consist of spent catalysts, spent filters, sludges, biological sludge from wastewater treatment, contaminated soil, packaging materials, reaction by-products, spent resins, and drying materials. The top five toxic chemicals released include ammonia, nitric acid, methanol, ethylene glycol, and acetone.

Chemical manufacturers also generate and manage a diversity of non-hazardous wastes, from wastewaters and wastewater treatment sludges to process wastes, contaminated soil, and trash. Although limited data is collected on non-hazardous waste, an earlier report (CMA 1992) indicates that the chemical industry produced nearly 6 billion tons of non-hazardous waste in 1991,with 99.6 percent of that being wastewater. While currently not subject to the same stringent regulations as hazardous waste, handling and disposing of these non-hazardous wastes still create a large financial burden for the industry. It is anticipated that some of these wastes could eventually be subject to some form of regulatory control.

The Industry Generates a Number of Criteria Air Pollutants

Chemical manufacturing processes are a source of **criteria air pollutants** regulated under the Clean Air Act and its amendments. These pollutants are produced directly by chemical processing, and through the combustion of fossil fuels in boilers and other heating systems used in processing.

With the exception of volatile organic compounds (VOCs), U.S. industry generally emits only a small fraction of most air pollutants compared to those generated by the transportation and utility sectors. Industrial processes are responsible for nearly 50 percent of total U.S. VOC emissions, however, with the transportation sector generating most of the remainder of these pollutants.

Table 1-29 shows the relative contribution of the chemical industry to the national total air emissions for criteria pollutants. The industry's contributions range from about 1 percent to 7 percent when combustion-related emissions are included. Combustion-related emissions were calculated based on energy consumed by the industry in 1996, using the emission factors shown in Table 1-30 (EPA 1995b, CMA 1998).

Sulfur and nitrogen oxides represent the largest share of combustion-related emissions from the chemical industry. Carbon monoxide is the largest air pollutant from chemical processes, although this pollutant represents less than 2 percent of total U.S. air emissions.

Table 1-29. Criteria Pollutant Emissions From Chemical Processes, 1996 (Million Short Tons)

Air Pollutant	Total U.S. Emissions	Chemical Industry Process Emissions	Chemical Industry Combustion-Related Emissions[a]	Total Chemical Industry Emissions (% of U.S.)
Sulfur Oxides	19.1	0.3	0.98	1.26 (6.6)
Nitrogen Oxides	23.4	0.2	0.46	0.66 (2.8)
Volatile Organic Compounds	19.1	0.4	0.09	0.49 (2.6)
Carbon Monoxide	88.8	1.2	0.12	1.32 (1.5)
Particulates	31.3	0.07	0.21	0.28 (0.9)

[a] Calculated based on energy consumption by fuel type in 1996 (CMA1998), using conversion factors developed by the U.S. Environmental Protection Agency

Sources: EPA 1986, 1988, 1995b; CMA 1998.

Table 1-30. Combustion Emission Factors By Fuel Type (lbs/million Btu)

Fuel Type	SO_x	NO_x	CO	Particulates	VOCs[a]
Distillate Fuel	0.160	0.140	0.0361	0.010	0.002
Residual Fuel	1.700	0.370	0.0334	0.080	0.009
Other Oils	1.700	0.370	0.0334	0.080	0.009
Natural Gas	0.000	0.140	0.0351	0.003	0.006
LPG	0.000	0.208	0.0351	0.007	0.006
Propane	0.000	0.208	0.0351	0.003	0.006
Steam Coal	2.500	0.950	0.3044	0.720	0.005
Petroleum Coke	2.500	0.950	0.3044	0.720	0.005
Electricity	1.450	0.550	0.1760	0.400	0.004

[a] volatile organic compounds

Sources: EPA 1986, 1988, 1996.

Slowing Global Climate Change and Reducing Greenhouse Gases Emissions May Be Future Challenges

Global climate change refers to the myriad of environmental problems that are believed to be caused, in part, by the reaction of the world's climate (temperature, rainfall, cloud cover) to rapidly increasing human activities such as the combustion of fossil fuels, emission of pollutants to air and water, changes in the Earth's reflectivity (albedo) due to deforestation, and emission of ozone-depleting chemicals.

Greenhouse gases refer to gases that trap heat in the atmosphere. In particular, they are transparent to solar radiation that enters the Earth's atmosphere, but strongly absorb the infrared thermal radiation emitted by the Earth. The most common man-made and natural sources of greenhouse gases are shown in Table 1-31. The natural greenhouse effect permits life to exist on Earth. Without greenhouse gases in the atmosphere, ambient temperatures would be much colder–below the freezing temperature for water–and the Earth would be incapable of sustaining life.

The Earth's climate system adapts relatively well to small, slow changes in atmospheric greenhouse gas concentration. However, rapid changes in anthropogenic (man-made) greenhouse gases may constitute a major force for climate change. Larger environmental disruptions may result from climatic disequilibrium caused by a combination of climate change forces, i.e., increasing greenhouse gases, albedo changes, and stratospheric ozone depletion. When climate forces are disrupted, global weather patterns

Table 1-31. Sources of Greenhouse Gases

Greenhouse Gas	Anthropogenic Sources	Global Emissions of Anthropogenic Sources (MMTCE)	Natural Sources	Global Natural Emissions (MMTCE)
Carbon dioxide (CO_2)	Combustion of fossil fuels; calcination of limestone, soda ash manufacture and use; aluminum production.	7,100	Biological processes	150,000
Nitrous oxide (NO, NO_2)	Combustion of fossil fuels; nitrogen fertilizers, manufacture of adipic and nitric acid.	4-8	Biogenic processes in soil; lightning.	6-12
Methane (CH_4)	Coal mining; oil refining; gas drilling and transmission; chemical, iron and steel production.	300-450	Aerobic decay of vegetation; termites (tropics); ruminant animals; rice fields.	110-210
Chlorofluorocarbons (CFC-11, CFC-12, CFC-113)	Release of engineered chemical refrigerants and solvents	0.2 (U.S. only)	No natural source.	—

Source: EIA 1994a.

become less predictable and may include an increase in the number of hurricanes and tornados, and in the amount of flooding. As greenhouse gases increase, the rate of change in global climate patterns may accelerate and limit the ability of ecosystems to adapt to these changes.

There is little doubt among the scientific community that global climate change could have significant impacts on the world as we know it. However, there is no scientific consensus that global climate change is actually occurring at the present time. NASA's satellite data fails to show net warming over the past 18 years, and actually indicates a slight cooling trend since the early 1900s. Surface temperature readings, however, show an increase of 1 Celsius degree over the past century, with most of the warming occurring before 1940 and before the majority of man-made emissions began to occur. These types of ambiguities in the available data have resulted in considerable disagreement among scientists over the potential for and extent of global warming.

A recent report of the Intergovernmental Panel on Climate Change stated that estimates of natural variability and uncertainties in key factors limit the ability of investigators to quantitatively determine the influence of humans on global climate. Scientists agree that extensive research is required, as well as long-term assessment of the impact of any temperature increase.

The Union of Concerned Scientists (UCS) is urging world leaders and the current U.S. administration to take immediate action and sign a global climate change treaty. At an international summit meeting in Kyoto, Japan, in late 1997, world leaders met to discuss and formulate an international agreement to reduce the generation of greenhouse gases. The resulting **Kyoto Protocol** calls for a significant reduction in greenhouse gases by the United States and European Nations by the year 2010 (CHEMWK 1999). The current Administration signed the agreement in November 1998, but had not yet submitted it for Senate ratification at the beginning of 2000. Pending the signing of the treaty, legislation is being proposed that would allow credit to companies for voluntarily reducing greenhouse gas emissions.

The Kyoto Protocol could have dramatic impacts on consumer prices and economic growth. Many industries are concerned that the economic impacts of such a treaty are not well understood, and are opposing proposed plans by the United States to sign the agreement. A recent study indicates that the economic cost would be high, and that mandatory emissions goals (holding emissions to 1990 levels) could result in a loss of gross domestic product of $227 billion (1992 dollars) in 2010 alone (WEFA 1997). According to the study, implementing the protocol would also mean sharply higher prices for energy, which could give developing nations (which are not required to reduce emissions) a competitive advantage over the United States and other developed countries. The study also indicates that energy-producing states would suffer the greatest amount of economic disruption.

Summary of the Kyoto Protocol

- United States to reduce greenhouse gas emissions by 7% below 1990 levels by 2010
- European Nations to reduce greenhouse gas emissions by 8% below 1990 levels by 2010
- No commitments from developing nations to reduce greenhouse gas emissions, and no agreement on a voluntary process for reducing/limiting their emissions
- Emissions trading for Annex I parties only (main sellers would be Russia and Ukraine)

Chemical Reactions and Combustion of Fuels in Chemical Processes Produce Some Greenhouse Gases

In the chemicals industry, greenhouse gases (carbon dioxide, methane, and nitrous oxide) are emitted during chemical reactions, from flue gas desulfurization processes, and from the combustion of fossil fuels.

The amount of carbon released when fossil fuels are burned is dependent on the carbon content, density, and gross heat of combustion for the particular fuel. The carbon coefficients and energy consumption data used to calculate **combustion-related emissions** of carbon dioxide are shown in Table 1-32 A detailed explanation of how carbon coefficients were derived can be found in *Emissions of Greenhouse Gases in the United States, 1987-1992* (EIA 1994a). Table 1-33 summarizes the emissions of greenhouse gases from both process and combustion-related sources in the chemical industry. Industrial carbon dioxide emissions represent only about 3 percent of the total U.S. emissions of carbon dioxide. Industrial emissions of nitrous oxide are larger, representing about 9 percent of the Nation's total emissions of nitrous oxides.

The production and use of soda ash (sodium carbonate) is another source of carbon dioxide in chemicals manufacture. As soda ash is processed into various products, additional carbon dioxide may also be emitted if the carbon is oxidized. Chemical products in this category include sodium silicate and sodium tripolyphosphate, which are manufactured from sodium carbonate and used as components in detergents. While soda ash has a number of uses outside the chemical industry in such areas as water treatment, glass manufacturing, and pulp and paper production, more than half the carbon dioxide emissions associated with soda ash originate in the chemical industry.

While emissions of methane are dwarfed by carbon dioxide emissions, methane is a more effective greenhouse gas. Considering just its heat-absorption potential, one molecule of

Table 1-32. Carbon Emissions from Combustion of Fossil Fuels in the Chemical Industry - 1997

Fuel Type	Carbon Coefficient (lbs CO_2/million Btu)	1997 Energy Use (Trillion Btu)	Carbon (MMTCE)	CO_2 (MMT)
Distillate Fuel	161.2	11	0.2	0.8
Residual Fuel	173.6	50	1.1	3.9
Natural Gas	116.9	1,927	27.9	102.3
Coal & Coke	207.5	250	6.4	23.6
Purchased Electricity	133.4	545	9.0	33.0
Electricity Losses	133.4	1132	18.7	68.5
Other Fuels	163.3	251	5.1	18.6
TOTALS	-	4,166	68.4	250.7

Note: MMTCE indicates million metric tons of carbon equivalents; MMT indicates million metric tons of carbon dioxide.
Source: EIA 1994b.

Table 1-33 Emissions of Greenhouse Gases From the Chemical Industry-1997 MMTCE

Greenhouse Gas	Total U.S. Emissions	Process Emissions	Combustion-Related Emissions	Total Chemical Industry Emissions (% of U.S.)
Carbon Dioxide	1,501	1.2[a]	49.7[b]	51 (3.4%)
Methane	168	0.4[c]	--	0.4 (0.3%)
Nitrous Oxide	86	7.4[d]	--	7.4 (8.5%)

Note: Carbon equivalents for gases other than carbon dioxide are calculated based on the global warming potentials of the individual gases (EIA1998).

[a] Based on estimated emissions from the manufacture of soda ash, sodium silicate, and sodium tripolyphosphate. Does not include consumption of soda ash in flue gas desulfurization, as this data is not available.
[b] Calculated based on energy consumption by fuel type in 1997 (CMA 1998), using conversion factors developed by the U.S. Department of Energy (EIA 1996). Includes losses for on-site and cogenerated electricity, but not purchased electricity.
[c] Based on emissions from production of ethylene, ethylene dichloride, styrene, methanol, and carbon black.
[d] Based on emissions from production of adipic acid and nitric acid.

Source: EIA1998

methane can have 24 times the heat-trapping effect of one molecule of carbon dioxide (EIA 1995). The primary source of methane emissions from chemical processing is the "cracking" of petrochemical feedstocks, which produces a number of chemical byproducts, including methane.

Emissions of nitrous oxide are much smaller than those of methane or carbon dioxide, but with a heat-trapping potential 310 times that of carbon dioxide, nitrous oxide can be a significant contributor to global warming. Chemical industry sources include the production of adipic acid, a fine, white powder used primarily in the manufacture of nylon fibers and plastics, and nitric acid, a primary ingredient in fertilizers (EIA 1998).

The relative heat-trapping potential of various gases has been studied extensively, which has led to the development of the global warming potential of various gases (IPCC 1995). Despite these studies, there are still many uncertainties about their effects, primarily due to the complex way in which these gases react in the atmosphere. Having precise information about how various gases contribute to the greenhouse effect would be very useful, particularly in helping policy-makers determine where to concentrate efforts in controlling emissions of these gases.

1.5 Targets of Opportunity for Improved Energy and Resource Efficiency

The chemical industry has reduced its energy intensity over the last decade and made significant progress in reducing the environmental impacts of chemicals production. However, to remain at the forefront in global markets and to maintain its competitive position, the industry will have to continue to takes steps to strengthen market share, such as increased development of markets where the United States has a technological advantage.

Improvements to energy and resource efficiency will also play an important role in the future competitiveness of the industry. Such improvements can increase productivity, lower production costs, and increase profits while enhancing the public image of the industry and reducing the depletion of the Nation's limited energy resources. Using the energy, materials, and waste data presented so far, a profile of the chemical industry's energy use, waste generation, and other factors is shown in Table 1-34. This data provides an initial means for identifying and ranking targets for improving energy and materials efficiency.

The profile shown in Table 1-34 reveals a number of major chemical products that rank high in four or five categories. These include ethylene, ammonia, propylene, sodium hydroxide, chlorine, and a few others. These chemicals are also feedstocks for many of the other chemicals ranking in the top 15. They can be categorized into the cohesive chemical

Table 1-34. The Top 15 Chemicals Ranked as Targets of Opportunity for Improved Energy and Materials Efficiency

Rank	Chemical	Production	Process Energy	Savings/ Theoretical	Savings/ Catalysts
1/3	Nitrogen/Oxygen	77,776	11/14	3	
2	Sulfuric Acid	35,707		6	
4	Ethylene	24,125	1	2	
5	Lime	21,175	4	5	
6	Propylene	14,350	2	10	
7	Ammonia	14,204		4	1
8/10	Chlorine/Sodium Hydroxide	24,835	5/6	1	2
9	Sodium Carbonate (Soda Ash)	11,838	8		
11	Ethylene Dichloride	10,088	10		13
12	Phosphoric Acid	9,909	7	11	
13	MTBE	9,038			
14	Vinyl Chloride	8,763	12	8	5
15/25/26	BTX (Benzene-toluene-xylene)		15	12	3
16	Ethylbenzene	6,950			
17	Nitric Acid	6,765		7	
18	Ammonium Nitrate	6,147			
19	Methanol	6,013			6
20	Urea	5,918			
21	Styrene	5,700	3	9	9
22	Terephthalic Acid	5,000			15
23	Hydrochloric Acid	4,219	9		
24	Formaldehyde	4,188		13	
27	Ethylene Oxide	3,550		15	7

Table 1-34. The Top 15 Chemicals Ranked as Targets of Opportunity for Improved Energy and Materials Efficiency (continued)

Rank	Chemical	Production	Process Energy	Savings/ Theoretical	Savings/ Catalysts
28	Cumene	2,913			
29	Ethylene Glycol	2,813			
30	Acetic Acid	2,425			
31	Phenol	2,175	13		12
32	Ammonium Sulfate	2,045			
33	Butadiene (1,3-)	2,038			4
34	Propylene Oxide	1,963			11
35	Carbon Black	1,750			
36	Acrylonitrile	1,663			8
37	Vinyl Acetate	1,500			10
38	Titanium Dioxide	1,478			
39	Acetone	1,463			14
30	Aluminum Sulfate	1,181			
41	Sodium Silicate	1,155			
42	Cyclohexane	1,100			
43	Bisphenol A	863			
44	Caprolactam	825			
45	Aniline	713			9
46	Isopropyl Alcohol	700		14	
47	Sodium Sulfate	639			
48	Methyl Chloride	563			
49	Propylene Glycol	538			
50	Methyl Methacrylate	313			

TOTAL PRODUCTION 1997 364,171,000 tons

"chains" that show how each major feedstock is used to produce a variety of downstream products. Rather than focusing individually on the most energy- or waste-intensive chemicals, it is more revealing to examine how the major constituents relate to the products they are used to create in terms of energy use, production quantities, and processes used.