Industrial Water Use and Its Energy Implications

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ABSTRACT

Water's ever-growing importance in the industrial manufacturing arena has been demonstrated by an increasing concern regarding the sufficiency of both its quantity and quality for use in industrial applications. Given this concern, U.S. industrial water utilization and its connections to energy consumption have been studied for several energy-intensive manufacturing sectors. Of the three primary industrial uses of water–process water, cooling, and boiler feed–the last is by far the most energy-intensive, despite being the least water-intensive.

Five manufacturing industries stood out in terms of their water use: forest products, steel, petroleum, chemicals, and food processing. These sectors were not only notable in relation to their water consumption, but also in terms of their water-related energy requirements. The combined energy demand throughout these five industries solely for boiler use and steam generation accounts for over one-third of the total U.S. manufacturing energy use.

Introduction

Diminishing quality water supplies, increasing water purchase costs, and strict environmental effluent standards are forcing industries to target increased water-efficiency and reuse. These factors, in combination with an estimated fivefold increase in worldwide manufacturing water use by 2030, will contribute to growing industrial water-related expenses in the near future (Royal 2000, 27). In 1995, the estimated water use for all domestic industries (including mining) was 30,870 Mgal/day, and currently the global annual cost to purify industrial-use water and wastewater exceeds $350 billion (Solley, Pierce & Perlman 1998, 40-44; Yamada 1998, 134).

The U.S. Department of Energy's Office of Industrial Technologies (OIT) is aware of water's key role in industrial production and, given the above issues, has examined water utilization in the following energy-intensive manufacturing sectors: forest products (pulp and paper), steel, petroleum, chemicals, aluminum, metal casting, mining, glass, and agriculture. Collectively known as OIT's Industries of the Future (IOF), these industries are the chief focal point of OIT's ongoing effort to promote the advancement of U.S. industrial energy-efficiency and environmental performance. Water use in semiconductor fabrication and food processing was also examined. The major goals of the study were to identify the principal water users among particular U.S. manufacturing industries, characterize water use within each of those industries, and investigate relationships between water use and industrial energy consumption.

Each industrial sector (e.g., chemicals, food processing, petroleum, etc.) depends on water for unique reasons. This demand is primarily divided among the three major industrial uses for water—process water, cooling, and heating—with a shifting emphasis for each industry. Figure 1, although representative of the state of Texas, provides a reasonable outline of how water is used in several major manufacturing sectors on a national scale (Bowman 1998a).

Perhaps no industrial application of water is more dependent on energy than process steam generation. Energy utilization devoted to boiler operation and steam generation comprises over half of the total energy consumed by the pulp and paper (82%), food processing (56%), and chemicals (52%) industries, in addition to significant portions of steel and food processing energy use (Jaber & Jones 1999, 2-4). Boiler and process steam generation and distribution systems likely present the greatest potential area for the achievement of significant industrial water-related energy savings.

The magnitude of boiler and steam generation energy consumption in the forest products, steel, petroleum, chemicals, and food processing industries paralleled their comparatively high quantities of water consumption in relation to other manufacturing sectors examined in the original study (e.g., aluminum, mining, etc.). The water use and water-related energy demand of these five industries are the ultimate focus of this paper.

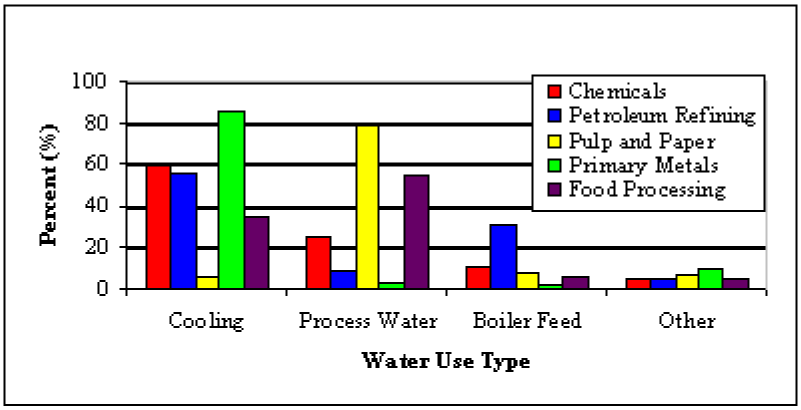

Figure 1. Types of Water Use by Industry

Industrial Water Consumption

Forest Products

Background. The forest products (pulp and paper) industry is the largest industrial process water user in the United States (EPA 1995a, 6). Surveys from 1975 found an average water use of 26,700 gal/ton-product for the pulp and paper industry. By 1988, this amount dropped to approximately 17,500 gal/ton-product. Currently, about 16,000 gallons of water are consumed per ton of product (Bryant, Woitkovich & Malcolm 1996, 451).

The rate of water use decline is still progressing at a modest pace in the forest products sector. Much of the decrease in forest products water use over the past several decades was "accomplished by small adjustments in the pulping and papermaking processes rather than by major changes in production techniques" (David 1990, 86). Nonetheless, water use reduction can have adverse effects in pulp and paper mills.

As water use decreases in a pulp or paper mill, contaminant concentration in the water may increase, leading to higher rates of scale deposition and other unwanted accumulation within the process line. Consequently, production costs may increase as systems become clogged and lose efficiency. The quality of a product also suffers from contaminant build-up. Therefore new economical technologies capable of purging water circuit contaminants may be necessary if significant future pulp and paper water use reduction is to continue (Bryant, Woitkovich & Malcolm 1996).

Water requirements. A recent survey of 663 U.S. and Canadian mills of varying classifications revealed a total daily water consumption for these mills of approximately 6.4 billion gallons per day. The survey, whose results are given in Table 1, categorized mills into 11 different areas based on the similarity of their products and processes (Bryant, Woitkovich & Malcolm 1996, 452).

Table 1. Water Use in Different Categories of Pulp and Paper Mills

Mill Type	Mean Water Use (gal/ton-product)	Median Water Use (gal/ton-product)
Integrated Bleached	23,400	22,900
Integrated Unbleached	11,400	10,100
Paper Mill >100 Air-dried tons (ADT)/day	8,000	3,600
Bleached Market Kraft Pulp	22,400	23,000
Newsprint (mechanical pulp)	10,400	9,700
Corrugating Medium (neutral sulfite semi-chemical)	6,400	4,500
Newsprint (mechanical and high-yield chemical)	19,700	15,500
Deinked Secondary Fibers	9,700	9,500
Dissolving Pulp	51,000	41,400
Paper Mill Producing <100 ADT/day	18,000	12,000
Market Non-kraft	18,000	4,500

Water costs. In one particular survey, the water prices at four North American mills were found to range from $125 to $350 for every Mgal used. An annual water cost of $0.7 to $2.3 million was found for a bleached kraft mill that used 16,500 gallons of water per ADT and processed approximately 1,000 ADT per day (Wohlgemuth, Mannisto & Mannisto 1996, 143).

In existing mills, the marginal price of water (i.e., the price for each additional unit) is determined by the costs of raw water treatment and biological effluent treatment. The marginal prices of water documented for three advanced treatment techniques were $1,800/Mgal for chemical flocculation, $4,000/Mgal for membrane filtration, and $4,100/Mgal for evaporation (Wohlgemuth, Mannisto & Mannisto 1996, 143).

However, some of the biggest costs of water use in pulp and paper mills are those associated with water discharge. In fact, "normal use and discharge of water costs millions of dollars annually [even] for relatively small mills" (Fogarty, Marks & Booth 1999, 1579). However, water cost savings alone often cannot fully justify water conservation initiatives. Other indirect cost savings resulting from decreased water use (e.g., steam and power cost reductions) are typically necessary to do so (Wohlgemuth, Mannisto & Mannisto 1996).

Steel

Background. According to the American Iron and Steel Institute (AISI), "Next to iron and energy, water is the industry's most important commodity" (AISI 1999, 21). Today per unit water use in the steel industry is less than half of what it was 20 years ago (GLC 1996). More than 95% of the water used for steelmaking is recycled within the plant, and often the recycled water "is returned to the source even cleaner than it was before" (AISI 2000).

In general, water is used in steelmaking as a: coolant for equipment, furnaces, and intermediate steel shapes; cleansing agent to remove scale from steel products; source of steam; medium for lubricating oils and cleaning solutions; and wet scrubber fluid for air pollution control (AISI 1999, 21). The type of steel being manufactured, its shape, and the efficiency of the equipment used to produce it all factor into steelmaking water requirements. Depending on the above variables, steelmaking water demands may vary by several thousand gallons per ton.

Water requirements. Currently, an approximate 75,000 gallons of water are required to produce 1 ton of steel (AISI 1999, 21). However, this figure includes recycled and reused process and cooling water. With high-rate recycling, typical steelmaking "fresh" water requirements range between 13,000 and 23,000 gallons per ton of product through all stages of production (Wakelin 1999, 386-93; Yamada 1998, 160). Average water use figures for specific steps in the steelmaking process are given in Table 2 (EPA 1995b, 2.6-2.14; Fruehan 1998, 386-93; Wakelin 1999, 366).

Table 2. Steelmaking Water Use

Step	Process Water (gal/ton-product)	BAT[1] Wastewater Discharge (gal/ton-product)
Cokemaking	120-900	100-120[2]
Ironmaking	3,200-6,000	50-120
Steelmaking		
Electric Arc Furnace	2,100	110
Basic Oxygen Furnace	1,000-1,100	50-110
Refining and Casting		
Vacuum Degassing	1,250-1,400	25
Continuous Casting	3,600	<25
Forming and Finishing		
Hot Forming	1,500-6,400	60-260
Cold Forming	Data not available	10-400
Oxidizing Operations	330-1,700	Data not available
Reducing Operations	325-1,820	Data not available
Acid Pickling	Data not available	90-1,500

[1] BAT: Discharges using Best Available Technology economically achievable.
[2] This figure excludes dilution water to optimize bio-oxidation.

Petroleum

Background. The petroleum industry has achieved more than a 95% decrease in water use per barrel of crude oil processed from the 2,000 gallon industry average present in 1975, yet it is still one of the four most water-intensive domestic manufacturing sectors (Eble & Feathers 1992). The petroleum industry's water use has consistently decreased in part because of substantial declines in cooling water intake. Ultimately, however, the most significant reason for the decrease in total water needed for crude oil refining was an industry-wide cutback in production (David 1990). Several key factors help determine water use within a petroleum refinery: process configuration, refinery complexity, capability for recycle, degree of sewer segregation, and local rainfall.

Petroleum refineries have the highest rate of water recycling of any major industry (GLC 1996). The recycling ratio in the petroleum industry is about 7.5 to 1 (David 1990, 86). In other words, a given quantity of raw water is typically reused an average of 7.5 times prior to being discharged. Most recycled water is routed to cooling applications, which are the most water-intensive processes in petroleum refining. As a result, the petroleum industry uses nearly ten times as much cooling water as it does process water (David 1990, 86).

Water requirements. Water use and wastewater discharge per barrel of crude oil processed range between 65 to 90 gallons and 20 to 40 gallons, respectively (Eble & Feathers 1992). Wastewater discharge data are summarized in Table 3 (Energetics 1998, 34-37).

Table 3. Petroleum Industry Wastewater Discharge

Step	Wastewater Discharge (gal/bbl)[1]
Topping/Separating Processes	
Crude Oil Desalting	1.2-4.0
Crude Oil Distillation	26.0[2]
Thermal and Catalytic Cracking	
Visbreaking	2.0
Delayed Coking	1.0
Fluid Coking/Flexicoking	–[3]
Fluid Catalytic Cracking	15.0
Catalytic Hydrocracking	2.0
Combination/Rearrangement	
Alkylation	2.6
Catalytic Reforming	6.0
Isomerization	Data not available
Ethers Manufacture	Data not available
Treatment Processes	
Catalytic Hydrotreating	1.0
Sweetening (Merox Process)	–
Sulfur Removal (Claus Process)	–
Specialty Products Manufacture	
Lubricating Oil	Data not available

[1] Gallons per barrel of crude oil processed.
[2] Total combined wastewater discharge from both atmospheric and vacuum distillation.
[3] "–" indicates insignificant or no wastewater generated.

Chemicals

Background. The chemicals industry is so large and diverse that generalizations about its water use efficiency cannot easily be made (Bowman 1998b). However, data do show the chemicals industry being historically one of the largest industrial consumers of water (Solley, Pierce & Perlman 1998).

The most prevalent use of water in the chemicals industry is for cooling. Many chemical reactions generate heat, and the reaction vessel must then be cooled so that "the temperature is controlled at the desired limit and the reaction does not get out of control" (David 1990, 84). Typically this heat is dissipated in cooling towers before water is returned to the plant for subsequent reuse. After an extended period of increase, water cooling demands are now declining.

Even though the U.S. chemicals industry's production is still growing, its water use per unit of production has shown a steadily decreasing trend over the last 40 years. Increased production efficiency and water recycling, and the substitution of air in place of water during certain cooling processes, have all been cited as explanations for the decrease in per unit water use (David 1990, 84).

Water requirements. Tables 4 and 5 show the chemicals industry's dependence on water by process and by sector, respectively (David 1990, 84).

Over 90% of this industry's recirculated water is used for cooling. Industrial organic chemicals manufacture is the most water-intensive chemicals sector, whereas agricultural chemicals is the least water-intensive. The chemicals industry uses approximately 26,400 Mgal/day of combined fresh intake and recirculated water (David 1990, 84).

The synthesis of different chemicals may require orders of magnitude differences in water, and ranges are even quite large for producing the same chemical. For example, the production of sulfur requires approximately 1,920 to 2,400 gallons of water per ton of product while lactose production requires between 144,000 and 192,000 gallons of water per ton, clearly demonstrating the complexity of the chemicals industry's water needs (Rogers 1993, 34).

Table 4. Chemicals Industry Water Use by Process

Manufacturing Process	Water Intake (Mgal/day)	Recirculated Water (Mgal/day)
Cooling	7,700	15.500
All others combined	1,610	1,500
Total	9,310	17,000

Table 5. Chemicals Industry Water Use by Sector

Sector	Water Intake (Mgal/day)
Industrial Organic Chemicals	4,150
Industrial Inorganic Chemicals	2,420
Plastics and Synthetics	1,170
Agricultural Chemicals	836
Other Chemicals	734
Total	9,310

Food Processing

Background. Some of the most common uses for water in the food processing industry are washing/cleaning food and equipment, pasteurization, cooking, and sterilization. It can also be used as an additive in canned fruits and vegetables (David 1990, 89-90). How water is used among various food processing sectors can differ substantially.

For sugar production, roughly half of the intake water is used for cooling and 20% or less for actual processing. Beverage manufacturers also use large quantities of water for cooling, although they require slightly more process water than cooling water. On the contrary, for meat processing and fruit preservation, about 60% of the intake water is used as process water (David 1990, 89).

Food processing techniques have not changed much over the last several decades. Despite this technological inertia, the food processing industry has shown a trend of decreasing water use since the mid-1950s. Water use peaked in 1968 at 2,100 Mgal/day but dropped to 1,500 Mgal/day by 1983. Over the same time period, per unit water use declined from 13.1 gallons to 8.6 gallons (David 1990, 89). Most of the decrease in water use has been a direct result of effluent regulation compliance.

The food processing industry has maintained similar recycling ratios over the past several decades while most other industries have doubled their respective rates (GLC 1996). The food processing industry's recycling ratio has stabilized at approximately 2.0:1 (David 1990, 89). Once water is discharged, it typically undergoes primary and secondary treatment using biologically based treatment systems, such as trickling filters and activated sludge (David 1990).

Water requirements. Water use requirements differ depending on both food processing sector and end-product. Table 6 shows estimated water demands for the processing of various foods as observed in a recent study (Rogers 1993, 34; David 1990, 89).

Table 6. Food Processing Water Needs

Product	Water Use (gal/ton-product)
Beer	2,400-3,840
Milk products	2,400-4,800
Meat packing	3,600-4,800
Bread	480-960
Whisky	14,400-19,200
Green beans (canned)	12,000-17,000
Peaches and pears (canned)	3,600-4,800
Other fruits and vegetables (canned)	960-8,400
Industry-wide average	8.6 gal/unit output[1]

[1] Example "unit output": 1gal. of milk.

Boiler and Steam Generation Energy Consumption

Background

This section presents data on the use of steam as a source of process heat. These data compared both the relative energy use between several large manufacturing industries and the proportion of energy used in each industry to operate boilers and generate process steam.

Steam plays a crucial role in a variety of industrial processes. Depending on a number of factors, such as boiler efficiency and condensate return, varying amounts of water may be necessary to produce the same volume of steam. Although process heating may not be the most water-intensive aspect of production for most manufacturing industries, boiler and process steam generation and distribution systems present a promising area for the achievement of significant industrial water-related energy savings. Currently steam accounts for $21 billion per year of U.S. manufacturing energy costs, but according to the Alliance to Save Energy a 30% improvement in thermal efficiency is generally attainable in most steam systems (Jaber & Jones 1999, 5).

Steam Generation By Industry

Chemicals. Although water serves primarily as a coolant in most industrial chemical manufacturing processes, its use in the generation of steam is important for a number of other tasks–machine drive, reactor heating, direct use, and low-temperature (800º F or less) furnace heating.

Approximately 52% of energy use throughout the chemicals industry is devoted to steam production. This amounts to 10% of the total industrial manufacturing energy consumed annually in the United States. Current trends indicate about a 4.3% average yearly growth rate for chemicals industry process steam demand. The implementation of energy conservation methods, process modification, and other factors could slow that growth rate by half (Jaber & Jones 1999, 3-4).

Food Processing. Some principal uses for steam in this industry are cooking, sterilization, blanching, pasteurization, and dehydration. The food processing industry typically uses smaller boilers than other major manufacturing sectors because health concerns dictate that food processing operations must use heat exchangers for heat transfer between food and steam, as opposed to direct contact.

The intensity of steam use varies depending on the food sector under consideration. As shown in Table 7, process steam generation fulfills a significant portion of the energy demand for most food processing sectors (Jaber & Jones 1999, 4).

Boilers consume approximately 56% of the total energy used throughout the food industry and 4% of the total U.S. industrial manufacturing energy consumption. The predicted annual growth rate for process steam demand in the food processing industry is approximately 2.6%. Conservation measures could potentially decrease this rate to around 0.2% (Jaber & Jones 1999, 4).

Table 7. Steam Energy Provision for Food Processing Sectors

Sector	Energy From Steam Generation (%)
Poultry/Egg Processing	23
Wet Corn Milling	31
Candy/Chewing Gum	41
Soybean Oil Mills	20
Malt Beverages	43
Distilled/Blended Liquors	40

Pulp and Paper. The pulp and paper industry utilizes large quantities of low-pressure steam. Table 8 shows the portion of energy steam provides to these processes (Jaber & Jones 1999, 2).

Table 8: Steam Energy Provision for Pulp and Paper Processes

Process	Energy From Steam Generation (%)
Pulping	24
Bleaching	20
Papermaking	41

Approximately 82% of the total amount of energy consumed by the pulp and paper industry is devoted to process steam generation. Pulp and paper steam generation energy demands amount to 13% of all industrial domestic energy consumption (Jaber & Jones 1999, 2).

Petroleum. Four major processes in which steam plays an important role in the petroleum industry are distillation, desulfurization, alkylation, and hydrogen production. Most of these processes use low-pressure steam, as is the case for the pulp and paper industry. Table 9 shows the energy provided by steam to these processes (Jaber & Jones 1999, 3).

Roughly 28% of all the energy used in the petroleum refining sector is for steam production. This energy use accounts for 6% of the total energy consumed by domestic manufacturing industries (Jaber & Jones 1999, 3).

Table 9. Steam Energy Provision in Petroleum Refining Processes

Process	Energy From Steam Generation (%)
Distillation	
Atmospheric	22
Vacuum	44
Desulfurization	
Naptha and Distillates	28
Gas Oil	18
Alkylation	79
Hydrogen Production	N/A

Steel. Over 2,600 boilers were in operation in the primary metals industries (of which the steel industry is a major component) in 1993, with a total capacity of roughly 190,000 million Btu per hour. A vast majority of boiler energy consumption goes into steam production. Steam use differs widely among plants, depending upon processing techniques and plant-output products.

Industry-wide, boiler use accounts for 22% of steel sector energy consumption and 3% of all industrial manufacturing energy consumed nationwide. Recent estimates have predicted a decline in the growth rate of steel industry process steam utilization from 1.7% to 0.3% per five year period (Jaber & Jones 1999, 2). Table 10 below shows how much steam is devoted to certain processes in one particular vertically-integrated steel plant (Jaber & Jones 1999, 2).

Table 10. Steel Steam Energy Distribution

Function	Fraction of Steam Use (%)
Mill Heating	33
Processing Line Functions	60
Drip/Tracer Applications	7
Total	100

Summary

Table 11 lists both the proportion of internal industry energy demand dedicated to generating steam and operating boilers, in addition to the fraction of total U.S. manufacturing energy consumption each industry utilizes to do so. As indicated in Table 11, over one-third of the total U.S. manufacturing energy consumption is used to meet boiler utilization and steam generation energy demands for these five industries (Jaber & Jones 1999, 2-4).

Table 11. Overall Industrial Boiler Operation and Steam Generation Energy Use

Industry	Industry Energy Used for Steam Generation and Boiler Operation (%)	Portion of U.S. Manufacturing Energy Use (%)
Chemicals	52	10
Food Processing	56	4
Petroleum	28	6
Pulp and Paper	82	13
Steel	22	3
Total	N/A	36

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