Water Use in Industries of the Future[1]

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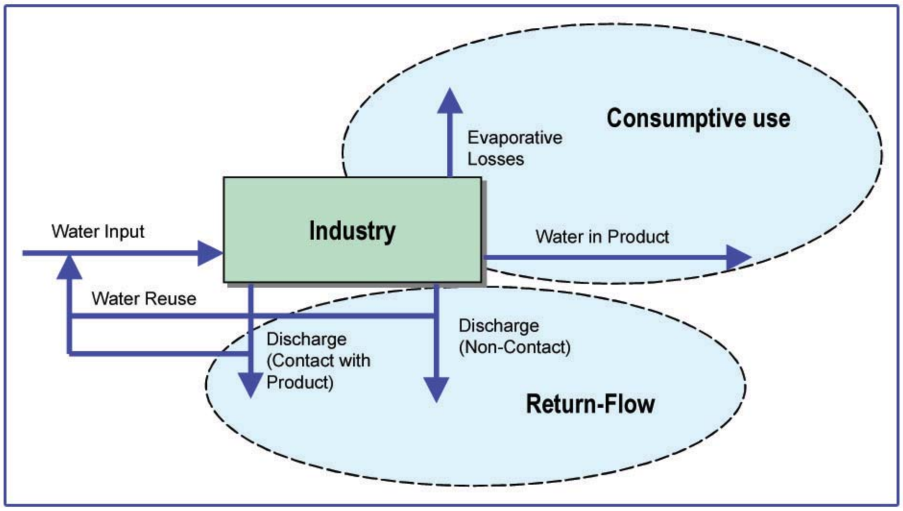

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[1] A chapter from the book, *Industrial Water Management: A Systems Approach*, 2nd Edition, prepared by CH2M HILL for the Center for Waste Reduction Technologies, American Institute of Chemical Engineers, 3 Park Avenue, New York, NY 10016.

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1.1 Overview

1.1.1 Introduction

For most of the industrial era, water has been viewed as a free or very low-cost commodity. This perception of a plentiful resource is rapidly changing, however, as communities across the country begin to face water supply limitations. Awareness of this issue is heightened as a result of recent developments such as:

- Widespread drought
- Increasingly strict standards for both withdrawal and discharge of water
- More rigorously enforced water rights limitations
- Increasing water demands of urban populations

The need to measure, control, and record water usage, neglected in the past, is starting to be addressed. Industry, a significant user of water, is becoming aware of the importance of measuring and managing water use. Energy-intensive industries, especially, are finding water scarcity to be a limit to growth.

To date, there has not been a credible or comprehensive study on how water is used in industry. Therefore, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (DOE-EERE) Industrial Technologies Program and the American Institute of Chemical Engineers' Center for Waste Reduction Technologies (CWRT) have assembled this study on water use, water reuse, and the relationships between water and energy for several energy-intensive industries, and then extracted themes and issues common across these industries.

This chapter examines water use, management of water, and the relationship of water to energy use in several Industries of the Future, selected by DOE for ongoing study because of the energy-intensive nature of their operations. The industries included in this study are:

- Agriculture
- Aluminum
- Chemicals
- Forest Products
- Mining
- Petroleum
- Steel

Following this overview, each industry is presented in its own subsection. All of the industry subsections follow the same general outline, which covers how the industry uses water, how different sectors of the industry use water, how major processes and unit operations use water, what trends there might be in water use over time in the industry, what practices are being used to manage and reuse water, and how water use and energy use in the industry are related.

This study is presented to DOE as a stand alone work, and also as a chapter integrated into the 2nd edition of CWRT's book on industrial water reuse. The work combines knowledge from CH2M HILL process specialists across all of these industries, and represents over 150 person-years of combined experience from the firm within these industries.

1.1.2 Cross-Industry Issues

One objective of this study was to highlight commonalities among these industries regarding water use, and present them as areas in which further research and development could lead to high-impact changes and reduction in water and energy use patterns. Following are the general themes identified during the study.

- A water balance, a materials balance, and an energy balance can be performed around each of these industries, although in practice representative water balances have been published for few industries. Because each of the industries is a system made up of interdependent processes, changing the energy balance at any point will change the water and materials balances as well, and vice versa. If discharged water is reused, energy might be required to perform that function, but it might be saved elsewhere. If pollutants are eliminated from air emissions, they might be put into a water stream for further treatment, requiring additional water. Most important, if processes are made more energy efficient, they will typically become less water intensive as well.

- A primary water-energy relationship in several Industries of the Future is heat transferred into cooling water. Industries such as steel, aluminum, petroleum, and chemical refining involve a number of heat-intensive processes. To control these processes and protect process equipment from the heat, cooling water is used to transfer waste heat away from the process. Cooling water use, and the associated evaporative losses, constitutes the highest consumptive use of water in most of these industries. An even higher amount of water is recirculated through cooling towers. The consumptive uses represent lost energy in the form of rejected heat and represent an important relationship between water and energy.

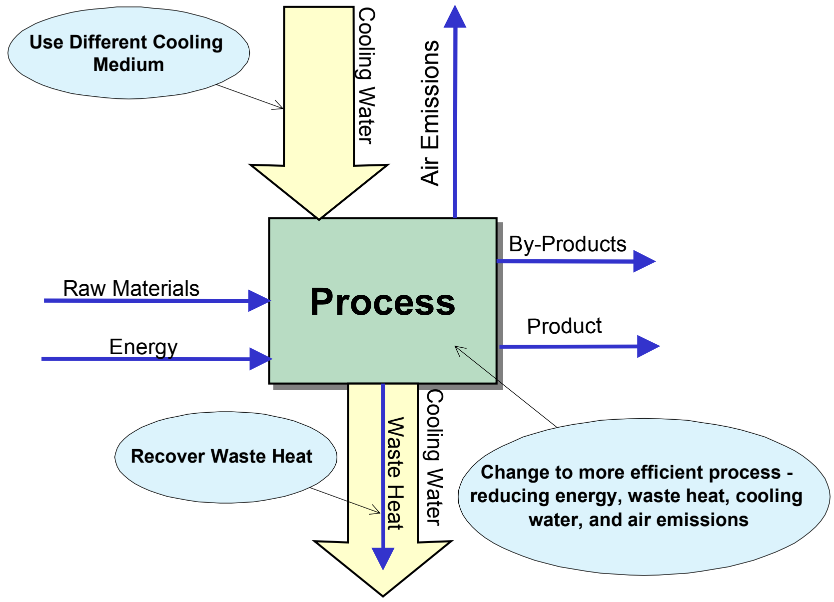

FIGURE 1.1-1
Water, Energy, Materials Balance

  Sometimes the water balance itself can be an indicator of the energy intensity and efficiency of a process; those that use large amounts of cooling water tend to be those involving large additions of heat. There are several opportunities in this area to recover the waste heat, to change cooling processes, and to change to more efficient production processes, which affects water, materials, and energy. The concept and opportunities are illustrated in Figure 1.1-1.

- Energy is also used in moving and preparing water, including pumping, conveyance, and treatment to required quality for processes. This energy cost is most apparent in agriculture, but it is a buried cost that is distributed among all industries. Again illustrating how water and energy balances affect each other, this energy cost can be reduced to the extent that water use for the process is reduced or conserved.

- Air emissions and water use are linked. Several industries, most notably steel and aluminum, reported that significant percentages of their water use are devoted to air emissions control, typically in the form of water or steam treatment of stack emissions, designed to mitigate air pollution from particulates such as soot, or nitrogen and sulfur compounds associated with combustion and other energy-intensive thermal processes. The addition of pollution control equipment serves to mitigate air pollution by moving the pollutants into a water stream that can be more easily treated, thus increasing water use by as much as 7–8% in some industries.
- Steam is a significant component of both water and energy use in some of the industries, most notably forest products, chemicals, and petroleum. Steam is used for process temperature control (heating), sterilization of critical process components, and co-generation of power and heat. In the forest products industry, steam is generated in boilers fired by waste products from the pulp and paper processes. Similarly, in the steel industry, by-product gases from blast furnaces and coke ovens, which cannot be released into the atmosphere untreated, have been burned in boilers to produce steam for heat and power.
- Economics drives decisions. In most industries, water is used more efficiently now than in the past, but could be used more efficiently still. In many cases, technologies already exist to improve efficiency. Economics is a significant factor in determining when these improvements are implemented. As resources such as water become more constrained, they tend to become more expensive to use. This trend makes resource conservation less costly than acquiring more of the resource, and drives conservation to new levels.
- Capital intensity and process lifecycle also affect the rate of adoption of more efficient processes. Industries that have high investments in capital equipment or mature technologies for production tend to modify or replace that equipment more slowly.
- Water scarcity drives decisions. For example, the ability to site and obtain permits for a new plant can be limited by water availability, and a number of cases exist in which this issue has driven water conservation and reuse projects that were planned into renovation or new construction projects.[1]
- For some industries, materials recycling is having an effect on water and energy use. This is an evolutionary trend that has been happening over decades in steel, aluminum, and forest products. The water and energy required to recycle scrap into new material is typically less than that required to manufacture new material from raw components. Possibly the best example is the steel industry, where transition from reducing raw ore in blast furnaces and oxygen furnaces to re-melting recycled steel in electric-arc furnaces can result in reductions in water use of up to 90%, and in energy use up to 65%. [2]
- The cost of water is only now beginning to drive monitoring and tracking of its use in industry. Water use (and any other resource use) is tracked in proportion to its effect on cost. In many cases, water use data are not tracked well by facilities and are not maintained in the public domain. Much of the data gathered for this study was synthesized from non-public sources, or estimated from personal experience by

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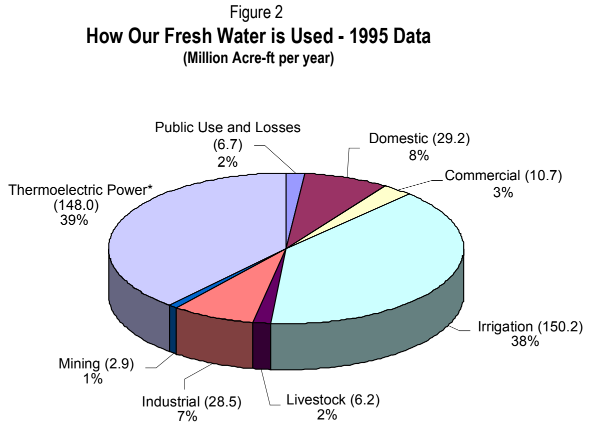
[1] The case studies section of CWRT's book, "Industrial Water Management: A Systems Approach," discusses a power plant and a semiconductor fabricator for which this is the case.

[2] These numbers are estimated from water and energy use figures reported in the Steel Industry section of this chapter, for various steel-making processes.

the process specialists doing the study. A primary reason is economics. Fundamentally, what industrial facilities track is cost, because it affects financial performance. If water is a very low cost or essentially free commodity, its use might be tracked only at one meter at the main header for the plant, if that. Water use information within plants often does not exist, and a number of the plants contacted for this study across different industries reported little or no knowledge of their water use.

1.1.3 How Water is Used in Industry

Figure 1.1-2 shows a breakdown of how we use fresh water in the United States. In total, this represents about 382 million acre-feet per year, or about 125 trillion gallons per year used. Within the breakdown, the irrigation and livestock categories represent the agriculture industry, included in this study. Irrigation accounts for more total water use than all other uses, including all of the other industries included in this study *combined*. The thermoelectric power category includes significant amounts of water use for heat transfer and cooling at power plants. Mining is broken into its own category, representing 1% of total fresh water use. All of the other industries in this study add up to 7% of total fresh water use. Figure 1.1-2 thus shows that most of the fresh water use in the United States is for growing crops and generating power.



*Category includes water used in the generation of electric power with fossil-fuel, nuclear, or geothermal energy.

Source: Solley, W.B., R.R. Pierce, H.A. Perlman (1998). Estimated Use of Water in the United States in 1995. Geological Survey Circular 1200.

FIGURE 1.1-2
How our Fresh Water is Used—1995 Data (million acre-ft per year)

Each of the other industries in this study, however, does use significant amounts of water, and faces ongoing challenges and opportunities in the areas of water and energy conservation. These industries have been in varying states of evolution over the past 100 years, from high growth to maturity. This evolution has had, and continues to have, a significant impact on industry economics, resource use (including water), and energy intensity.

1.1.4 The Nature of Water Use

Industrial and agricultural use of water has a large impact on communities, watersheds, and natural habitats. We should, however, be specific in what we mean by "water use." Water is a ubiquitous resource that in almost all cases is neither created nor destroyed through our use of it; humans do not make water "disappear." The impact of human water use takes three major forms:

1. Water is moved from one place to another.
2. Water quality is altered.
3. Water is rendered unavailable by evaporation or other consumptive use.

When water is moved out of a local watershed or ecosystem not to return (rendered unavailable), we call that "consumptive use." Examples include water that evaporates from cooling towers and water that becomes part of a product from a factory. When water is used and then returned to the local watershed or ecosystem, we call that "return-flow use." Rinse water or cooling water brought into a facility, used, and then discharged into the same body of water either directly or through a publicly owned treatment works is an example of return-flow use.

Both consumptive and return-flow uses can, and usually do, affect water quality. Evaporation, such as from a cooling tower, tends to concentrate constituents in the water that remain for return flow. Discharged water that has come into contract with a product, or to which materials have been added during a process, typically contains some of those materials and/or some of the product.

Figure 1.1-3 provides a generalized illustration that can be applied to any industry, or water user, including agriculture. The illustration shows that, as has been discussed elsewhere, the study of water use can be driven by the mass-balance concept, wherein (water in) = (water out). Over time, the amounts of water coming out of the "black box" for any industry will be the same as the amounts going in. The two real questions to ask are, "Where is the water going?" and "How is water quality being affected?"

As shown in Figure 1.1-3, most of the opportunities for water reuse exist in the return-flow use categories. Opportunities for conserving energy and water do exist in the consumptive use categories, however, particularly in reducing energy losses in order to reduce evaporative losses from cooling towers. It might also be possible to recover heat energy from some of the consumptive or return-flow uses, especially cooling water. In all cases, in the study of water reuse opportunities, the two questions listed previously—"Where is the water going?" and "How is water quality being affected?"—are most relevant to the analysis.

Figure 1.1-3 can be applied to any industry, but the use patterns shown vary among industries. The steel industry, for example does not put any water into its products, but uses a significant amount as non-contact cooling for heat-intensive processes. Much of this non-contact cooling water is discharged to a local body of water, while some evaporates through cooling towers in order to remove heat. The aluminum industry exhibits similar patterns, though it uses somewhat less cooling water, because less heat is necessary for the production process. Agriculture, on the other hand, does put water into many of its products, with large consumption in the processes of evaporation and transpiration that are part of the natural cycle of plant growth.

Table 1.1-1 compares major water uses for the various industries studied here, describes some of the challenges these industries face related to these water uses, and shows how some of them are meeting these challenges.

1.1.5 Water Use Trends

Figure 1.1-4 shows water use trends from 1960 to 1995, as estimated by the U.S. Geological Survey (USGS), for several water use categories as broken out in Figure 1.1-2. For both irrigated agriculture and industry, which are studied here, the trend shows a steady in crease in use from 1960 to 1980, then a decrease from 1980 to 1995. USGS attributes these trends to the following major factors (Solley et al., 1998):

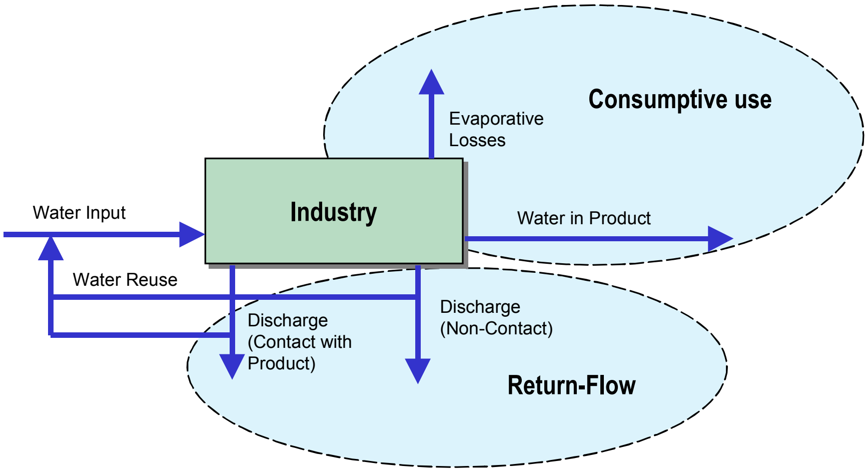


FIGURE 1.1-3
Industry's consumptive and Return-Flow Use

TABLE 1.1-1
Water Use Issues for Different Industries

Industry	Major Purposes for Water Use	Types of Water Use (Consumptive vs. Return-flow)	Challenges Regarding Water Use	How Challenges are Being Met
Agriculture	Irrigating Plants, Feeding Livestock	Consumptive use as part of food growth process and put into the products, Return-flow in the form of agricultural runoff	Largest Water-user. High evaporative losses from spray irrigation and transpiration, losses to groundwater through unlined irrigation ditches	Drip and spray irrigation systems replacing gravity-flow systems, channeling of runoff to multiple fields
Aluminum	Removing heat from energy-intensive processes, rinse water in metal forming and finishing processes	Consumptive use from cooling tower evaporation, Return-flow discharge of boiler and cooling tower blowdown and used rinse water	Large use of cooling water, including cooling of rectifiers used to convert power for use in primary process. Rinse water requiring treatment prior to discharge or reuse	Replacing primary reduction with recycled material, replacing once-through cooling with closed-loop cooling systems, cascade reuse of rinse water
Chemicals	Removing heat from energy-intensive processes, Medium for chemical reactions, facilities wash-down	Consumptive use from cooling tower evaporation and some water into products, Return-flow discharge of boiler and cooling tower blowdown and used process and wash-down water	Large use of cooling water to remove heat from heat-intensive processes, representing large heat loss Lack of water use data for specific plants	Cooling water reuse, Tertiary treatment and reuse of process wastewater and backwash water.
Forest Products	Medium for chemical reactions, Removing heat from energy-intensive processes, facilities wash-down	Consumptive use from cooling tower evaporation and some water into products, Return-flow use from cleaning, preparation and conveying feedstock materials, steam production and air emission controls	Large use of cooling water, significant amounts of contact process water requiring treatment prior to discharge, many mills have old equipment that has not been updated, lack of water use data for specific mills	Process water reuse, counter-current rinsing steps, reuse of steam condensate, reuse of non-contact cooling waters
Mining	Dust control, slurry medium for product transport, drilling, grinding	Consumptive use from dust control and some slurry transport.	Large consumptive use for dust control in water scarce areas, Recovery of water used for conveyance of product, Many mines produce excess drainage water, which may require treatment.	Alternatives to water use for dust control in water-scarce areas, use of rainwater and drainage water.
Petroleum	Removing heat from energy-intensive processes, Medium for chemical reactions, facilities wash-down. Large amounts of water also used in oil fields	Consumptive use from cooling tower evaporation, Return-flow use from steam condensate and cooling tower blowdown, and process water discharge	Large use of cooling water and steam, process water requiring treatment prior to discharge or reuse	Recovery and treatment of boiler and cooling tower blowdown, reuse of process water for other processes. Reclamation and use of other wastewater in oil field operations.
Steel	Removing heat from energy-intensive processes, rinse water in metal forming and finishing processes	Consumptive use from cooling tower evaporation, Return-flow discharge of boiler and cooling tower blowdown and used rinse water	Large use of cooling water, both contact and non-contact.	Changing away from water and energy-intensive processes to more efficient processes, greater use of recycled material in electric-arc furnaces, cascade reuse of rinse water

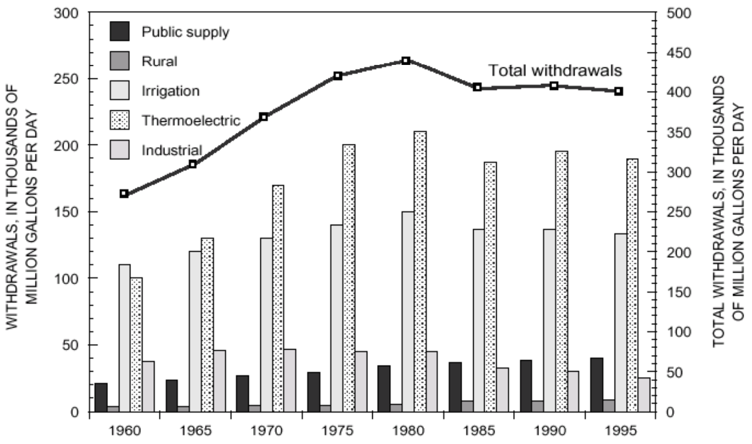


FIGURE 1.1-4
Trends in water withdrawls (fresh and saline) by water-use category and total (fresh and saline) withdrawls, 1960-95 [Source: USGS (Solley, 1998)]

- Increases from 1950 to 1980 related to expansion of irrigation and energy development, and plentiful ground water supplies
- Decreases in irrigation use from 1980 on, related to higher energy prices in the 1970s, draw-down in ground water levels, which increased irrigation water costs, and downturns in the farm economy, which decreased irrigation demand
- Decreases in the industrial sector from 1980 on, related to improved technologies, plant efficiencies water recycling, high energy prices, and regulatory pressures that restricted water discharges
- Enhanced awareness by the general public about water resource issues and conservation programs

These factors match some of the general themes illustrated earlier. Water scarcity and economics drive decisions, and therefore water demand, and energy-related drivers affect water use. Each of the industry studies is affected by these drivers as discussed in the following subsections.

1.1.6 Steps to Take for Further Action to Reduce Water Use in Industry:

The following steps are suggested for instituting a good water management and conservation program:

- **Develop a step-wise, systematic approach to water management at facilities, and corporation-wide.** Water use reduction and management has often been done on a piecemeal basis within individual departments. Results have often been less than satisfactory, or programs have not been carried through or measured. Water management must be viewed as an *ongoing* management process.
- **Think holistically about a facility, or even beyond the facility, to include the entire watershed.** As mentioned previously, each industry and facility can have a mass balance drawn around it; when this is done, it can be seen that changes in one part of the system affect the entire system. When this is understood, changes that detrimentally affect the system can be avoided, and changes that increase efficiency in all parts of the system can be planned.
- **Institute a rigorous system of water use measurement**. Although the instrumentation need not be sophisticated, it should be reliable, and all significant water uses should be measured and recorded.
- **Quantify the energy losses from the use of cooling water.** Given the increasingly short supply of water, it could be that for some processes, cooling is no longer best accomplished with water. A comprehensive evaluation of energy usage should be performed.
- **Reduce the practice of once-through cooling water.** Cooling towers should be utilized wherever possible to decrease en-

ergy consumption and reuse as much cooling water as possible.

- **Educate employees and the public on the importance of water conservation.** Employees generally respond to issues on which they're well informed and on which management attention is focused, as indicated by training and other emphases.
- **Eliminate leaks and other inefficiencies.** Although a number of facilities have implemented housekeeping and/or water conservation programs, leaks in sewer systems and other piping continue to waste water.
- **Identify water reuse opportunities that also reduce energy consumption.** Industry has often failed to explore water reuse because of its extensive infrastructure investments. As water and energy costs escalate, the drivers for water reuse increase, and the opportunities for associated energy reductions are numerous.
- **Continue research and development efforts focused at low energy, low water processes.** Several companies report impressive advances in processes that were previously thought impractical. Technology is likely to be integral in realizing even greater gains in the challenge of water and energy minimization.

1.1.7 Relationship of Water to Energy

Water-energy relationships in industry are complex and take many different forms, because industry is made up of many different processes and activities that use both water and energy. As discussed previously, the most pronounced water-energy relationship occurs where heat energy is added to a process and residual heat is carried away in cooling water. Figure 1.1-5 presents a generalized diagram for a number of typical industrial activities that use water. Virtually all of these activities require energy input, and some of them reject heat to the environment, representing an energy loss.

The diagonal arrows represent these energy inputs and losses, so that this is an approximate pictorial diagram of a typical water-energy relationship in industry. The significance of specific activities varies among industries.

Figure 1.1-5 is really a more detailed adaptation of Figure 1.1-3, for any industry. Starting from diagrams such as this, analytical frameworks can be used to optimize both water and energy use in complex industrial systems.

It is intuitive to say that processes that are less water intensive must use less energy as well, and often this is the case; however, water-energy relationships can have both positive and negative correlation, depending on specific processes. A positive correlation, for example, would be an energy-intensive process, such as a blast furnace for steel, replaced by a less heat-intensive, more energy-efficient process such as direct reduction, which also requires less cooling water. An example of negative correlation can be found in the forming and finishing operations of the aluminum and steel industries. Rinse water can be reused, sometimes to 100%, saving significant amounts of water. However, the recycled water might have to be treated, which requires extra energy input.

1.1.8 Organization of Industry Subsections

1. Each of the industry subsections follows the same general outline: An overview of the industry, including what the industry produces, what its major sectors are, which sectors were included in this study, and how the industry has been structured

2. A discussion of how the industry uses water, including:

- Major end uses for water
- Consumptive uses versus return-flow uses

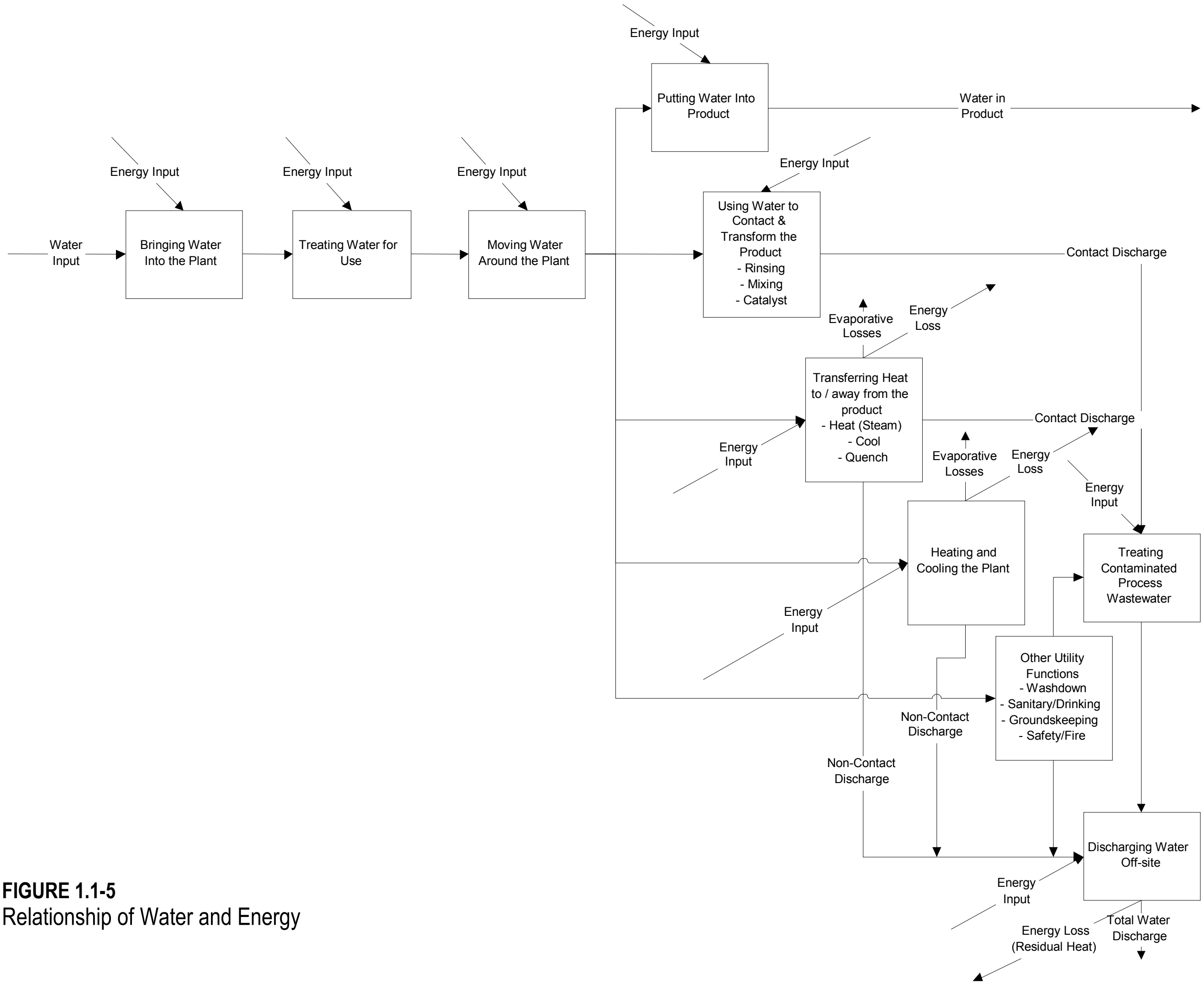


FIGURE 1.1-5
Relationship of Water and Energy

- How different sectors of the industry use water (where data were available)
- Which unit operations or processes in the industry use the most water

3. An analysis of the relationship between water and energy use in the industry, including:

- A comparison of which operations and processes are energy intensive versus which ones are water intensive
- A comparison of energy used per unit of product versus water used per unit of product (where data were available)
- A summary of trends and practices in energy and water use in the industry (where data were available)
- A discussion of water reuse practices and challenges in the industry, including, for some industries, a summary case study exemplifying how water reuse is being practiced in that industry

2.1 Agriculture Industry

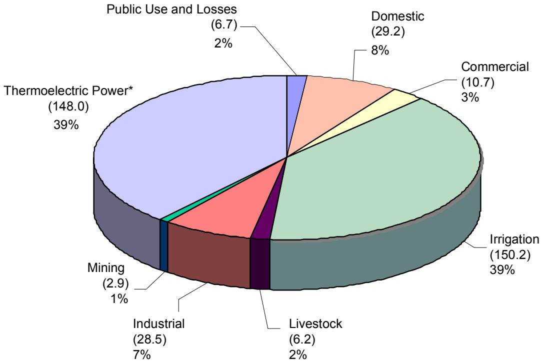
Contributed by Mark Madison and Henriette Emond, in CH2M HILL's Portland, Oregon, office.

2.1.1 How Water is Used in the Industry

Water Use by Agriculture

Agriculture is the largest water user in the world. According to the World Water Council, agriculture accounts for 70 percent of freshwater withdrawals world-wide (World Water Council, 2000). These withdrawals consist of water for irrigation and livestock production. In the United States, according to a USGS 1995 data set, 40 percent (156.4 million ac-ft) of annual renewable freshwater withdrawal was for agriculture—making agriculture the largest freshwater user in the United States, as well as in the world (Solley et al., 1998).

Figure 2.1-1 illustrates the relative percentages of water uses among groups in the United States.



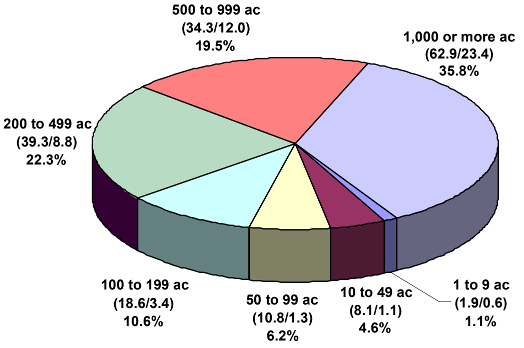
Note:
*Category includes water used in the generation of electric power with fossil-fuel, nuclear, or geothermal energy.

Source: Solley et al., 1998.

FIGURE 2.1-1
How Our Fresh Water is Used—1995 Data (million Ac-ft per year)

According to the USGS, nearly 96 percent (150.2 million ac-ft) of the water withdrawn for agriculture is used for irrigation. The remainder is used for watering livestock and for other farm activities such as building wash-down. Water used for processing food and other biological resources is categorized separately from agriculture.

Figure 2.1-2 shows the relative sizes of farms in irrigated agriculture in the United States. Nearly 36 percent of irrigated farms are greater than 1,000 acres, and nearly 80 percent are over 200 acres in size.



Note:
* Exclude abnormal and horticulture specialty farms.
Total acres in farmland is 176 million acres; acres irrigated is 50 million.
**Acres in farm/acres irrigated (million acres)

Source: USDA, NASS, 1998

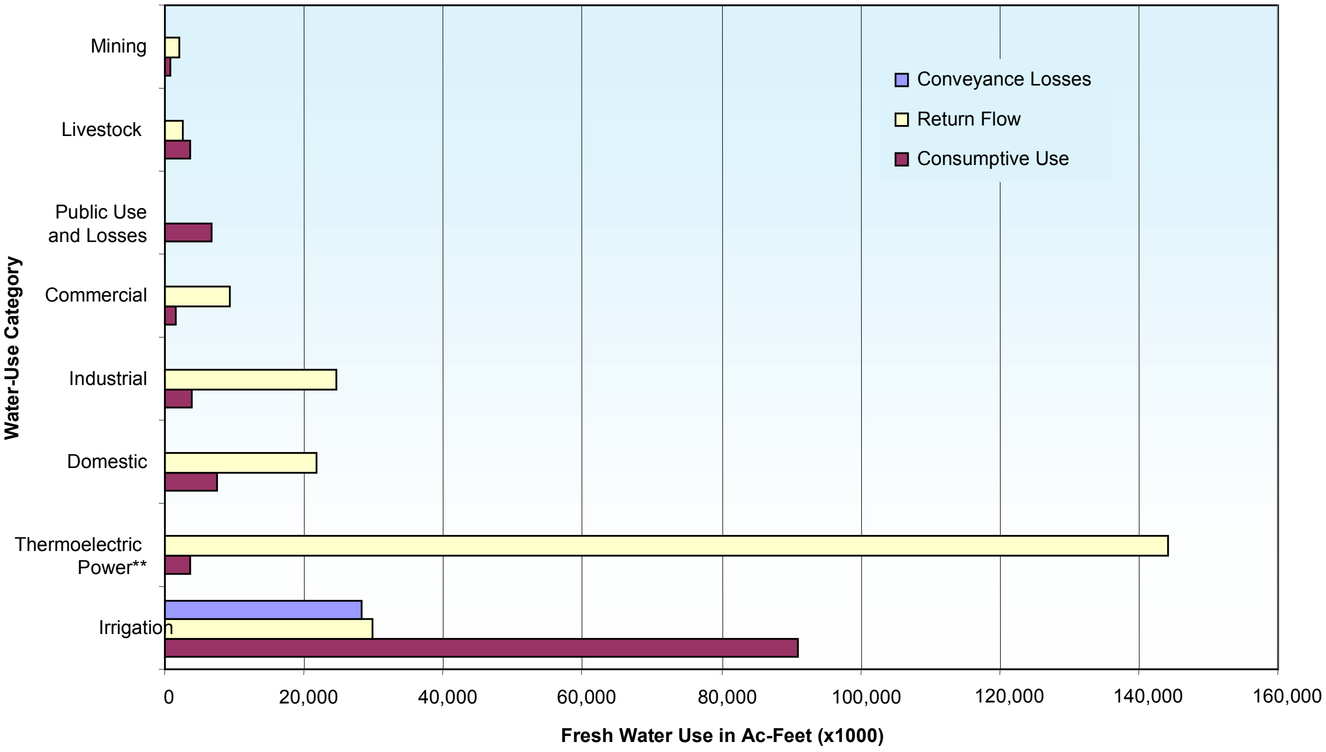
FIGURE 2.1-2
Integrated Farms by Acres Irrigated (million acre)

Consumptive Uses

Water is used by plants, in conjunction with sunlight, to produce bio-mass and is then released as water vapor from leaf stomata. Water use by plants is actually a purification process for water. A plant takes in water that might contain any number of constituents and releases clean water into the atmosphere.

Consumptive use of water means that water is drawn from the local source (river, lake, well, or municipal supply) and not returned. About 60 percent of freshwater withdrawn for irrigation is actually consumed (Figure 2.1-3). Twenty percent of the remaining water is either reused or returned in return flow, and the other 20 percent is lost in conveyance.

Excess return flow and conveyance losses have both financial and environmental impacts. Financial impacts are reflected in the cost of water not used, as well as in the cost of energy for pumping excess water and the cost of addi-



Note:
*From a total fresh water withdrawal of 382 million ac-ft
**Category includes water used in the generation of electric power with fossil -fuel nuclear, or geothermal energy.

Source: Solley et al., 1998.

FIGURE 2.1-3
Total Fresh Water Withdrawal by Water-Use Category

tional fertilizer and other chemicals flushed off the land in the unused water. Environmental impacts on surface water and groundwater resources result from the degradation of water quality as water flows over the land or percolates below the root zone but is not beneficially used by plants.

Water for irrigation might not be used either consumptively or beneficially, because of the type of irrigation system used or because of irrigation water management. Surface irrigation practices tend to be less efficient, because water typically is applied at a limited number of locations in the field, and then left to spread, which results in uneven distribution of water across the field and varying amounts of water infiltrating the soil. However, surface, or gravity flow, irrigation systems are generally less expensive to install and run than pressurized or other types of systems.

Pressurized systems, such as sprinkler irrigation and drip irrigation systems, tend to be more efficient than surface irrigation methods, both by virtue of how the water is distributed on the surface of the soil and how it is left to move below the surface. Pressurized systems either distribute water evenly over the soil surface (e.g., sprinkler irrigation) or concentrate the application of water at specific locations where it is needed (e.g., drip irrigation). Pressurized systems are used primarily with high value crops or in areas where water itself has a high value.

In recent years, progress has been made toward more efficient methods of water distribution. Between 1979 and 1999, there was a

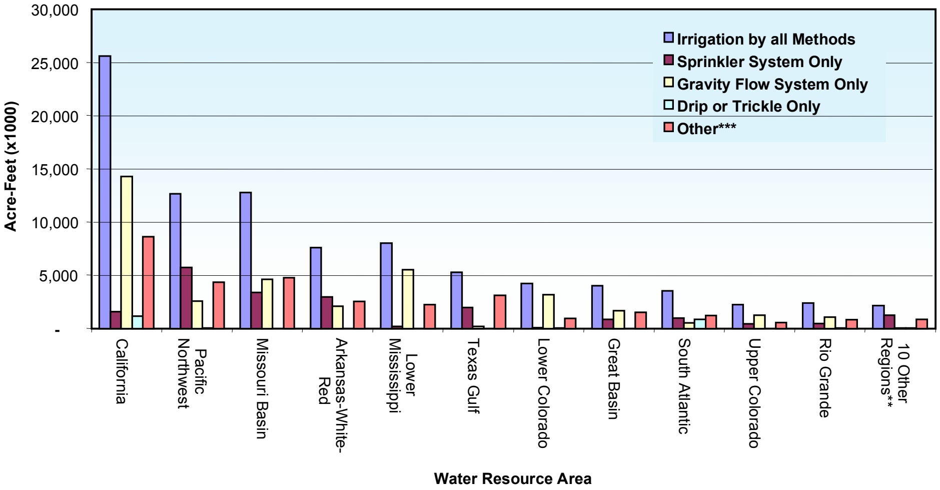
20 percent decline in gravity flow systems, along with a 25 percent net increase in all types of sprinkler irrigation systems and a 554 percent increase in drip and trickle irrigation systems (USDA, ERS, 2000).

Regardless of the irrigation system used, however, if irrigation water management is not responsive to the antecedent soil and moisture conditions on the farm, uneven water distribution and infiltration can result, reducing irrigation efficiency. For example, sand can allow water to infiltrate too rapidly, without providing adequate distribution around the field, and clay-rich soil can promote runoff without proper infiltration.

Water Use by Sector

Regional irrigation water use is presented in Figure 2.1-4. Irrigation occurs primarily in the arid west and southwest, although some irrigation is used elsewhere to supplement growing season rainfall. As Figure 2.1-4 shows, nine western water resource regions account for 94 percent of the total water used for irrigation. In 1997, of a total of 326.8 million acres of cultivated cropland, only 15 percent, or 48.9 million acres, was irrigated (USDA, NRCS, 1997). The greatest concentration of irrigated acres occurred in Texas (8.2 million irrigated acres), followed by Nebraska (7.4 million irrigated acres) and California (5.1 million irrigated acres). Thus, although agriculture withdraws the greatest amount of water among all water use sectors, 15 percent of the cropland uses the bulk of the water. Although it does not have the most irrigated acres, California leads all other areas in the total amount of irrigation water applied.

The estimated quantity of water applied in different regions of the United States with various methods of irrigation is presented in Figure 2.1-5. Of special interest is that gravity flow systems apply nearly twice as much water to the same amount of land as pressurized sys-

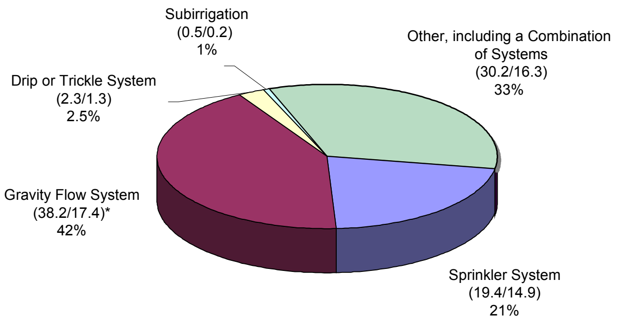


Note:
*Total fresh water applied, and consumptively used, from all sources is 91.0 million acre-feet. Other uses of irrigation water outlined in the census data include: crop cooling to delay early budding or blooming or to reduce heat stress; preventing freeze damage; leaching to remove salts from soil; and land disposal of livestock waste.
**The 10 other water resources regions are New England, Mid-Atlantic, Great Lakes, Ohio, Tennessee. Upper Mississippi, Souris-Red-Rainy, Alaska, Hawaii, Caribbean.
***Other includes farms with more than one method of water distribution. Nine western water resource areas account for 94% of total water used for irrigation. They are California, Pacific Northwest, Missouri Basin, Great Basin, Upper Colorado, Lower Colorado, Rio Grande, Texas-Gulf, Arkansas-White-Red.

Source: USDA, NASS, 1998

FIGURE2.1- 4
Estimated Quantity of Water Applied Using Only One Method of Distribution for Water Resources Area*

tems.



Note:
* (million ac-ft of water applied/million acres of land irrigated)

Source: USDA, NASS, 1998

FIGURE 2.1-5
Estimated Percentage of Water Applied Using Only One Method of Distribution

Figure 2.1-6 illustrates the amount of irrigated and non-irrigated land dedicated to the major crops grown in the United States. Most crops with the most planted acres also receive the most irrigation; however, only a small proportion of the total acreage planted is irrigated. For example, approximately 70 million acres of agricultural land is dedicated to corn production for grain and seed; but only 14 percent, or about 10 million acres, of that corn land is irrigated. For soybeans, the second largest agricultural crop grown on more than 65 million acres, only 4 million acres, or 6 percent, of that land is irrigated. Hay and wheat for grain each account for about 60 million acres of agricultural land, but only 16 percent of hay and 6 percent of wheat for grain are irrigated.

Figure 2.1-7 shows the amount of water used to irrigate a variety of crops. The nature of the available data dictates that this graph show only total irrigation amount and the amount of water associated with single irrigation methods. When more than one type of irrigation is used on a farm, the amounts of water used are represented only in the irrigation totals, and are not reflected in the irrigation types.

The largest amount of water is not necessarily used to irrigate the greatest acreage. Rather, the largest amount of water typically is used for crops irrigated predominantly by gravity flow, such as alfalfa, rice, cotton, pastureland, and hay. A large proportion of the water for growing corn is used by farms having more than one method of water distribution.

2.1.2 Relationship of Water to Energy

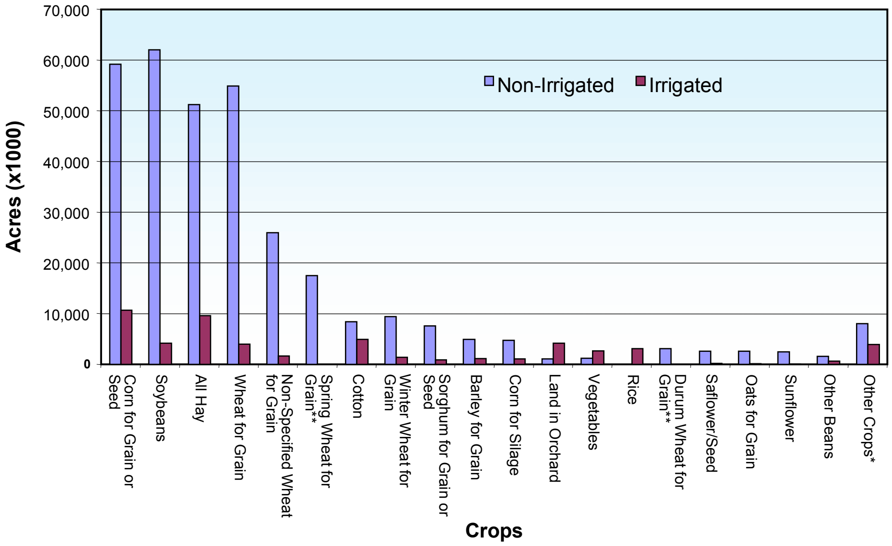
Water Use and Associated Energy Costs

Energy use as related to water use in agriculture occurs mainly in the pumping of groundwater and surface water resources to the site.

In 1997, the total amount of energy consumed in the United States was 85.8×10^{15} BTU, or 85.8 Quads (WRI, 2001). Agriculture accounted for only about 1 percent, or 0.9 Quads, of total energy use (Figure 2.1-8).

Data obtained between 1974 and 1977 indicated that 23 percent of the on-farm energy used in crop production was attributed to water pumping alone (Sloggett, 1979). Based on this information, we can assume that, of the 0.9 Quads of energy used in agriculture, 0.2 Quads of energy are used for irrigation water pumping.

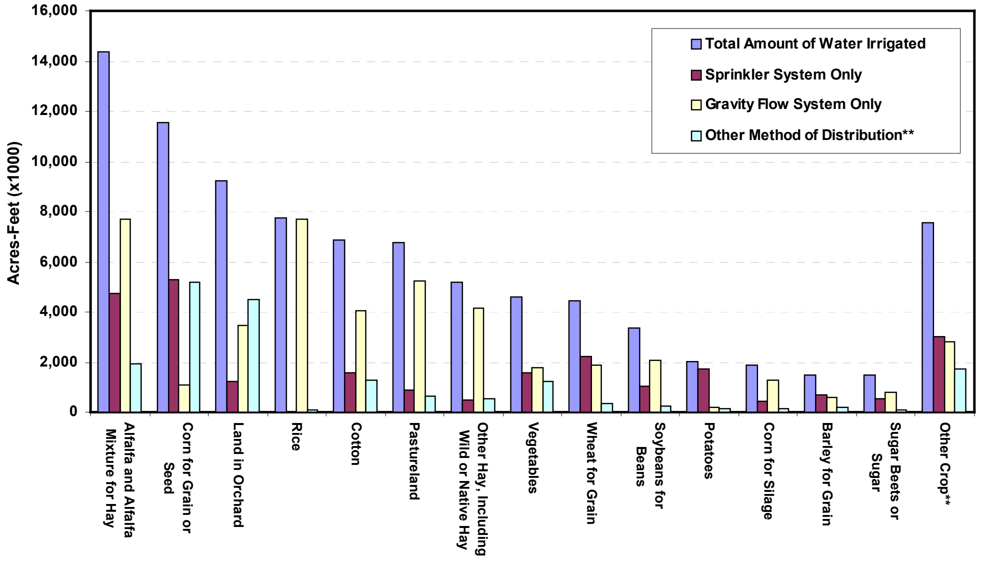
Pumped water is used to supply essentially all pressurized irrigation systems, as well as some, but not all, gravity-fed systems. Pressurized systems account for about 58 percent, or 53 million ac-ft, of water consumptively used in agriculture (Figure 2.1-5). If only pressurized systems are considered to have pumping requirements, then about 11 BTUs are expended per gallon of water pumped and consumptively used. As 38 million acres are served by on-farm pumped water, and 32 million acres are in non-gravity-fed systems, we might reasonably assume that 33 percent of the water consumptively used in gravity systems also has pumping needs.



Note:
*Other crops include buckwheat, rye for grain, tobacco, sugarcane, popcorn, sweet corn, canola and rape seed, peanuts, potatoes, sweet potatoes and sugar beet, nursery and greenhouse.
**The acreage under irrigation is categorized in the census as "withheld to avoid disclosing data for individual farms."

Source: USDA, NASS, 1998

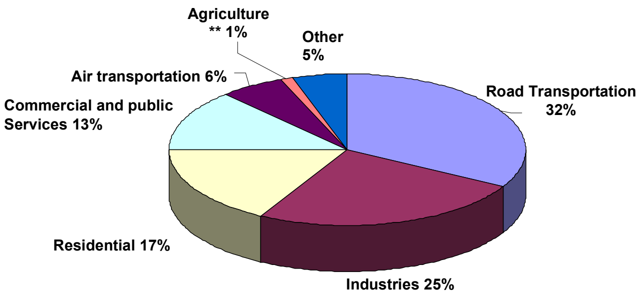
FIGURE 2.1-6
Irrigated and Non-irrigated Land Use for Selected Crops



Note:
*Other crops include:Dry edible beans, sugar beets, sorghum for grains, peanut, totmatoes, sw eet corn, lettuce and romaine, berries tobacco, oats.
** Other mehods of distribution include trickle, drip and subirrigation systems. They also include farms w ith tw o or more combinations of the different methods of w ater distribution.

U it St t C f A i lt 1998

FIGURE 2.1-7
Estimated Quantity of Water Applied and Method of Distribution by Selected Crop



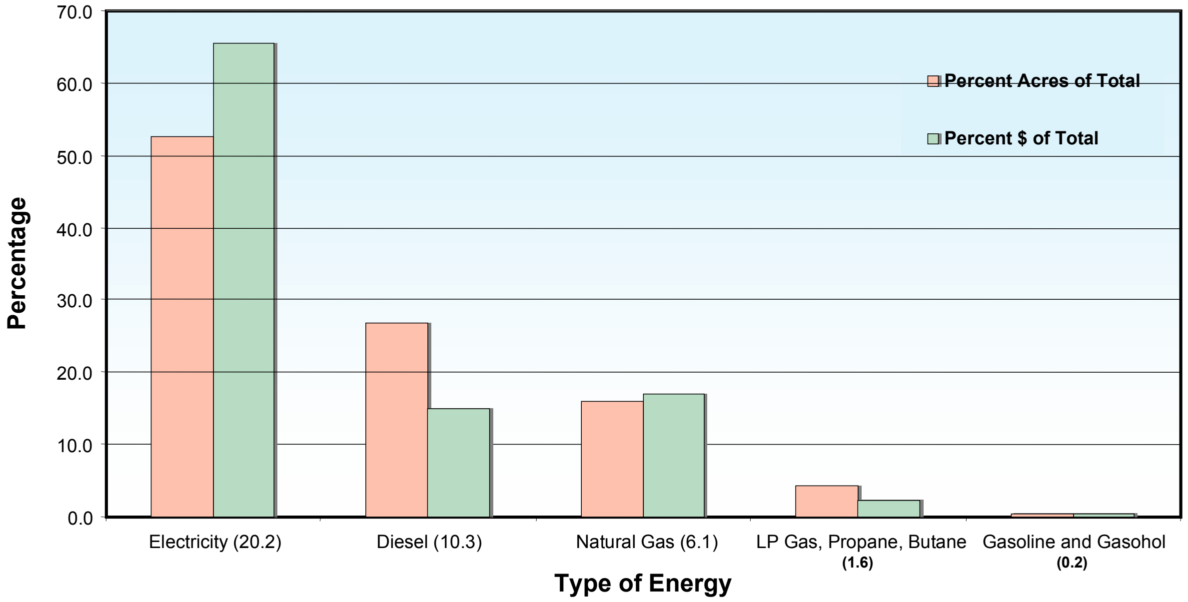
Note:
*Total U.S. energy consumption for 1997 was 85.8 x 10^{15} BTU
**Agriculture sector refers to all agriculture and forestry activity, including ocean, coastal, and inland fishing. International Energy Agency (IEA) reports that it can be difficult to distinguish between agriculture, commercial, and public service sectors, and that the figure for "total energy" is more accurate than those for individual sectors.

Source: World Resources Institute, 2001

FIGURE 2.1-8
Energy Consumption by all Sectors 1997*

If we include the pumping needs of both gravity and pressurized systems, then an estimated 9 BTUs are expended per gallon of water pumped and consumptively used.

The total expenditure for on-farm irrigation water pumping is $1.2 billion (USDA NASS, 1998). Figure 2.1-9 shows the relative breakdown by acre and dollars spent on energy for the various types of energy supply. The greatest number of acres and most money spent were related to electricity; 52 percent of the irrigated acres had water pumped by electricity, while 65 percent of pumping expenditures were for electricity. The next largest energy source, diesel, accounted for about 27 percent of the acres served, but less than 15 percent of energy expenditures. On a per-acre basis, the operating costs associated with electricity are higher than for other energy types. However, pumping by electricity has the advantages of having an easily accessible source of power, relatively low capital equipment costs, and easy maintenance.



Note:
*Total acreage under irrigation is 38 million acres
**Total expenditure is $1.2 billion

Source: USDA, NASS, 1998

FIGURE 2.1-9
On-Farm Pumping of Irrigation Water by Type of Energy*

2.1.3 Water Reuse Practices and Challenges in the Industry

Water reuse in agriculture comes under a number of guises. Reuse is fairly common in agriculture, although the amount and type of reuse vary with local conditions.

Many gravity-fed irrigated farms have tailwater reuse systems, whereby water coming off the bottom end of a field is collected in a tailwater pond and pumped back to the top of the farm to be reused for future irrigation. Otherwise, this water is collected and simply discharged as return flow for reuse by downstream users.

Another type of reuse comes in the form of groundwater recharge. Some shallow aquifers are connected to river systems, such as the South Platte River in Colorado and Nebraska. In this region, over-irrigation actually augments the aquifer supply and therefore increases the flow and extends the flow duration of the river when the supply from snowmelt runoff is typically at a low. Although this recharge mechanism minimizes the seasonal constraints of a surface water supply, one drawback is the adverse effect on groundwater quality from water passing through the root zone. One way to offset diminished groundwater quality is to implement another reuse technique that involves using wastewater or groundwater containing high nitrate levels. In Oregon, for example, groundwater with nitrate concentrations ranging from 10 to 50 ppm is pumped from a depth of 30 to 100 feet and used to replace or supplement fertilizer applications (Warkentin, 1991).

Another type of reuse becoming more common involves land application of industrial or municipal wastewater to reduce surface water discharge to rivers. Water coming from an industrial or food processing plant or a wastewater treatment plant is applied at agronomic rates to a field to dispose of the wastewater and produce an agricultural or forestry crop.

Challenges in achieving widespread agricultural water reuse include (1) lack of knowledge about the alternatives for reuse, (2) the financial burden associated with installing a reuse program, and (3) a reluctance, on the part of the public, to re-use water that has already passed through an industrial process. But as demand and competition for limited clean water resources continue to increase, reuse is slowly being integrated into the acceptable social landscape.

2.14 Example

The Eastern Oregon Farming Company has implemented a variety of irrigation system improvements over the past 10 years. A computer model is used to control daily operations of the 10,500-acre irrigation system. Energy savings in the first year of use exceeded the total cost of the system modifications. Field calibration and use of data from a monitoring and control system has allowed the model to be accurate to ±3 percent. This project received a national award from the Irrigation Association for water and energy conservation.

3.1 Aluminum Industry

Contributed by Jim Mavis, in CH2M HILL's Seattle, Washington, office

3.1.1 Structure of the Aluminum Industry

Overview – Mining through Recycling

Aluminum became available in commercial quantities after about 1886 with the independent discoveries of Hall and Heroult that aluminum could be produced electrolytically from a solution of alumina (aluminum oxide) in molten cryolite. The advent of commercially feasible reduction of aluminum oxide to the metal forged the essential link between mining and alumina production and metal working methods that had already been established for many other metals, in some cases in ancient times.

After nearly 120 years of evolution, the modern-day aluminum industry consists of 5 major components, as illustrated in Figure 3.1-1. The starting point is bauxite, an aluminum-rich mineral that is no longer produced in the continental United States. Bauxite is digested in sodium hydroxide, and purified aluminum oxide trihydrate ($Al_2O_3 \bullet 3H_2O$) is precipitated and calcined to alumina (Al_2O_3).

Alumina is the immediate feedstock used in the electrolytic production of aluminum metal. The segment of the domestic industry that uses the Hall-Heroult process is present in the United States, and is referred to as the "primary aluminum," the "reduction," or the "smelting" segment of the industry.

Metallic aluminum, usually as ingots (or other solid form), but sometimes in molten form, is used in the production of intermediate or finished products. This segment of the domestic aluminum industry is frequently termed the "forming" industry. Excess material trimmed during manufacturing is recycled internally or sold as scrap to recyclers.

Products circulated in the marketplace eventually exceed useful life or otherwise become

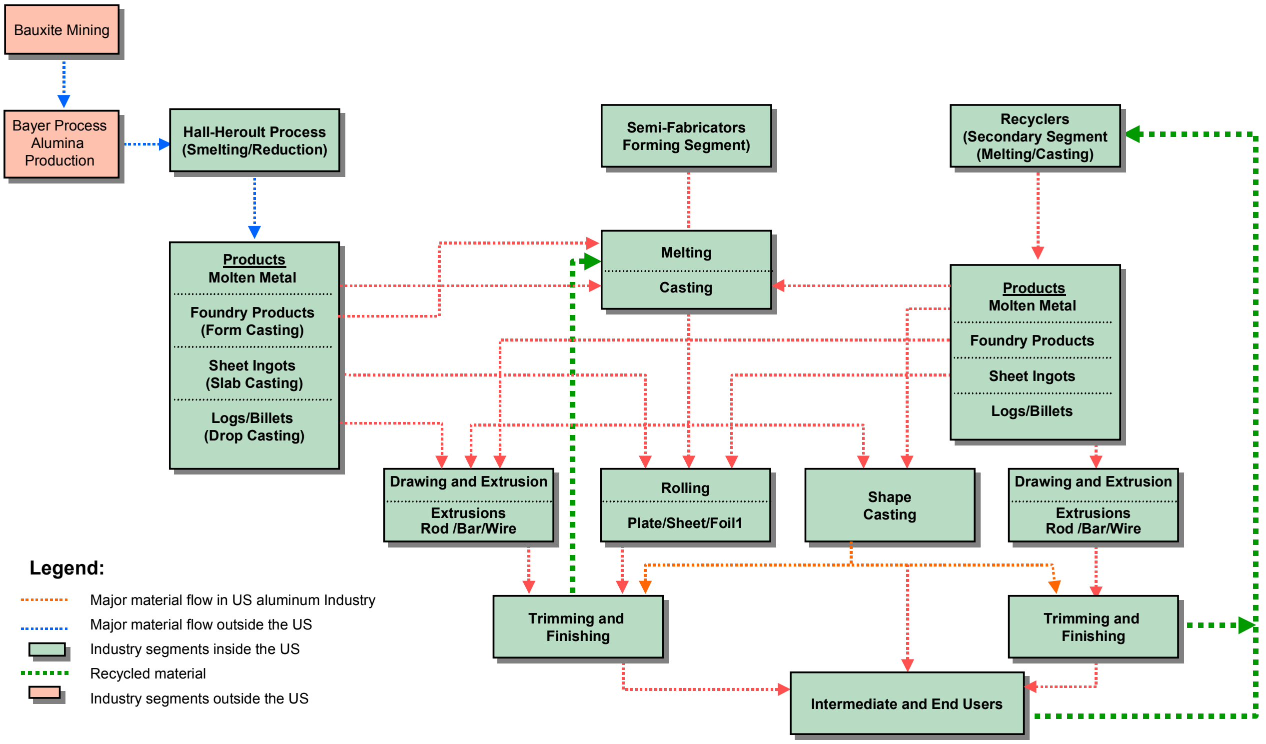


FIGURE 3.1-1
Summary of Aluminum Industry Structure in the United States

scrap. Aluminum scrap can be converted back into products at considerably lower cost than is possible when the reduction segment is involved. Over the previous 30 years, progressively larger percentages of aluminum have been reclaimed as scrap and reused as intermediate or consumer products. The aluminum recycling segment of the industry is often referred to as the "secondary aluminum" segment.

The aluminum industry in the United States consists of the reduction (Hall-Heroult) or smelting segment, the forming (intermediate or finished product fabrication) segment, and the recycling segment. Two decades ago, the lines between aluminum industry segments in the United States were more distinct than they are now. During that time, economies of scale and synergies have been exploited, blurring some features of these once-distinct segments.

Nevertheless, it is convenient to consider the smelting (Hall-Heroult reduction) segment as distinct and to consider forming along with recycling in describing aluminum industry water use characteristics.

Precursor Segments of the Domestic Aluminum Industry

Aluminum production in the United States is predicated on bauxite mining and processing. Originally, bauxite deposits in the southeastern part of the country supplied the downstream industry segments in this country. Economically recoverable bauxite deposits are no longer available in the United States and bauxite refining is now performed at only two domestic facilities.

Since the depletion of economic reserves in the United States, bauxite has been shipped into the country to feed the few remaining domestic bauxite processing plants, which use the Bayer Process to recover refined aluminum oxide from crude bauxite. Bauxite processing is often referred to as "refining."

The Bayer plants convert the aluminum-rich mineral into aluminum oxide, the feedstock used in the smelting segment. Bayer Process plants dissolve aluminum oxide from bauxite in hot alkali, forming a crude sodium aluminate solution, while keeping insoluble iron and other metal oxides in the solids phase.

Digested liquor is separated from the insoluble solids, and aluminum oxide-trihydrate is precipitated by cooling. Other constituents are left behind. The aluminum oxide trihydrate is calcined to form aluminum oxide that can be reduced to aluminum metal in a smelter (reduction plant). The aluminum-depleted stream is recycled and regenerated with lime to form crude caustic soda to be used in the next digestion cycle.

Hall-Heroult Process (Smelting) Industry Segment

Aluminum metal is produced by electrolysis of alumina that is dissolved in molten cryolite. Reduction plants fall into two categories based on the form of the carbon anode (positive electrode).

Pre-bake plants use carbon anodes that are formed from pitch binder and petroleum coke, which is baked at high temperature to form a solid carbon block. Soderberg plants use an uncured pitch-coke blend that cures as it is heated while it slowly drops into the molten cryolite bath. The anodes are consumed during the process and have to be continuously replenished (Soderberg anodes) or replaced (prebake anodes).

A simplified schematic of a pre-bake plant is shown in Figure 3.1-2. Aluminum oxide (alumina/ore) is stored on site in silos and some of it is used in fluid bed contactors to adsorb fluoride from the electrolytic cells ("pots") and to adsorb hydrocarbons from the anode bake furnaces. The fluoride- and hydrocarbon-enriched alumina is fed into the pots along with virgin alumina. The pots resemble steel tubs—steel shells lined with thermal insulating material.

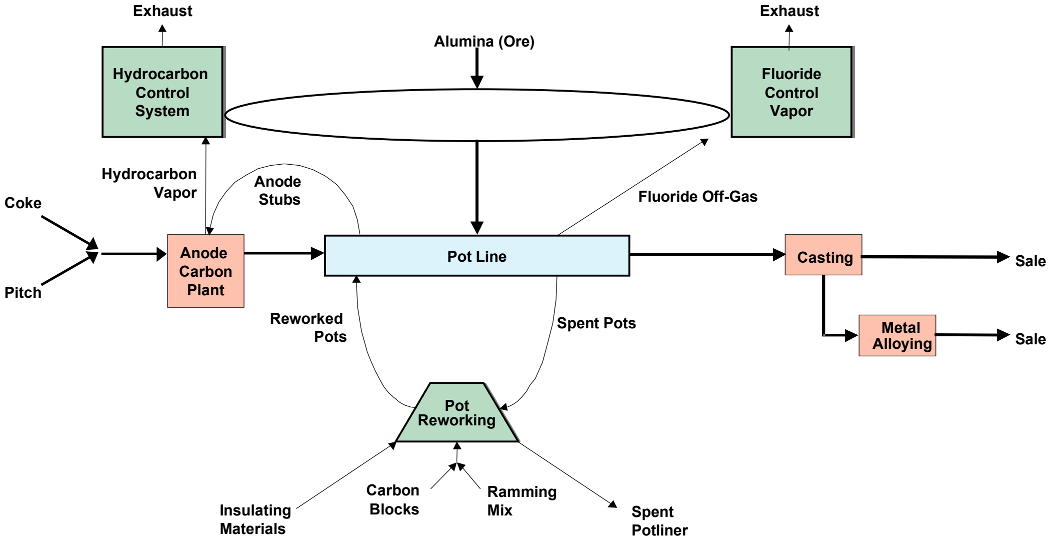


FIGURE 3.1-2
Schematic of a Pre-Bake Aluminum Smelter

Inside the refractory layer is a lining of carbon blocks, which act as the cathode (negative electrode for the electrolytic reaction) that is in contact with molten cryolite.

In the pots, alumina is electrolytically converted to aluminum metal (reduction) in the pots, and to carbon dioxide and monoxide at the anodes. The cryolite is unaffected by the electrical current, making it necessary to replenish only the aluminum oxide as it is converted into metal. The metal remains molten until it is removed for casting or other uses. (Some aluminum users accept molten metal instead of cast ingot or cast shapes, provided they are close enough to a producer of molten metal.)

Water is not used directly in the reduction of alumina to aluminum metal. It is used only in casting of the molten metal into the various smelter products. Common products from a reduction plant are regular ingots (pigs and sows), sheet ingots, tees, logs, and billets.

Semi-Fabrication (Forming) Industry Segment

The forming industry is very diverse, compared to the refining and smelting industry segments. For purposes of water use, the forming segment is divided into three major subcategories based on the types of operations used in processing the metal: drawing and extrusion, rolling, and shape casting. Other classifications are also used, such as end use vs. intermediate products, or type of end use, such as beverage containers. Figure 3.1-1 shows the forming segment in relation to the other aluminum industry segments.

Facilities that perform drawing and extrusion operations typically combine those operations with numerous other ancillary processes to produce intermediate or finished products. Drawing and extrusion are performed with lubricants to prevent galling. These lubricants are removed by various cleaning processes prior to further manufacturing steps, such as surface finishing or assembly. Manufacturing wastes may include scraps from trimming the aluminum parts to the correct size tolerances. Scrap metal might be recycled back to on-site melt furnaces, or sold to commercial recyclers.

Rolling mills produce aluminum sheet or foil, whether for sale as an intermediate product or for packaging and sale to end users. Irregular edges are trimmed and sent to recycling facilities. As with drawing and extrusion, rolling may be performed with organic lubricants. Rolled aluminum stock may be cleaned and it is often coated for protection against damage during storage, shipping, and handling.

Aluminum casting and forging may accompany other forming operations at a semi-fabrication facility. The source of aluminum may be ingots, or in some cases, molten metal sold "over-the-fence." Depending on the intended end use, cast aluminum parts may undergo surface finishing, may be machined to final tolerances, or may be otherwise processed before final assembly or sale. Scrap aluminum can usually be returned to the melting furnace for on-site reuse.

Recycling Industry Segment

Aluminum recycling has grown rapidly over the past 10 to 20 years, with improved efficiency in collecting scrap metal from end users of retail products and from commercial sources. Many recyclers use aluminum scrap in manufacture of their own products, significantly blurring the once-distinct lines between recycling and the rest of the aluminum industry.

Scrap aluminum may be remelted and alloyed to meet intermediate product specifications of purchasers who buy ingot or molten metal. By production of ingots, sheet ingots, foundry products, logs, or billets, the recycling segment of the aluminum industry duplicates certain operations that are also characteristic of the smelting segment. And by producing various cast shapes, rolled intermediates, and finished products such as beverage cans, the recycling segment overlaps with the forming segment. The extent to which the recycling segment overlaps with the smelting and forming segments is indicated in Figure 3.1-1.

3.1.2 Water Use by Industry Segment

The discussion of water use in the domestic aluminum industry focuses on smelting (primary or reduction), forming (semi-fabrication) and recycling, since these are the main segments currently represented in the United States. A very brief discussion of bauxite refining is also included here, since it represents such a small fraction of the domestic aluminum industry.

Information about the smelting segment came from several sources, but mainly from a combination of public documents (EPA, 1986) pertaining to water use and wastewater discharge permits and permit applications, and from industry experts. Similarly, information about water use in the forming segment was abstracted from about 20 wastewater discharge permits and other contact with the industry.

Much of the available information emphasized wastewater quantity and quality because of the focus on environmental issues over the past 30 years. Actual water use practices were either taken from facility water balance diagrams or were estimated from information about water uses within the plants.

The water uses and production-normalized usage rates were taken for plants or systems in which reasonable water conservation measures were in place. Once-through water systems were not included in the water use compilation discussed in the following subsections. Selection of the most water-efficient examples does not imply that site-specific issues do not warrant once through or low-recycle water uses. The selection was based on a desire to identify typical water demands for specific operations within each industry segment.

Bauxite Refining

Digesting bauxite and extraction of alumina is a water- and chemical-intensive process. High-value sodium hydroxide (caustic soda) is added to an aqueous slurry of bauxite and heated to dissolve aluminum as sodium aluminate. Aluminum oxide trihydrate precipitates when the digestion solution cools, leaving impurities and some of the caustic behind.

The caustic is expensive, so Bayer plants recycle water that has residual caustic, in order to optimize economic performance of the bauxite refinery. In practice, virtually all water that is added to the process is recycled (only in high rainfall areas does surplus water accumulate). Usage varies, but estimates from published accounts indicate that about 450 gallons of water are used per ton of bauxite processed (Aughinish Aluminia, www.aughinish.com; Solymar et al., 1997; TMS, 1997).

Hall-Heroult Process (Reduction Segment)

Water is not used directly in the Hall-Heroult process (reduction of alumina to aluminum metal), but is essential as cooling water for casting ingots, logs, tees, and other solid products. Water is also an important resource for the aluminum smelting industry in the Pacific Northwest and Upstate New York where, until the recent energy crisis, it was the source of low-cost hydroelectric power.

Water uses and quantities used in aluminum smelting are summarized in Figure 3.1-3. Although not used in the reduction process, cooling water is essential in metal casting operations in the smelting segment. Together, direct contact and non-contact cooling comprise about 44 percent of the water use in the smelting segment of the aluminum industry, used in roughly equal amounts.

Non-contact cooling water is used to some extent for cooling molds, melt furnace doors, and other devices, and is typically low in environmental contaminants. Direct contact cooling is sprayed directly onto logs, tees, and other shapes as they are being drop-cast, and typically contains suspended solids, oils, and other possible impurities. Non-contact cooling water can be reused through reduction of its temperature in a cooling tower, or by cascade reuse in other processes. Direct contact cooling water reuse normally involves oil and particulate removal, and temperature reduction in a cooling tower.

Drop casts require short, high volume flows of cool water. Because of the high instantaneous flow rates used for drop casting, a cooling tower with its limited cold-side reservoir capacity usually cannot supply enough water for these bursts. The common practice is to supplement recirculating cooling water with cool, raw water, thereby using a greater volume of water than if there were large cold water reservoir from which to draw.

The next largest water use in aluminum smelting is non-contact rectifier cooling. Rectifiers convert thousands of amperes of alternating current into direct current, which is used to electrochemically reduce aluminum oxide to the metal, plus keep the pots hot enough to maintain cryolite in its molten state. About 23 percent of the water used in the aluminum smelting segment is used for rectifier cooling (Figure 3.1-3). Rectifier cooling water is warm but is otherwise not contaminated, making it suitable for on-site reuse in other operations such as makeup to wet air pollution control systems.

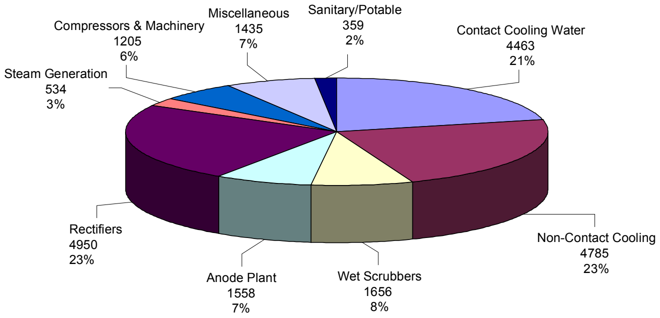


FIGURE 3.1-3
Water Consumption: Gallons per Ton of Primary Aluminum

Each of the next three largest water consuming operations in aluminum smelting uses about one-third the amount of the three already described. Wet air pollution control devices (scrubbers) consume about 8 percent of the water used in a reduction plant; anode production (pre-bake plant) consumes another 7 percent; and miscellaneous uses take another 7 percent.

Wet scrubbers do not necessarily require good quality water, and often are supplied with wastewater from other areas in the plant. Consequently, wet scrubbers should not be viewed as imposing *additional* demand for fresh water resources, unless too little wastewater is available to supply the air pollution devices, or if aerosol formation restricts use of wastewater in air pollution control devices. It is noteworthy that poor quality makeup can result in deposition of mineral scale inside the pollution control systems, creating operating and maintenance problems.

The demand for water in baked anode production varies among plants. In some facilities, water does not come into contact with the anodes, whereas in others, anodes may be spray-cooled. Miscellaneous water uses also vary widely among plants in the aluminum smelting segment, and generalization would be difficult. Basically, miscellaneous uses are those not accounted for after all known significant and minor uses have been identified.

Only small quantities of water are used for cooling machinery and compressors, for boiler makeup, and for sanitary consumption. Compressors and machinery uses comprise approximately 5.7 percent of water used in a "typical" aluminum smelter, while boilers consume another 2.5 percent and sanitary consumption constitutes only 1.7 percent of the water used.

Semi-Fabrication (Forming) Segment

The structure of the forming segment of the aluminum industry sharply contrasts with that of the aluminum smelting segment. Aluminum smelters are based on one fundamental process (electrochemical reduction of refined bauxite) and produce a limited number of products (ingots, specialized castings, and molten metal). The forming segment employs numerous manufacturing processes, many not represented in the majority of the forming facilities, and produces a wide variety of intermediate and final products, in contrast to the aluminum smelting segment.

Water consumption in the highly diversified forming segment is described in the following discussion in terms of individual manufacturing (core) operations and ancillary operations. Water consumption is expressed as volume of water used per ton of finished product. Figure 3.1-4 summarizes water usage for the core and ancillary operations in aluminum forming. The list of operations is indicative of the aluminum-forming segment, but is not exhaustive because of the diverse nature of the segment. Some data for the use categories overlap, but the information was used as received (confidential sources within industry), because insufficient detail was available to support further analysis.

As for the smelting segment, there was a wide range of water usage per ton of finished product reported. Data based on once-through cooling and abnormally low-cycle reuse (i.e., low-cycle cooling towers) were removed, and the remaining water use rates were averaged for incorporation into Figure 3.1-4.

Figure 3.1-4 indicates more than a 50-fold range of average water usage per ton of finished product. Throughout the following text, cases in which averages are strongly biased because of unusually high water consumption in one facility are identified. The water uses in Figure 3.1-4 are grouped according to the subcategories in Figure 3.1-1.

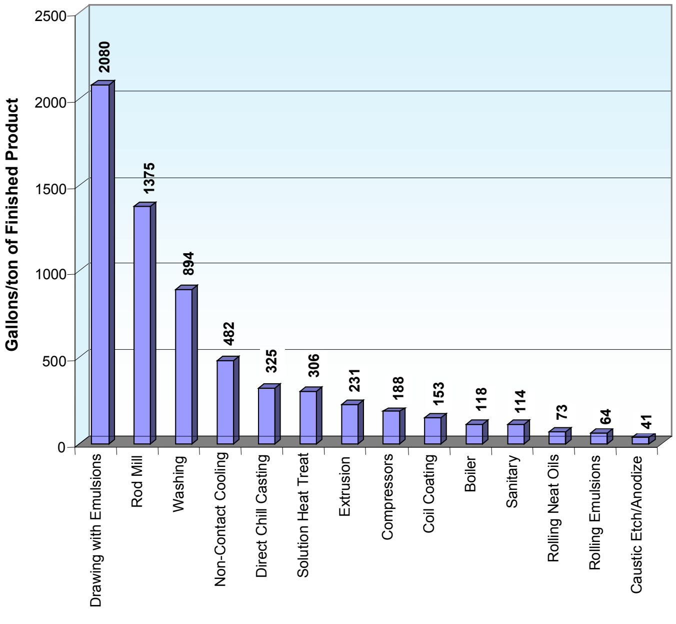


FIGURE 3.1-4
Water Usage in Various Aluminum Forming Operations (Source: Data compiled from confidential CH2M HILL HILL clients)

Shape Casting Operations

Cast aluminum may be cooled with a combination of non-contact and direct contact (direct chill) cooling water. Based on a use-per-ton of finished product, the direct chill cooling water rate averaged about 325 gallons/ton of finished product, based on information from two facilities (91 and 558 gallons/ton, respectively). In addition, non-contact cooling water may be used to cool molds and other equipment, including utilities. Non-contact cooling water at the single facility for which data were available was about 482 gallons per ton of finished product. Cooling water is usually recycled through cooling towers to reduce the volume of effluent that must be discharged. The heat removed during casting cooling is dissipated as "low-grade" heat from the evaporative cooling towers.

Water use in the single rod mill for which data were available was about 1,375 gallons per ton of finished product.

Drawing and Extrusion Operations

Drawing (with emulsions) consumed the largest *average* volume of water of all the operations for which information was available—nearly 2,100 gallons per ton of finished product, based on information from three facilities with flow rates ranging from 170 to 5,900 gallons per ton. This usage rate was strongly biased by a single source that consumed nearly 6,000 gallons of water per finished ton of product. The other two facilities reported consumption rates of 170 to 190 gallons per ton of finished product.

Water use in aluminum extrusion averaged about 230 gallons per ton of finished product (data were from two plants), with over a 6-fold range in the consumption rate between the lowest and highest usage rates (the range was 64 to 397 gallons per ton).

Rolling

Rolling with emulsions consumed an average of 64 gallons per ton of finished product, based on data from three facilities. The range of water consumption rates spanned a factor of 2, with a low rate of 35 gallons per ton and a high rate of 71 gallons per ton.

Rolling with neat oil (oil with no water) had an average water consumption of 73 gallons per ton of finished product. The data were taken from two facilities. Individual water consumption rates were 29 gallons per ton and 118 gallons per ton, respectively.

Solution Heat Treating

Solution heat treating used contact cooling water to quench heated aluminum. Two facilities reporting water consumption for heat-treating consumed an average of 306 gallons per ton of aluminum, more than a 4.5-fold range from lowest to highest rate (111 and 500 gallons per ton, respectively). As with other cooling operations, water normally is recycled through cooling towers to reduce the volume of wastewater that must be discharged. Heat that is picked up by cooling the metal is dissipated to the atmosphere as "low-grade" heat from the evaporative cooling towers.

Caustic Etch and Anodizing

Facilities reporting water consumption for caustic etch or anodizing operations used an average of 40.8 gallons per ton of aluminum, ranging from 22.3 gallons per ton to 78 gallons per ton. Data were available from three plants.

Washing

Water consumption for washing operations from 5 facilities averaged 894 gallons per ton of product, but the average was highly skewed by a single consumption rate of 3,970 gallons per ton. Omitting the outlying consumption rate, the wash water rate ranged from 14 gallons per ton to 188 gallons per ton, averaging 125 gallons per ton.

Coil Coating

Only two plants reported coil coating, but the average for those two was 153 gallons per ton of aluminum product, with a twofold range in consumption rates (100 and 207 gallons per ton, respectively).

Boilers

Boilers consumed an average of 118 gallons per ton of aluminum, based on data from three plants. The range was 21.1 to 214 gallons per ton.

Compressor Cooling

A single plant broke out compressor cooling. Its water consumption rate was 188 gallons per ton of aluminum product.

Recycling Segment

Recycling of aluminum is economically attractive because it uses only about 10 percent of the energy that is needed to convert alumina to aluminum metal[1]. Taking into account other cost factors, the overall cost for recycling is about half the cost of producing virgin aluminum.

Recycled scrap is melted, and may be realloyed and held in furnaces for use in casting or for delivery of molten metal delivery to other processors. Whether the recycled aluminum is used in-house or is sent to off-site processors, the water consumption rates are reflected in the preceding section on the forming segment. Consequently, water use patterns discussed in previous subsections are not repeated here.

3.1.3 Relationship of Water to Energy

Historically there has been a strong association between the aluminum smelting industry segment and water through use of low-cost hydroelectric power to operate the Hall-Heroult reduction cells. Smelting plants near Niagara Falls and in the Pacific Northwest supplied electricity at a cost that made these regions prominent suppliers of aluminum metal.

Until the power supply situation on the West Coast in the winter of 2000 and 2001, smelters in the Pacific Northwest supplied about 40 percent of the nation's aluminum. During the crisis, Northwest smelters shut down completely, solidifying the cryolite in the pots, and making startup unlikely for most of the facilities.

A possible outgrowth of limitations (mainly cost) of electricity is on-site electrical generation. Long-term contracts for natural gas supply are needed to make this a viable, and some of the Northwest plants would not restart, without assurances of long-term supplies of affordable electricity.

Renewable energy sources have been mentioned as an alternative to low cost hydroelectric power, particularly windmills, photovoltaic and solar thermal systems. At present these alternatives cannot compete economically with established current energy sources, and there are no renewable energy projects to supply power to an aluminum smelter. Fuel cells have also been mentioned as a promising technology. Technical advancement into direct use with hydrocarbon fuels and more favorable economics may make this option viable in the future.

Besides hydroelectric power, there is another relationship between water and energy. In smelting, forming and recycling aluminum industry segments, cooling water is used extensively to cool aluminum being processed. The rate of cooling is closely controlled to give metal products the qualities needed for their end uses, so both temperature and flow rate are important considerations in production. (Hence, although large amounts of heat energy are transferred to the cooling water when aluminum is processed, the wastewater from these facilities must be maintained at such a low temperature to maintain metal product quality that energy recovery is economically infeasible.)

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[1] Anchorage Recycling Center: a Smurfit-Stone Recycling Company, www.anchoragerecycling.com, indicates 95 percent energy savings; additional energy is for collection, handling, forming, and distribution.

3.1.4 Water Reduction and Reuse Practices and Challenges

As shown previously, most water used in the aluminum industry is for solidifying molten metal or cooling hot metal. Over the past 25 years, many plants have reduced water use in response to economic and regulatory incentives related to the environment.

Water conservation measures consist of a sequence of steps, such as eliminating water use where possible, reusing non-contact cooling water in other plant operations where practical, and reducing water consumption to a large extent by installing cooling towers, changing manufacturing practices, and numerous other means. In conserving water, there is a balance between flow reduction by recycling water and the resulting concentration of constituents to the point that they become contaminants, and therefore regulated in plant discharge. Hence, in many cases, continued increases in water recycling would eventually alter a “water problem” into a “dissolved solids problem.”

Metal surface treatment may be a better candidate for water use reductions than recycling cooling water through evaporative cooling towers. The main incentive for addressing surface treatment operations differs from the familiar concern over water conservation. Surface treatment chemicals (anodizing, pickling, conversion coatings, and related intermediates or finishes) are often expensive, and if they can be recovered cost effectively from spent baths, the aluminum industry and its suppliers have strong motivation to work out technical and economic problems. Under this approach, the water used to prepare surface finishing baths would not be needed, because the bath would be “rejuvenated” by removing contaminants that make the bath ineffective, and by supplementing constituents that are lost during routine operation. This area of technical innovation has been in development for over two decades and significant technical challenges remain.

4.1 Chemical Industry

Contributed by Dr. Sandra Dudley, in CH2M HILL's Atlanta, Georgia, office

4.1.1 Introduction to the Chemical Industry

The chemicals industry is very large and diverse, as documented elsewhere (Energetics, 2000). It provides many of the fundamental materials and building blocks used in other industries, including the other Industries of the Future. The industry has been divided into several major sectors based on groupings of Standard Industrial Classifications (SICs) by the Office of Management and Budget (OMB, 1987, 1997):

- Industrial inorganic chemicals
- Industrial organic chemicals
- Plastics and rubbers
- Pharmaceuticals
- Soaps and cleaners
- Paints and varnishes
- Agricultural chemicals

This industry is a key component of the U.S. economy, with annual shipments of over 360 million tons of product, at a value estimated at almost $400 billion (DOC; 1997, CMA, 1998). A 1994 Manufacturing Energy Consumption Survey (MECS) estimated energy use in the U.S. chemical industry for that year at about 5.3 quads (quadrillion BTU) (MECS, 1994). Table 4.1-1 shows approximate 1997 production volumes for leading categories:

TABLE 4.1-1
Top Chemical Categories: Annual Production

Category	1997 Production
Top 50 Chemicals	364.2 million tons
Organic	141.7 million tons
Inorganic	102.4 million tons
Agricultural Chemicals	44.9 million tons

Source: CMA, 1998

Unlike several other Industries of the Future, the chemical industry is characterized by a wide variety of products and processes. Hundreds of different chemicals are produced, and there can be several routes for the manufacture of a given product, so that water and energy use for a particular product might vary significantly across companies. Even within the same company, more than one process might be used in the manufacture of a single chemical. Also, water historically has been essentially free and unlimited in supply for many regions of the United States. In the chemical industry, it is rarely used as a primary feedstock or reactant, but rather for cooling, so there has not been a strong driver to force the tracking of its use. Thus, the chemicals industry has not traditionally tracked the usage of water in its processes.

Data searches over the past 5 years for CWRT have found some anecdotal data on chemical industry water use, but nothing comprehensive. This conclusion was verified for this study through contacts with several major chemical companies, trade associations, and internal consultants, each of whom described the measurement and recordkeeping of water usage as sporadic at best.

Because of the increasing importance of water scarcity issues, a basic understanding of water usage in the chemical industry is important in identifying and modifying key processes that could help the industry meet anticipated standards and limitations. In order to present such an analysis in the face of scarcity of actual water use data in chemical processes, the PEP Yearbook International, prepared by SRI Consulting, was used as the basis of the numbers presented in this chapter. This yearbook contains design data on 908 chemical processes, including steam, cooling, and process water usage. Data from these individual uses were added to estimate "total water" for individual processes. Annual totals were estimated by means of the base capacity of each process.

Although actual energy data are more readily available than water data, energy estimates from the PEP yearbook were used for the sake of consistency. Electricity, fuel oil, and natural gas consumption were added together to estimate total energy requirements.

4.1.2 How Water is Used in the Industry

Consumptive and Return-Flow Uses

According to design data, the various processes in the worldwide chemical industry have the capacity to use over 100 trillion gallons of water annually (SRI Database). Although there are some consumptive uses, such as water in the product and evaporative losses, most water used by the chemical industry is for return-flow applications. In fact, most is used as non-contact cooling water, without contacting the chemical being produced. The exact quantity of water that is consumptive is unknown because the available data were reported only as cooling, steam, or process water. However, it is estimated here that less than 5 percent of water used is incorporated into final products in the chemical industry. Comprehensive data on the amount of evaporative losses in the chemical industry were not available, but the largest source of evaporation probably is cooling towers.

Major Uses

Based on design data for unit processes listed in the PEP yearbook, the largest use of water in the chemical industry is for cooling, with steam (e.g., heating and autoclaving) and process water (for mixing, dilution, reactants, wash, or rinse water) being the other significant uses. Chemical facilities are made up of varying combinations of these unit processes and water flows between processes. Cooling water recycled through cooling towers is not accounted for in the design data for individual unit operations. Therefore, actual distribution of water at the facility level is different from design data for individual processes. Historical data on distribution of water use at the facility level is scant; however, it is estimated that process cooling, process dilution, and steam production represent the most significant water uses at chemical facilities.

In a similar manner, the estimated total water use capacity of 100 trillion gallons per year for the chemical industry is a summation of base design capacities for each chemical process identified in the SRI database, and could be thought of as a theoretical upper bound for potential water use by the industry. Water reuse, especially closed-loop cooling with cooling towers, is not accounted for in this estimate. Such water reuse reduces the amount of total freshwater withdrawal by the industry. The proportion of cooling water recirculated through cooling towers versus once-through cooling is not documented, so that the actual world-wide freshwater withdrawal by the chemical industry is not known, but is probably substantially less than 100 trillion gallons per year. Where open-cycle cooling with cooling towers is used, it can represent up to 90–95 percent reduction in freshwater withdrawn for cooling purposes, with a commensurate reduction in return flow [3]

4.1.3 Major Water Users in the Chemical Industry

Ten processes account for over 95 percent of the water used in the chemical industry. As shown in Figure 4.1-1, six methods for producing Synthesis Gas (or "Syngas") are responsible for the use of over 87 percent of the industry's total water use capacity. Another 7 percent is used in the production of hydrogen. The annual total estimates are based on the representative base capacities of the processes. The numbers in Figure 4.1-1 are water capacity, to illustrate how much water is involved in these processes. They do not take into

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[3] CH2M HILL, 2002. CH2M HILL Approximation Analysis, assuming an average temperature rise of 50 degrees Fahrenheit for processes, and 6 cycles of concentration for typical cooling towers in the industry.

account recycle of water used for non-contact cooling and boiler feed, which can reduce actual consumptive use by over 90 percent from the numbers shown in Figure 4.1-1. This fact is discussed further in the next subsection.

As one would expect, based on the distribution of water use described in the previous section, 9 of the 10 processes shown in Figure 4.1-1 are heavy cooling water users. The exception is production of Synthesis Gas from bituminous coal by gasification, which is the seventh highest annual water user. The process relies on large amounts of steam and process water to reduce the total water use by more than an order of magnitude.

The chemicals that have the highest volume of production in the United States are not among the highest water users, nor are they the most water intensive processes, discussed in the following subsection. As shown in Table 4.1-2, their water use is more closely correlated with their rank in production volume. Total consumptive use is estimated using assumptions for typical recycle rates for the various water use categories. Actual water use practices vary, so that the consumptive waster use is an estimated range.

Certain processes use large amounts of water on a per pound basis. Table 4.1-3 shows the top 10 per pound water users in the chemical industry. The per pound water table represents the sum of cooling, steam, and process water requirements per pound for these processes. As with Table 4.1-2, recycle of boiler feed and cooling water is estimated to give a range for consumptive water use. Of these processes, only Ethylene Plant Feedstock is among the highest annual water users (Figure 4.1-1). The combined annual total of the top 10 per pound water using processes is only 0.7 percent of the annual water usage in the chemical industry.

Cooling Water Intensive Processes

Not surprisingly, given the proportion of water that is used for cooling, the chemical processes represented in Figure 4.1-1 also account for the top 10 cooling water users on a per pound basis. In fact, the cooling water requirements are

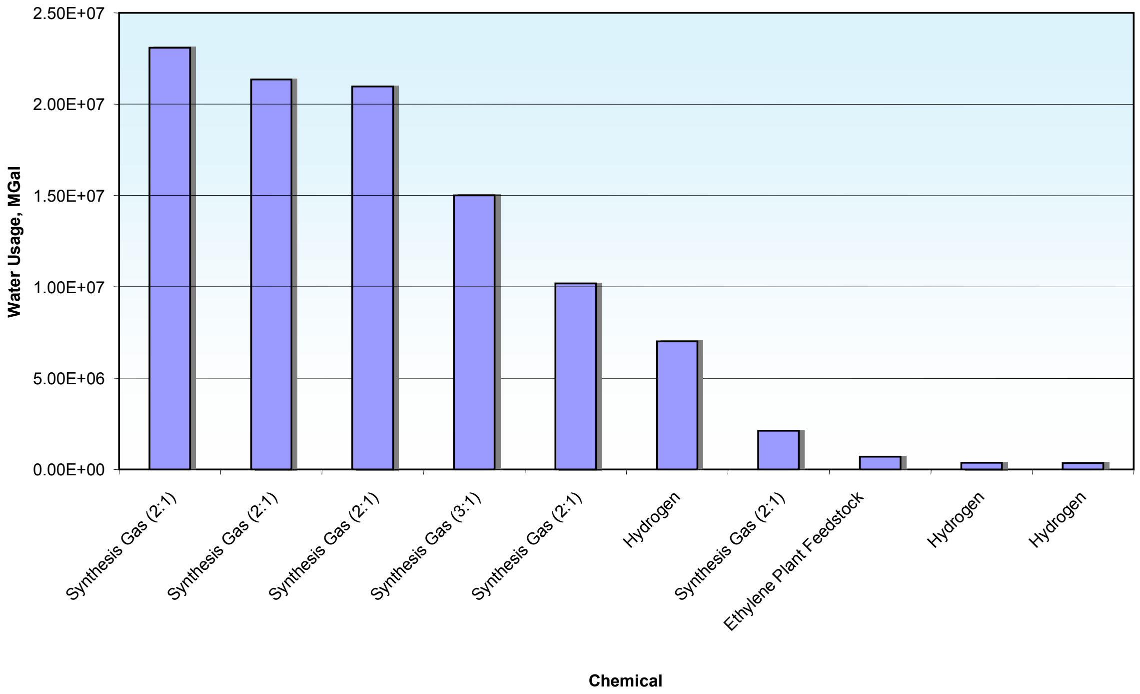

FIGURE 4.1-1
Highest Annual Water Users

TABLE 4.1-2

Water Usage of the Top Volume Manufactured Chemicals

	Cooling Water		**Process Water**		**Water for Steam**		**Total Water Use Capacity**	**Typical Range of Consumptive Use (lb/lb)**
	Amount Used (lb/lb of product)[1]	**Typical Fraction Recycled[2]**	**Amount Used (lb/lb of product)[1]**	**Typical Fraction Recycled**	**Amount Used (lb/lb of product)[1]**	**Typical Fraction Recycled**	**lb/lb of product**	**(Total Water Use less fraction recycled)**
Nitrogen	676	90 - 95%	N/A	Varies Widely - as low as 0%	N/A	80 - 99%	676	30 - 70
Ethylene	198		3.6		14.5		216	10 - 30
Ammonia	140		0.9		N/A		141	7 - 15
Phosphoric Acid	135		4.2		1.3		141	10 - 20
Propylene	135		2.4		0.8		138	9 - 18
Polyethylene	82		0.5		0.4		83	4 - 9
Chlorine	70		3.0		1.8		75	6 - 12
Sulfuric Acid	66		0.4		-0.4		66	3 - 7
Oxygen	21		N/A		N/A		21	1 - 2

1. Source: 2002 PEP Yearbook International, published by SRI Consulting.
2. Source: Approximation Analysis, assuming an average temperature rise of 50 degrees Fahrenheit for processes, and 6 cycles of concentration for typical cooling towers in the industry.

TABLE 4.1-3

Highest Per Pound Water Users

	Cooling Water		**Process Water**		**Water for Steam**		**Total Water Use Capacity**	**Typical Range of Consumptive Use (lb/lb)**
	Amount Used (lb/lb of product)[1]	**Typical Fraction Recycled[2]**	**Amount Used (lb/lb of product)[1]**	**Typical Fraction Recycled**	**Amount Used (lb/lb of product)[1]**	**Typical Fraction Recycled**	**lb/lb of product**	**(Total Water Use less fraction recycled)**
Silicon Nitride	15529	90 - 95%	N/A	Varies Widely - as low as 0%	249	80 - 99%	15778	770 - 1600
Silicon, High-Purity, Silane Decomp	13878		28.8		N/A		13907	700 - 1400
Polyaryloxyphosphazene	8674		5.3		195		8873	400 - 900
Ethylene Plant Feedstock	5321		N/A		N/A		5321	250 - 550
D-phenylalaniline	3866		N/A		194		4060	200 - 420
Permethrin, Kuraray	3503		85.1		32		3620	250 - 450
Permethrin, Sagami	3419		82.6		31		3533	250 - 450
Silicon, High-Purity, Chlorosilane Reduction	3430		5.1		N/A		3435	180 - 360
Aramid Spun Yarn	2802		26.6		40		2868	170 - 320
PI Film, Fluoropolymer	2796		N/A		N/A		2796	140 - 280

1. Source: 2002 PEP Yearbook International, published by SRI Consulting.
2. Source: Approximation Analysis, assuming an average temperature rise of 50 degrees Fahrenheit for processes, and 6 cycles of concentration for typical cooling towers in the industry.

essentially indistinguishable from the total water requirements. However, Permethrin by the Sagami Process and High Purity Silicon by the Chlorosilane Reduction Process are reversed in order of cooling water usage because High Purity Silicon has a slightly larger cooling water requirement while Permethrin has a higher steam and process water usage for a higher total water usage. Because of these visually undetectable differences, a separate chart for the top 10 cooling water processes is not included.

Process Water Intensive Processes

Figure 4.1-2 depicts the 10 chemical industry processes that use the most process water. Of these, only the Permethrin processes are also shown in Figure 4.1-1 for high per pound total water usage. Only the Hydrogen and Synthesis Gas by gasification of bituminous coal appear on the chart of highest annual water users (Figure 4.1-1). As shown in Figure 4.1-2, the total water requirement (represented largely by cooling water) is significantly higher than the process water for all but three of the processes. Figure 4.1-2 does not account for recycle of cooling water or boiler feed water in the total water requirement, but shows total capacity for water use. Actual consumptive water use for each of the chemicals shown is lower, and varies on a per pound basis between different facilities because of different operating practices.

Steam Intensive Processes

The most steam intensive processes in the chemical industry are represented in Figure 4.1-3. The top 3 steam users are also among the top 10 per pound water users shown in Figure 4.1-1. Only Hydrogen appears on the list of highest annual total water users in Figure 4.1-1. With the single exception of Ethylene production, which actually results in an overall net generation of water, the total water requirement per pound is significantly higher than the steam usage alone for the most steam intensive processes. Figure 4.1-3 does not account for recycling of cooling water or boiler feed water in the total water requirement, but shows total capacity for water use. Actual consumptive water use for each of the chemicals shown is lower, and varies on a per pound basis between different facilities because of different operating practices.

4.1.4 Relationship of Water to Energy

Because the largest uses of water are for cooling and steam, water use and energy use are closely tied in the chemical industry. However, because the chemical industry has not historically tracked its water usage, it is difficult to quantify that relationship. For example, the top 10 total per pound water users, as shown in Figure 4.1-4, are not all high energy users, and a distinct correlation between water use and energy use is not well defined. However, the amount of energy consumed by the high volume of cooling water used in the chemical industry is intuitively high (though the specific amount is not available). The energy represented by electricity, fuel oil, and natural gas might for some processes be considerably less than the energy consumed by cooling water.

The processes that use the highest per pound amounts of total electricity, fuel oil, and natural gas are shown in Figure 4.1-5. As with Figure 4.1-4, the highest water users are not the highest energy users. However, the two High Purity Silicon processes shown in Figure 4.1-3 among the highest per pound water users also require the highest amounts of electricity, fuel oil, and natural gas forms of energy. Three of the processes, Synthesis Gas, Ethylene Plant Feedstock, and Hydrogen, are also among the highest annual total water users shown in Figure 4.1-1.

As with Figures 4.1-2 and 4.1-3, Figures 4.1-4 and 4.1-5 do not account for recycling of cooling water or boiler feed water in the total water requirement, but show total capacity for water use.

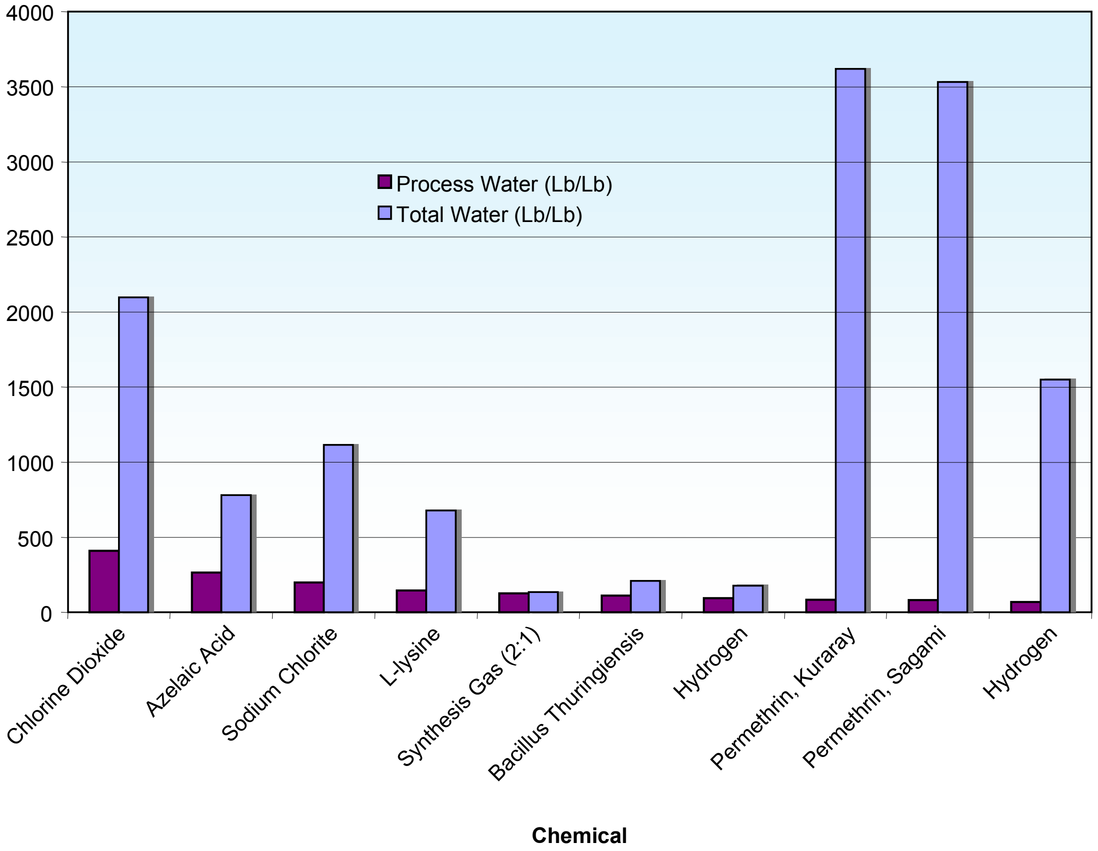

FIGURE 4.1-2
Most Intensive Process Water Users

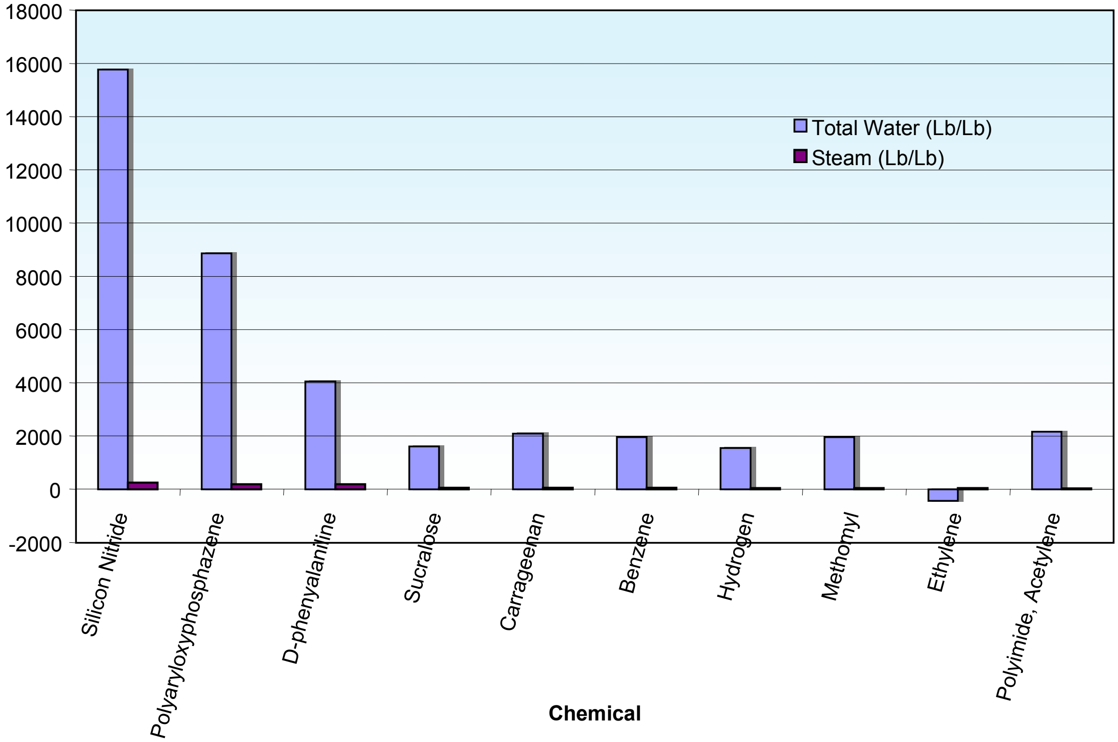

FIGURE 4.1-3
Most Steam Intensive Processes

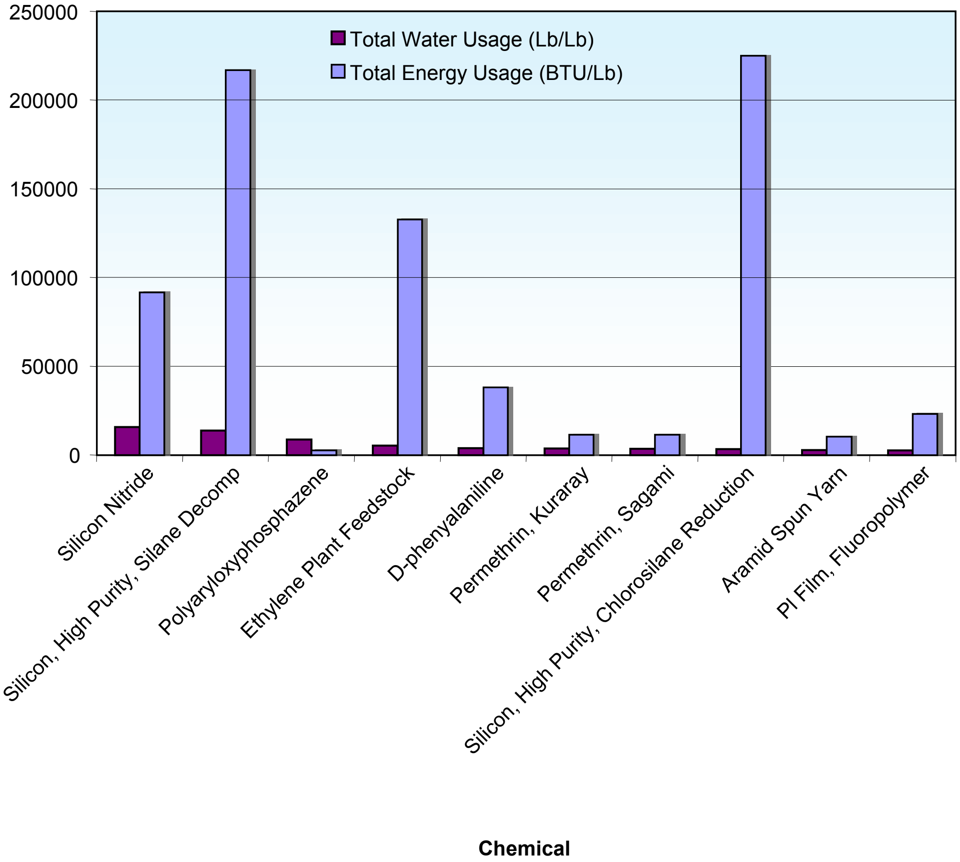

FIGURE 4.1-4
Energy Usage of Highest Per Pound Water Users

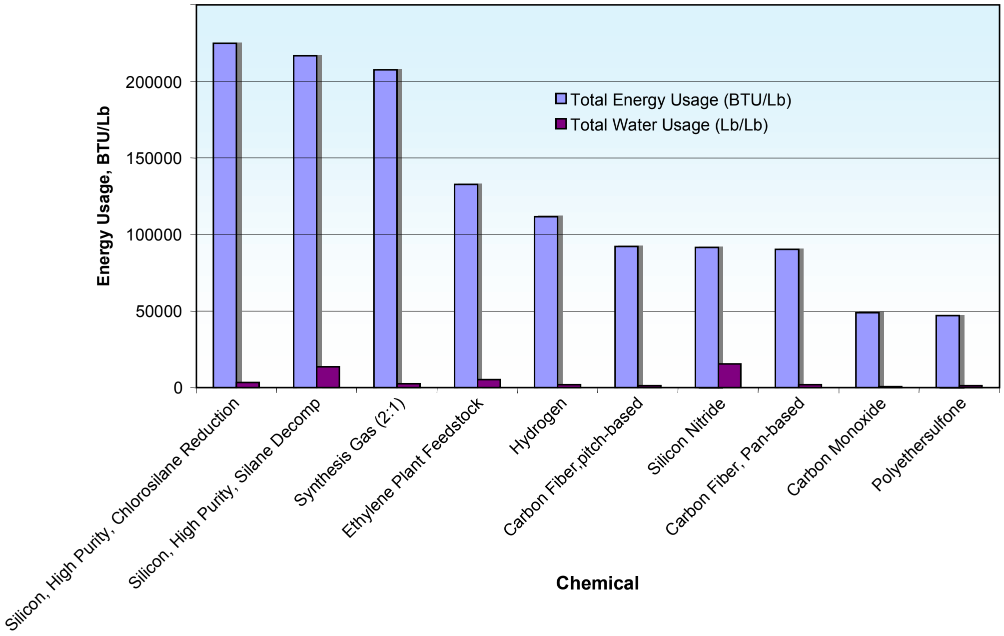

FIGURE 4.1-5
Highest Per Pound Energy Users

4.1.5 Water Reuse Practices and Challenges in the Chemical Industry

Like water use, water reuse has not been widely documented in the chemical industry. The majority of known cases involve the tertiary treatment of wastewater, e.g., contact water. For example, industrial facilities that already operate a wastewater treatment plant might select to add unit processes such as carbon adsorption, sand filtration, ion exchange, and/or membrane processes to facilitate return of the treated wastewater to upstream processes. A number of plants are leading the industry by exploring increasingly popular zero water discharge options. Recent attention to the water limitations listed in the Introduction of this chapter make water reuse far more attractive than it was only a few years ago. Chemical industry contacts are more commonly naming water needs as among their greatest environmental challenges. Therefore, the trend of process water reuse is expected to continue to increase in popularity.

However, it is clear from the design data presented in this chapter that the highest potential for water conservation lies in the reduction of cooling water usage. A number of the water intensive processes are also energy intensive and vise versa. Given the unquantified energy losses associated with cooling water, it is likely that water use reduction may be coupled with a reduction in energy use.

To further define the challenges of water reuse and conservation, the following are recommended for individual chemical processes:

- **Institute a rigorous system of water use measurement**. Although the instrumentation need not be sophisticated, it should be reliable, and all significant water uses should be measured and recorded.
- **Quantify the energy losses from the use of cooling water.** Given the increasingly short supply of water, it could be that for some processes cooling is no longer best accomplished using water. A comprehensive evaluation of energy usage should be performed.
- **Reduce the practice of once-through cooling water.** Cooling towers should be utilized wherever possible to decrease energy consumption and reuse as much cooling water as possible.
- **Educate employees and the public on the importance of water conservation.** Employees generally respond to issues on which they're well informed and on which management attention is focused, as indicated by training and other emphases.
- **Eliminate leaks and other inefficiencies.** Although a number of facilities have implemented housekeeping and/or water conservation programs, leaks in sewer systems and other piping continue to waste water.
- **Identify water reuse opportunities that also reduce energy consumption.** The chemical industry has often failed to explore water reuse because of its extensive infrastructure investments. As water and energy costs escalate, the drivers for water reuse increase, and the opportunities for associated energy reductions are numerous.

- **Continue research and development efforts focused at low energy, low water processes.** Several chemical companies report impressive advances in processes that were previously thought impractical. Technology is likely to be integral in realizing even greater gains in the challenge of water and energy minimization.

5.1 Forest Products Industry

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5.1.1 Forest Products Industry Overview

The forest products industry produces a wide range of consumer products manufactured from trees and recycled fiber. Products include paper, lumber, board products, engineered wood products, fuels, landscape materials, and many other specialty items. Water is used sparingly in the manufacture of most forest products, with the exception of pulp and paper. Modest amounts of water are used in the manufacture of hardboard and medium density fiberboard; however, the total water consumption used in the manufacture of these products pales in comparison to amounts used by the pulp and paper industry. Consequently, this chapter focuses on the pulp and paper segment of the forest products industry.

Over 600 facilities in North America produce pulp and paper products. A majority produce both pulp fiber and final paper products at the same site and are referred to as integrated facilities. Facilities that produce only pulp used to manufacture final paper products at other locations are termed market pulp mills. Plants that produce final paper products from purchased pulp only (i.e., no onsite pulping capability) are referred to as non-integrated mills.

Hundreds of different paper products are manufactured in this industry. Products vary according to strength, color, brightness, adsorbancy, printing qualities, permanency, and other physical characteristics. Final product requirements and cost dictate the type of pulp used for manufacturing particular products. Wood pulp used for the manufacture of shopping bags, brown paper, corrugated boxes, and similar products is not bleached. Products such as newsprint, copy paper, magazine stock, and book paper grades are manufactured from pulps that have been bleached using various combinations of bleaching chemicals.

A variety of pulping processes are used to produce virgin (new) pulp from wood: kraft, sulfite, soda, neutral sulfite semichemical (NSSC), thermomechanical (TMP), chemithermomechanical (CTMP), and groundwood (GWD). Pulp is also produced from recovered and recycled paper products, such as trim from paper making, old newspapers, post-consumer mixed wastepaper products, old corrugated containers, and magazines. Blending of virgin and recycled pulps is common in the manufacture of many paper products.

The complexity and capacity of pulp and paper manufacturing plants varies considerably. Specialty mills may produce less than 100 tons/day, while large integrated facilities can manufacture in excess of 2,000 tons/day. As expected, water consumption varies significantly throughout this industry. It is influenced primarily by the type of pulping process used, production capacity, age of facility, and type of pulp bleaching (if any) employed. Small facilities, non-integrated plants, and newer recycle facilities are able to operate with relatively small volumes of water—some as low as 100 gallons/minute (144,000 gallons/day). Very large integrated plants, especially older facilities, might use more than 40 million gallons/day (mgd) of fresh water.

5.1.2 Water Use and Energy

Compared to other types of manufacturing, the pulp and paper industry is considered to be the third largest consumer of both fresh water and energy (Garner, 2002).

Because of the wide variability in the types and sizes of manufacturing facilities within the pulp and paper industry, it is necessary to narrow this discussion of water and energy usage to the most common types of pulping processes used by the vast majority of North American facilities:

- Chemical pulping (unbleached and bleached kraft pulping)
- Mechanical pulping (groundwood and thermomechanical pulping)
- Recycle pulping (deink and old corrugated containers)

Essentially all North American integrated pulp and paper facilities use one or more of these pulping processes. The discussions related to water usage in this industry address paper manufacturing as separate from pulping.

5.1.3 Water Use in Pulp and Paper Manufacturing

Water serves four essential functions in the manufacturer of pulp and paper products: making up process chemicals, conveying/controlling material through the various pulping and paper manufacturing unit processes, separating and purging contaminants from the product, and removing heat from the processes. For example, water is used for initial chip cleaning, pulping liquor preparation, liquor separation, screening, bleaching, bleached pulp washing, conveying of pulp stock, control of stock consistency on to the paper machine, steam production, and emission controls.

Water use is commonly measured as a unit of production. Pulp production is typically expressed in metric units as cubic meters per oven dry metric ton (m^3/odt) or cubic meters per air dry metric ton (m^3/adt), or in English units as gallons/oven dry short ton (gal/ODT) or gallons/air dry short ton (gal/ADT). By definition, an air dry ton contains 10 percent moisture.

Water used in the manufacturer of paper is normally expressed as a unit of actual product weight, without respect to moisture content, i.e., cubic meter/metric ton (m^3/t) and gallons/short ton (gal/T). These conventions are adhered to for the specific water uses described in the following paragraphs for the major pulping operations and for papermaking.

Chemical/Kraft Pulping

Kraft pulping is the leading process for producing chemical pulp. Kraft pulp is used mostly for papermaking on site (integrated mills), but some is shipped as market pulp to non-integrated paper mills as well as to other integrated pulp and paper mills.

Process water use varies with the age of the mill and whether the mill employs cooling towers or rejects its excess low grade heat in the form of tempered, non-contact cooling water. Typical water use for operating unbleached and bleached kraft mills is as follows (Turner, 1994; Hynninen, 1999; IPPC, 2001; Woitkovich, 1996; Chandra, 1997; Erickson et al., 1996).

Unbleached kraft pulp:

- 20–35 m^3/adt (4,800–8,400 gal/ADT) without non-contact cooling water
- 35–55 m^3/adt (8,400–13,200 gal/ADT) including non-contact cooling waters

Bleached kraft pulp:

- 55–90 m^3/adt (13,200–21,600 gal/ADT) without non-contact cooling water
- 70–110 m^3/adt (16,800–26,400 gal/ADT) including non-contact cooling waters

Table 5.1-1 shows typical ranges of water use for the various unit processes and mill operations. Current design/best available mill concepts are discussed in subsection 5.1.5, Overview of Water Reuse and Reduction Practices.

Mechanical/Groundwood and Thermomechanical

Mechanical pulping lines are usually integrated with paper manufacturing, and the water sys tems usually incorporate a high degree of water reuse. Fresh water is used primarily for equipment seals, cooling, and chemical dilution.

TABLE 5.1-1
Water Use in Typical Kraft Mill Operations (Turner, 1994; IPPC, 2001; Chandra, 1997)

Area	m^3 / adt	Gallon/ADT
Wood room (net)	0.3	72
Digesting	1.0	240
Washing and Screening	1.8 – 4.2	430 – 1000
Evaporators, Recovery	1.3 - 2.8	310 - 670
Recausticizing	1.4 – 2.6	340 – 620
Power house	3.4 – 5.0	820 –1,200
Effluent treatment	0.5 – 1.0	120 –240
Sub-total brown stock mill	9.7 – 16.9	2,320 – 4,050
Bleach plant chemical preparation	0.5 - 0.8	120 –190
Bleach plant acid stages	21.0 -25.0	5040 –6,000
Bleach plant alkaline stages	10.0- 30.0	2,400 – 7,200
Sub-total bleach plant	31.5 – 55.8	7,560 – 13,400
Pulp dryer rejects	1.3	310
Pulp dryer general	4.9 – 5.2	1,180 –1,250
Sub-total pulp dryer	6.2 -6.5	1,480 – 1,560
Total process use	47.4 – 79.2	11,400 – 19,000
Excess non-contact cooling water	15.0 -20.0	3,600 – 4,800
Water supply	5.0 -10.0	1,200 – 2,400
Total mill raw water use	67.4 – 109.2	16,200 – 26,200

Additional water may be required to purge the process of dissolved substances. This wash water can be supplied as paper machine white water[2] in an integrated mill or fresh water in a market pulp mill. The amount of wash water, referred to as overall pulp mill dilution factor, depends on the amount of dissolved substances that must be removed and the mill equipment configuration. Groundwood pulping produces the least amount of dissolved material and bleached chemi-thermomechanical pulp (BCTMP) the highest amounts.

Typical water use figures for operating mechanical pulping operation are shown in Table 5.1-2 (Turner, 1994; IPPC, 2001).

A special group is the zero effluent BCTMP technology that uses a combination of aggressive in-process physical/chemical treatment combined with effluent evaporation to produce water for reuse (Reid and Lozier, 1996). In this

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[2] White water is a term used to describe process water that contains fiber fines. On the paper machine, white water is produced during the forming and dewatering of the fiber sheet.

TABLE 5.1-2
Water Use in Typical Mechanical Pulp Mills

Area	GWD (m^3/t)	TMP (m^3/t)	BCTMP (m^3/t)
Pump seals	0.5 – 5.0	0.5 – 5.0	0.5 – 5.0
Potable /boiler make-up	0.5 – 1.0	0.5 – 1.0	0.5 – 1.0
Chemical dilution	0	0.0 – 0.5	0.9 – 3.5
Dilution factor	4.0 – 10.0	4.0 – 15.0	10.0 – 20.0
Other incl. cooling	1.0 – 4.0	1.0 – 3.5	3.1 – 20.5
Total water demand	6.0 – 20.0	6.0 – 25.0	15.0 – 50.0

design, internal process water conservation is incorporated at the design stage, so that total water demand is reduced to 12.0–14.0 m^3/t, rather than the 15.0 m^3/t at the low end of the range shown for BCTMP mills in Table 5.1-2. Furthermore, water is treated and reused so that the only freshwater need is about 2.0 m^3/t to replace the moisture lost to the atmosphere from pulp drying and process vents. The clean condensate available for reuse is in the range of 10.0–12.0 m^3/t.

Recycled Pulp Production/Deink and Old Corrugated Containers

Almost half of all paper (48 percent or 49.4 million tons of paper in year 2000) is recovered for recycling in the United States (American Forest & Paper Association, 2001). This source of secondary fiber supplies almost 40 percent (39.1 percent or 37.6 million tons in 2000) of the fiber content of all domestic paper and paperboard production. The remainder of the recovered fiber is used for non-paper domestic uses or exported to other countries.

Processing of the recovered paper varies with end use product requirements and with the quality of the recovered paper. Recycled paper processing can be generalized into three categories:

- **Mechanical cleaning** only (without deinking). Products include corrugating medium, linerboard or carton board.
- **Mechanical cleaning and deinking**. Products include newsprint and printing and writing papers.
- **Mechanical cleaning, deinking and ash removal.** Products include tissue and some fine papers.

More processing and higher quality end products result in higher fresh water demand to purge contaminants during recovered paper processing. Deinked fiber is frequently bleached, resulting in an additional requirement for clean water.

Table 5.1-3 illustrates typical water use as effluent discharged from flotation deinking of recovered paper (Turner, 1994). Tables 5.1-4 and 5.1-5 illustrate water use as effluent discharged from secondary fiber paper and board mills with non-deinking and from paper mills with deinking processes (Turner, 1994).

Papermaking

Paper making is a water intensive process. Water is used to transport fiber and to form the sheet on the paper machine from a dilute fiber suspension. Water is also used in paper making to disperse fibers, dilute fillers and additives, clean and remove contaminants, and seal and lubricate the paper machine vacuum pumps.

Paper mills have always relied on the recirculation of white water for stock dilution to conserve water and energy. In an open-loop white water system where fresh water is used for the

TABLE 5.1-3
Secondary Fiber Flotation Deinking Water Use

Unit Operation	Average Effluent Flow	
	(m^3/odt)	(gal/ODT)
Trash Extraction	0.035	8.4
High Density Cleaning	0.035	8.4
Course Hole Screening	4.0	960
Flotation	3.0	720
Reverse Cleaning	1.5	360
Forward Cleaning	0.0	0.0
Fine Slot Screening	3.0	720
Subtotal	12.17	2,920

TABLE 5.1-4
Typical Non-Deink Paper/Board Mill Water Use

Paper/Board Mills Without Deinking	Average Effluent Flow	
	(m^3/odt)	(gal/ODT)
Folding Paperboard	16.7	4,000
Container Board	12.1	2,900
Tube, Setup, Chipboard	12.5	3,000
Other	64.3	15,400

TABLE 5.1-5
Typical Deink Paper Mill Water Use

Paper Mills With Deinking	Average Effluent Flow	
	(m^3/odt)	(gal/ODT)
Fine Paper, flotation and washing	26.7	6,400
Tissue, washing	35.5	8,520
Tissue, flotation and washing	28.1	6,740
Newsprint, washing	30.0	7,200
Newsprint, flotation and washing	27.0	6,480

machine showers, water use can approach 100 m^3/t (24,000 gal/T). Modern mills have implemented more closed-loop white water systems to reduce fresh water consumption, by filtering white water for reuse on the machine showers.

The cooling demands for a paper mill are satisfied either by direct discharge of excess tempered (warm) non-contact cooling water or by using cooling towers to reject heat to the atmosphere.

Table 5.1-6 shows the typical uses of fresh waters in a paper mill (Turner, 1994; IPPC, 2001)

Water Balance for Pulp and Paper Manufacturing

The overall water balance in Table 5.1-7 shows the typical sources and uses (losses) of water for various types of pulp and paper manufacturing (Turner, 1994; IPPC, 2001). As shown, the largest water uses are process water and cooling water. Large amounts of process water are used to separate, dilute, and transport wood fibers around the mill. Where thermal processes are used, cooling water is used to remove heat from the process as needed.

The ranges for process and cooling water use are also notable. The high end of the 1,200 – 19,200 gal/T range for cooling water use represents mills that tend to use fresh water for all process needs. Few mills practice that now; most practice at least some process water reuse. Those that feed water used in cleaner processes into processes that do not require high purity fall toward the low to mid-range, while those at the lowest end of the range tend to design water conservation into the processes, and treat used process water to reclaim it for reuse in high-purity processes.

Those mills at the high end of the range for cooling water use tend to utilize once-through cooling, while those toward the low end of that range recycle cooling water through cooling towers.

Overall Water Use by Pulp and Papermaking Sector

Average water consumption in the U.S. pulp and paper industry for the year 2000 was about 15,000 gal/T (62.5 m^3/t). Total annual industry output was on the order of 105 million short tons, which corresponds to total water use by the U.S. pulp and paper industry of approximately 4.5 billion gallons per day, assuming an average of 350 operating days per year.

5.1.4 Relationship of Water to Energy

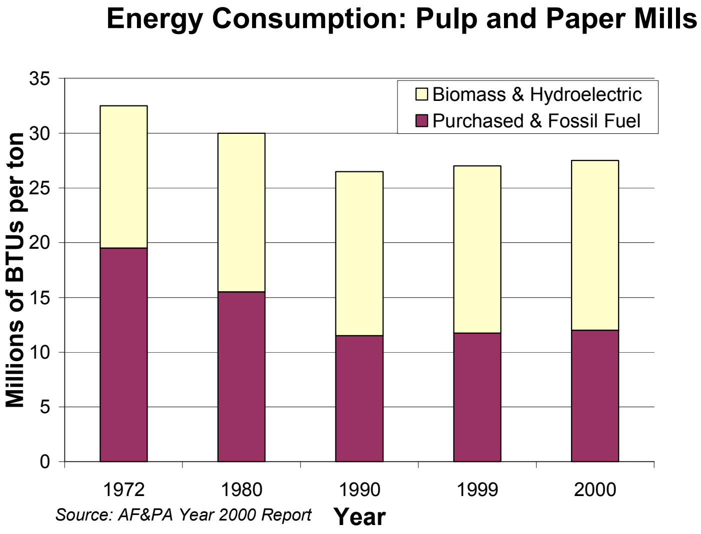
Long-term historical trends for water and energy use in the industry are shown in Figures 5.1-1 and 5.1-2 (American Forest & Paper Association, 2001; Chandra, 1997).

TABLE 5.1-6
Typical Paper Mill Fresh Water Use

Water Use	Production Unit Volume	
	m^3/odt	gal/ODT
Machine showers	5-20	1,200-4,800
Seal water	2-5	480-1,20
Dilution of fillers and additives	1-3	240-720
Miscellaneous, dilution	1-5	240-1,200
Vacuum pump seal water	1-5	240-1,200
Total excl. cooling water	**10-38**	**2,400-9,100**

TABLE 5.1-7
Typical Overall Water Balance for Pulp and Paper Mills

Water Inputs to Pulp and Paper Mills	**Production Unit Volume**	
	m^3/t	**gal/T**
Water with purchased pulp	0.05-0.10	12-24
Water with waste paper	0.10-0.15	24-36
Water with wood (mechanical pulps)	1.-1.2	240-290
Water with wood (unbleached kraft)	2.0-2.2	480-530
Water with wood (bleached kraft)	2.1-2.3	500-550
Process water	5-80	1,200-19,200
Cooling water	1-20	240-4,800
Water Outputs, Pulp and Paper Mills	**m^3/t**	**gal/T**
Water in product	0.05-0.10	12-24
Dryer evaporative loss	1.2-1.4	290-340
Recovery boiler/kiln (unbleached kraft)	0.5-0.8	120-190
Recovery boiler/kiln (bleached kraft)	0.6-0.9	140-220
Moisture with solid waste	0.0-0.6	0-140
Process effluent	5-80	1,200-19,200
Non-contact cooling water	1-20	240-4,800



Source: AF&PA Year 2000 Report

FIGURE 5.1-1
Historical Energy consumption Trend

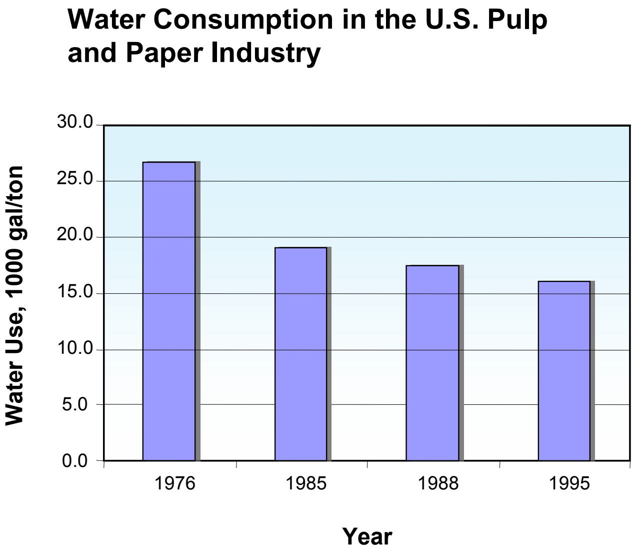


FIGURE5.1- 2
Historical Water consumption Trend

The declines in energy and water use since 1972 are related. Much of the energy use in a typical pulp mill is for treating, heating, and pumping water. When water is conserved, reused between different processes, and reclaimed through treatment, energy is saved from reductions in:

- Pumping fresh water into the plant
- Treating fresh water for use
- Heating water (to the extent that heat is recovered from cooling water or steam)
- Pumping waste water for disposal

These energy savings can be additive, so that for some processes, each gallon of water saved or reused reduces energy usage in all of these areas.

Measures implemented to date to reduce water use have resulted in the following benefits (including significantly improved energy efficiency) :

- Modern management systems, training, and education of staff and operators
- Efficient process control and process information systems
- High degree of preventive maintenance, eliminating upset conditions
- Efficient internal purification of process waters, leading to high levels of reuse
- Significant reduction in pumping and treatment of process water, as well as effluent treatment and disposal
- Increased in-mill liquid storage capacity, improving the water demand/supply balance and reducing the need for intermittent process water make up.
- Collection and reuse of clean cooling waters

Process modernization has resulted in power boilers operating at higher steam pressures, allowing higher power yield from back pressure turbine generators and improved energy conversion efficiencies.

The net result of this energy efficiency improvement trend has been an industry wide increase in energy self sufficiency with better utilization of the resources, as shown in Figure 5.1-3 .

5.1.5 Overview of Water Reuse and Reduction Practices

The pulp and paper industry has significantly reduced water consumption in the past 40 years as shown in Figure 5.1-2 (Turner, 1994; Chandra, 1997; Bryant et al., 1996). The measures commonly implemented for water reduction are discussed in the following paragraphs for each of the three most common pulping processes, together with current state-of-the-practice targets for water and energy use.

As U.S. mills continue to modernize, as inefficient plants close, and as new mills are built, water consumption will continue to decline, albeit at a slower rate. Pulp and paper mills operating with best available technology (BAT) generally include the following practices to minimize water consumption:

- Training, education, and motivation of staff and operators

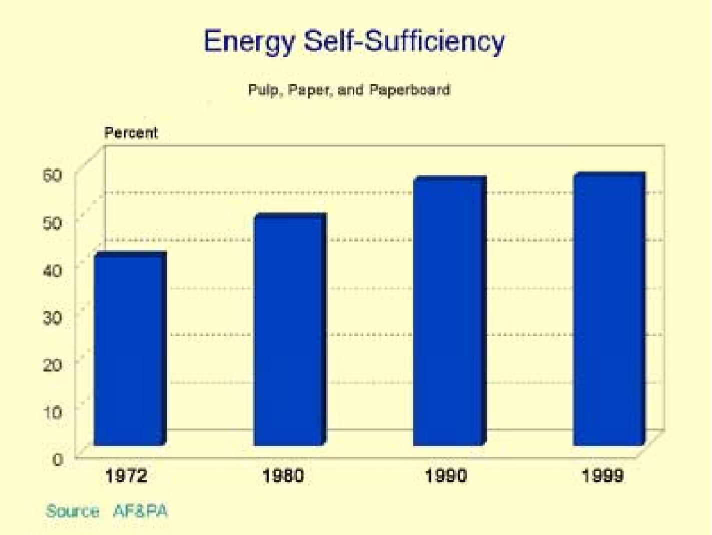


FIGURE 5.1-3
Energy self-sufficiency trend

- Process control optimization with relevant process data monitoring and analysis
- Efficient maintenance of facilities, to minimize process upsets and production interruptions
- Modern systems for environmental and process management

Chemical Pulping/Unbleached and Bleached Kraft

The most common water use reduction practices employed in unbleached Kraft pulping include (Turner, 1994; IPPC, 2001):

- Dry debarking of wood
- Highly efficient brown stock washing and closed cycle brown stock screening
- Effective spill control, including monitoring, containment and recovery
- Steam stripping and reuse of all pulping condensates
- Collection, segregation by temperature, and reuse of cooling waters
- Efficient countercurrent flow of process waters from the paper machine back to bleaching and pulp washing
- Process cooling water reuse

The following practices are also used in bleach kraft mills:

- Digester extended delignification and/or oxygen delignification prior to bleaching
- Elemental chlorine free (ECF) or total chlorine free (TCF) bleaching with alkaline filtrate recycle

Water use for mills that have implemented these measures is expected to be in the range of (IPPC, 2001):

- 30–50 m^3/adt (7,200–12,000 gal/T) for bleached pulp
- 15–25 m^3/adt (3,600–6,000 gal/T) for unbleached kraft pulp

This represents a 40–60% decrease in water use compared to the numbers presented for typical mills in 5.1.3.

The corresponding thermal and electrical energy use for bleached kraft mills is in the range of (IPPC, 2001):

- 10–14 GJ/adt (8.6–12.1 MM BTU/ADT) of thermally generated process steam
- 0.6–0.8 MWh/adt (0.54–0.73 MWh/T) of electrical power

Modern bleached kraft mills are fully self sufficient in steam and power production and can use condensing turbines to generate electrical power for sale from excess steam, if there are no other onsite users of process steam.

Mechanical Pulping —Groundwood, Thermomechanical, and Chemithermomechanical

The common water reduction measures for minimum water use in mechanical pulping include:

- Dry debarking of wood (thermomechanical pulps)
- Effective segregation and counter current reuse of paper mill process water, with the purge of the dissolved materials leaving the mechanical pulping and chip washing operations
- Use of thickeners or presses prior to pulp drying
- Segregation of non-contact cooling and process waters for reuse
- Adequate liquid storage to balance process water requirements and prevent intermittent overflows of process water

- Installation of efficient washing equipment of pulp to achieve lower water use in BCTMP and CTMP mills

The expected water use for mechanical pulp mills that have implemented these water reduction measures is in the range of (IPPC, 2001):

- 12–20 m^3/t (2,900–4,800 gal/T) for integrated mechanical pulp and paper mills making newsprint, light weight coated (LWC) and supercalendered (SC) papers
- 15–20 m^3/adt (2,900–4,800 gal/ADT) for standalone BCTMP and CTMP market pulp mills (This represents up to a 60% decrease in water use compared to the numbers presented for typical BCTMP mills in Table 5.1-2.)
- 2 m^3/adt (480 gal/ADT) for zero-effluent BCTMP market pulp mills (This represents an 85–95% decrease in water use compared to the numbers presented for typical BCTMP mills in Table 5.1-2.)

The corresponding energy use for a newsprint/SC paper mill using 100 percent TMP (IPPC, 2001) is:

- A possible steam surplus of 0.3 – 1.3 GJ/t (0.26–1.12 MM BTU/T) from the electrically powered refiners.
- 2.1–2.2 MWh/t (1.9–2.0 MWh/T) electrical power

The corresponding energy use for a CTMP pulp mill (IPPC, 2001) is:

- 0 GJ/adt thermally generated process steam consumption (refiners provide all process steam requirements)
- 2.0–3.0 MWh/adt (1.8–2.7 MWh/T) electrical power

Recycle Pulping – Deink and Old Corrugated Containers

The common water reduction measures employed in recycled pulping operations include:

- Separation and countercurrent reuse of less contaminated process water from more contaminated process effluents to optimize water use
- Process water filtration, gravity clarification, or flotation internal to the pulping process allowing reuse to displace the need for fresh water
- Segregation of non-contact cooling water from the process effluents allowing reuse
- Adequate liquid storage to balance process water requirements and prevent intermittent overflows of process water
- Internal biological treatment of process waters to remove dissolved organic material and partial recycle of biologically treated effluent with in the pulping process

Water use from various types of secondary fiber mills that have implemented these flow reduction measures is anticipated to be (IPPC, 2001):

- < 7 m^3/t (< 1,700 gal/T) for integrated mills producing corrugating medium, linerboard, or carton board from old corrugated containers (a 40 – 60% decrease in water use compared to numbers presented in Table 5.1-4 for typical non-deink paper/board mills)
- 8–15 m^3/t (1,900–3,600 gal/T) for mills with deinking producing newsprint or printing and writing papers (a 40–70% decrease in water use compared to numbers in Table 5.1-5 for typical mills of this type)
- 8–25 m^3/t (1,900–6,000 gal/T) for mills producing recycled paper based tissue product (a 30–70% decrease in water use

compared to numbers in Table 5.1-5 for typical mills of this type)

- 10–20 m3/adt (2,400–4,600 gal/ADT) for mills producing deinked pulp

Energy use for recycled paper based paper and board mills without deinking is anticipated to be (IPPC, 2001):

- 6.0–6.5 GJ/t (5.2–5.6 MM BTU/T) process steam and 0.7–0.8 MWh/t (0.64–0.73 MWh/T) of electrical power

The energy use for integrated newsprint or printing and writing paper mills with deinking operations (IPPC, 2001) is anticipated to be:

- 4.0–6.5 GJ/t (3.4–5.6 MM BTU/T) process heat consumption and 1.0–1.5 MWh/t (0.91–1.36) electrical power

Energy use for integrated tissue mills with deicing operations is anticipated to be (IPPC, 2001):

- 7 –12 GJ/t (6.0–10.3 MM BTU/T) process heat consumption and 1.2–1.4 MWh/t (1.1–1.3)electrical power

Papermaking

Common water reduction measures used to minimize non-integrated paper mill water use include (Turner, 1994; IPPC, 2001):

- Installation of efficient white water filtration equipment to maximize the use of lean (low fiber content) white water for paper machine showers and for chemical dilution
- Sufficient volume in the white water circulation system to balance both system and paper machine water supply requirements and with the reserve/surge capacity to eliminate the need for fresh water make up during upset conditions and sheet breaks
- Segregation and collection of non-contact cooling waters for reuse or separate discharge

Water reduction measures for paper machines integrated with pulp production include (Turner, 1994; IPPC, 2001):

- Clarification to provide a suitable quality whitewater for use as make up water in the pulp mill
- Counter current washing of incoming pulp to minimize contaminant purge requirements

Figure 5.1-4 illustrates the fresh water makeup and flow distribution balance for a paper mill using 10.5 m3/t (2,520 gal/T) freshwater and cooling towers for non-contact cooling water for the paper machine vacuum pumps (IPPC, 2001).

Table 5.1-8 shows the expected water and energy use for non-integrated mills that have implemented these water conservation measures (Turner, 1994; IPPC, 2001). Compared to typical paper mill water usage numbers presented in Table 5.1-6, this represents a 35–40% decrease:

Table 5.1-9 presents achievable fresh water consumption for various paper grades (Turner, 1994; IPPC, 2001). These numbers, when compared with those in Table 5.1-6, represent possible water use reductions of 35%, and up to 60% in some cases.

5.1.6 Water Use Reduction Potential Versus State of the Industry

The water use numbers presented in 5.1.5, and in Tables 5.1-8 and 5.1-9 represent what is achievable, and what has been implemented as best practice. As shown, where comparable numbers are available for typical U.S. mills today, water use reductions of 30% to 70% may be possible, if water conservation, reuse, and reclamation practices are implemented. Energy use reductions would also be realized.

This evidence leads us to conclude that:

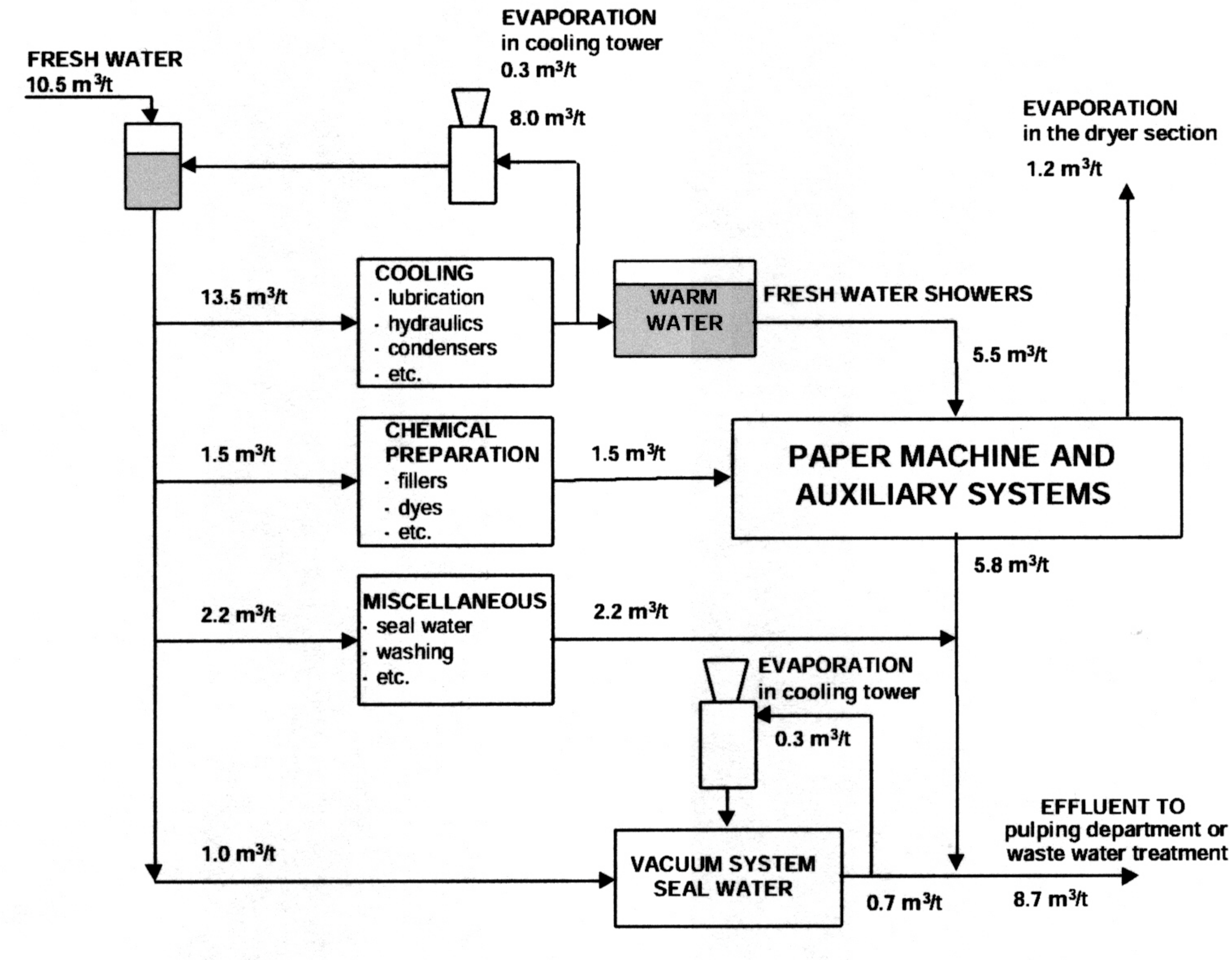


FIGURE 5.1-4
Typical Paper Mill Water Balance

TABLE 5.1-8
Water and Energy Use for Non-Integrated Mills Employing Water Conservation Measurers

Type of mill non-integrated	Water use		Process steam (net)		Electric power	
	(m^3/t)	(Gal/T)	GJ/t paper	(MM BTU/T)	(MWh/t)	(MWh/T)
Uncoated fine paper	10 – 15	2,400 – 3,600	7.0 – 7.5	6.0-6.5	0.6 - 0.7	0.54 – 0.64
Coated fine paper	10 - 15	2,400 – 3,600	7.0 – 8.0	6.0-6.9	0.7 – 0.9	0.64 – 0.82
Tissue	10 - 25	3,600 – 6,000	5.5 – 7.5	4.7-6.5	0.6 – 1.1	0.54 – 1.0

TABLE 5.1-9
Typical Non-Integrated Mill Water Use for Various Paper Grades

Paper Grade	Fresh water use	
	(m^3/t)	(gal/T)
Corrugating medium, liner	4 -10	960 – 2,400
Uncoated fine paper	5 -12	1,200 – 2,900
Coated fine paper	5 - 15	1,200 – 3,600
Newsprint	8 - 13	1,900 – 3,100
Multiply board	8 - 15	1,900 – 3,600
LWC paper	10 -15	2,400 – 3,600
SC paper	10 -15	2,400 – 3,600
Tissue (virgin fiber, heavy wt. or lower quality).	10 - 15	2,400 – 3,600
Tissue (virgin fiber, light wt. high quality)	15 -25	3,600 – 6,000

Water and energy use in this industry have decreased from where they were 30 years ago, however,

- Further significant reductions are achievable, if water conservation and reuse practices discussed above are implemented.

New pulp and paper mills tend to be built to the latest standards of water conservation. Therefore most of the room for improvement exists in older mills that have not been modernized. As new mills are built throughout the world, and global trade increases, it is anticipated that older mills that have higher water and energy use patterns will become less and less competitive. The consequences for these older mills are likely to be that they are either modernized and updated to best-practices with regard to water use, or that they are shut down.

Modernizing pulp and paper mills in order to maintain global competitiveness requires significant capital investment. It is estimated that this can be done with a positive return on investment; however quite often that return is not high enough to match the rate of return required by private companies on investments to upgrade existing facilities. Thus the drivers to modernize old, inefficient mills are often not strong enough to make these changes happen.

There are economic benefits that can accrue to a mill from more efficient resource use that are often not counted in the investment decision. These include:

- Value of excess water or energy that could be sold in the marketplace
- Value of water rights that might be transferred or sold
- Resource self-sufficiency, resulting in lower exposure to volatility of market prices for these resources
- Reduced environmental liability, which could result from reduced need for permits, or reduced pollutants discharged from the mill

Furthermore, social benefits accrue from improving existing facilities, including:

- A stable job base for the local economy
- Improved environmental quality
- Greater resource availability in the area around the mill

These social benefits may be high, but they do not accrue to the mill, so they are not counted in the investment decision. However, they could be transferred to the mill to some extent through government action such as tax incentives, grants, and regulatory assistance. Energy-efficiency tax credits, which exist both on the federal level, and in many states, are one example of such incentives.

6.1 Mining Industry

Contributed by Jim Mavis, in CH2M HILL's Seattle, Washington, office

6.11 Structure of the Mining Industry

Mining Industry Segments

Mining in one form or another has existed since ancient times. The modern industry has evolved by incorporating gradual improvements into common practice. Mining in the United States can be classified in several ways. The classification used in this chapter recognizes four segments:

- Hard rock
- Sand and gravel
- Industrial (soft rock) minerals
- Coal

Each of these categories can be further be subcategorized; moreover, each mine or deposit has unique features. This chapter must necessarily provide only overview discussions of each major category, but acknowledges the diversity of the industry, and of deposits and methods for any one type of product.

Hard Rock

Hard rock mining produces ore for a variety of metals and minerals in the United States. Typical operations at hard rock mines, whether underground or open pit, include drilling, blasting, ore transporting and stockpiling, and, usually, size reduction.

Water use in the context of hard rock mining refers to process water that is necessary for routine functioning of the mine-mill complex, and not to incidental water such as excess mine water, accumulated precipitation, or other "nuisance" sources of water that must be dissipated. Nevertheless, incidental water, including mine water or natural precipitation, may be used for routine operation of the mine, if the mine is located in a water-short region.

Hard rock mines typically require water for drilling, and for any associated size reduction facilities. Water consumption can be stated in terms of gallons of water per ton of ore produced, except for production drilling and site dust control. For present purposes, size reduction is assumed to consist of crushing, wet screening, semi-autogenous grinding, and ball and rod mills (McNulty, pers. comm.)

Table 6.1-1 shows nominal water consumption rates for key operations at either an open pit or an underground mine.

Sand and Gravel

Sand and gravel are widely used as bedding material, in preparation of concrete mixes, and in many other construction applications. An estimated 90 percent of commercial sand and gravel is produced from "loose material." Only about 10 percent comes from hard rock. The following discussion describes water use during sand and gravel production from loose deposits.

Step 1. In a typical operation, rock less than 12 inches, long dimension, is screened through coarse bar screens ("grizzlies") and the passing material is crushed in a jaw crusher to intermediate size rock.

Step 2. Coarse-crushed rock passes through a three-level screen, and oversize material is returned to the jaw crusher.

Step 3. The smallest, sand size fraction is stockpiled for use in concrete, while the intermediate size rock fraction is either stockpiled for aggregate (nominally 1 inch and below), or is further crushed in a gyratory cone crusher.

Step 4. Crushed intermediate material is screened, and oversized material is returned to the cone crusher, or further processed in a rolling mill or a vertical impact mill, depending on product specifications.

Step 5. a. The size fraction that passes the screen drops into a tank (or vat) from which

TABLE 6.1-1
Hard Rock Mining Water Consumption

Operation	Gross Water Use, gallons per ton	Net Water Use, gallons per ton	Comments
Drilling	--	2 – 5 gpm/hole	Per-ton usage highly variable – spacing, diameter, depth, orientation, explosive type/loading
Crushing (dust control)	--	1 – 6 nominal	
Wet Screening	30 - 250	--	Gross use – once-through solids and water
Semi-Autogenous Grinding	475 – 700 nominal	125 – 200 nominal	Net use – net solids and net water makeup
Ball/Rod Mill	500 – 700 nominal	150 – 300 nominal	

sand size material (3/16 inch to ¼ inch and below) is withdrawn with a sand screw (about half of the installations). **b.** As an alternative, the fraction passing through the screen may be classified according to size in a gravity classifier (about half of the installations) to recover the sand fraction.

Step 6. Clays and silts are sent to a settling pond, from which decanted water is returned for use in the process.

Overall, a typical sand and gravel plant might produce 70 to 80 percent of its processed material as gravel and 20 to 30 percent as sand. Clays and silts normally comprise less than 10 percent of a viable loose material deposit; the settled clay mass might contain around 5 percent solids and 95 percent moisture.

Table 6.1-2 summarizes water use in a typical sand and gravel plant.

Industrial Mineral Mining

A variety of minerals are mined for use in manufacturing, in construction, and for purposes other than heating value (coal) or metal recovery. Industrial mineral (“soft rock”) mining practices vary widely, according to the mineral produced and the nature of the deposits.

Two familiar examples of industrial minerals are kaolin (clay) and silica sand (used in glass making). Each is mined and processed with different methods. Kaolin clay mining and processing serve as an example. Kaolin is used

TABLE 6.1-2
Sand and Gravel Water Consumption

Operation	Gross Water Use, gallons per ton	Net Water Use, gallons per ton	Comments
Crushing (dust control)	--	1 – 6 nominal	
Wet Screening	60 – 180 nominal		
Sand Screw	~60 nominal		
Gravity Classifier	~90 nominal		
Clay Retention		1,500 – 5,000 nominal	Clays and silts retain a high percentage of moisture because of their high capillary tension

in a variety of industries, including paper manufacture, ceramics, and paint formulations. Papermaking uses a large amount of kaolin clay, and crude kaolin is not useful as a mined product until it is processed to remove impurities.

In Georgia, kaolin deposits are normally located and mapped from exploratory cores to depths typically from a few tens to about 200 feet. During mining, the overburden is stripped from one to a few acres to expose the kaolin layer. No water is used in actual drilling, but up to 1,000 gallons per core may be used in exploration and mine development.

Relatively large volumes of water are used at kaolin processing plants, which are usually located some distance from the mining area. Mined kaolin is usually slurried near the mine and transported to processing facilities through a pipeline as a clay suspension dispersed in water. Although processing methods vary with the run-of-mine clay quality and the end use for the processed clay, they usually include suspension or dispersion (deflocculation), screening, grit removal (e.g., gravity separation, centrifugation), flotation, brightening (e.g., magnetic separation, oxidation), flocculation, filtration, drying, and packaging.

Water usage varies with the specific operations needed to refine the clay for its end use, but a nominal estimate from one source indicates typical usage is ~2,000 gallons per ton of finished product. Approximately 80 percent of the finished kaolin shipped to the paper industry is in slurry form, which is 70 percent kaolin and 30 percent water.

Coal

Coal is mined in a number of areas in the United States. It is used most extensively in electrical power generation, with coke making and byproduct chemical recovery among other uses. In the eastern United States, coal is often mined underground, where risks of gas buildup cannot be tolerated. In the western United States, more coal is strip mined.

Water use in coal mining varies according to the method of mining, the equipment used, and the availability of water. Underground coal mines in West Virginia rely on the use of water for cooling the cutting surfaces of mining machinery and for inhibiting friction-induced ignition of coal fines or gas. Surface mines in the Western United States do not use water in actual mining, but they do suppress dust on haul roads with water and aqueous solutions of calcium chloride and magnesium chloride.

Statistical information about the use of water in coal mining is not available from readily accessible sources. However, one surface mine operator reported that aside from minor uses for personnel (sanitary, showers, potable), equipment maintenance, and miscellaneous uses, the overwhelming use was for dust control. Dust control consumed about 5.2 gallons per ton of coal produced. In addition, small amounts of magnesium chloride solution (~0.01 gallon of solution per ton of coal) and calcium chloride (~0.003 gallons solution per ton of coal) were used to retain moisture, since both these salts are hygroscopic (take moisture from the air).

6.1.2 Relationship of Water to Energy

Water and energy may be directly or indirectly related in the mining industry, and the connection is mainly through pumping power to transfer the water or aqueous slurries of mineral products to another location. Most mines both consume and produce water, which often must be imported for operating purposes from locations remote from the mine, or transferred as surplus mine water from within the mine to a treatment and/or discharge location. Water might also be involved in three production-related areas: mining, downstream processing, and product conveyance.

Production and Consumption

Most mines penetrate into water producing formations or fracture systems during exploration or operation. Depending on the nature of the ore and the geochemical conditions of the formation, this groundwater might either be of good quality or be contaminated to the extent that treatment is needed before discharge. Mine water must be removed from operating mines to prevent flooding, the removal rate equaling the inflow rate. Except for cases in which the mine is elevated above the surrounding topography, mine water must be pumped to a treatment system or to a discharge point. Energy consumption can be significant, not only because of large volume, but because of appreciable lift from deep within the mine to the surface, often several thousand feet.

If water is used in mining or in ore processing at a mine site, the mine water can be used for production. Some mines are water deficient, necessitating the import of water from offsite.

Mining, Processing, and Conveyance

Water use in mining operations can be divided into three categories: mining, processing, and mineral conveyance. In most types of mining, relatively little water is used in actual ore production. A notable exception is underground coal mining, where water is used as one of several measures to reduce the hazard of fires or explosions. Because of this, water and energy are related at the mine site in two ways. The rate of water use increases in rough proportion to the total energy used to operate mining machinery; since coal is mined for energy production, water use in underground coal mines might be roughly proportional to the energy equivalent of the coal. Most other types of mining use very little water in ore production, and will not be discussed in this context.

Many mined minerals are partially processed in the immediate vicinity of the mine site. The particle size of run-of-mine ore from hard rock mines often measures several inches to a foot along the longest dimension; thus particles must be reduced in size so that mineral values can be recovered in downstream processes. Water is used in crushing mainly for dust control. But screening, grinding, and milling can require significant amounts of water, depending on the scale of operation. Water use is not related directly to energy usage, but can be a function of the ore tonnage being processed, which *is* related to mill throughput. Hence, water use and energy are indirectly related.

Once ore is crushed (not needed for kaolin clay, which occurs naturally in finely divided form), the mined product can be transported through a pipeline as an aqueous slurry to a processing plant some distance away. Energy use is a function of the distance the slurry is transported, friction losses along the pipeline, and the volume and density of the slurry. Water use depends on the rheological (flow) properties of the slurry and, in some cases, the purity or contaminants in the water used to prepare the slurry. Therefore, energy is related to water use in transport of mineral products by virtue of energy required to pump mineral-containing slurries to a central processing location.

6.1.3 Water Use Practices and Challenges in the Industry

Regional climatic conditions, the type of mineral being mined, the processes being operated at the mine, and local regulatory considerations all affect whether water is viewed as a valued resource or as a nuisance that requires management and disposal. Most mining operations require at least a nominal quantity of water with which to perform critical operations such as drilling, dust control, and minimal ore processing.

Many water uses are insensitive to water quality, merely requiring a nominal volume with which to perform essential operations. Other uses, typically mineral concentration based on flotation, might dictate that certain minimum standards of quality be maintained to recover economic percentages of mineral values at sufficient grade to keep the mine profitable. A comprehensive discussion of these issues is beyond the scope of this discussion and is highly site specific.

Most mining operations reuse water to the extent possible, within constraints imposed by quality requirements, water availability, and discharge consideration. Surplus water from precipitation or from the mine is discharged, if it is not needed to operate the mine and associated crushing and grinding systems.

Transport of mineral products long distances through conveyance pipelines can cause water resources at the point of origin to become depleted, and introduce contaminants into the water during conveyance that makes the water undesirable at the final destination. This can occur with coal, for example, with the leaching of common salts, boron, heavy metals, fluoride, and other undesirable constituents. Water that accompanies coal through long-haul pipelines is not normally returned to the point of origin to be reused for additional coal shipments because of the cost of constructing a second, parallel pipeline, and because contaminants leaching from the coal would accumulate after many cycles of reuse. This controversial issue has been under study for many years in certain parts of the country, and could again warrant reevaluation in the western United States.

7.1 Petroleum Industry

Contributed by Gary Giesbrecht, in CH2M HILLs Calgary, Alberta, office

7.1.1 How Water is Used in the Petroleum Industry

Overview

Water use in petroleum refining occurs in two main areas: steam production and cooling service. Some water is also used to remove water soluble inorganic compounds from hydrocarbon streams. Steam is sometimes used in direct contact with hydrocarbons, which results in production of process wastewater.

Cooling water makeup and boiler feedwater makeup each typically account for about 40-45 percent of the total water consumption, with utility water and potable water making up the balance. In terms of actual end use, process water demands are often satisfied with steam condensate, which translates into an increase in boiler feedwater makeup rate. Process wastewater originates primarily from steam or condensate used in direct contact with the process stream or as cleaning or flushing water. Most of the water consumed is lost through evaporation, with only about 20 percent discharged as wastewater. Process wastewater typically accounts for about two-thirds of the wastewater and cooling tower blowdown about one-third. These water and wastewater rates apply to refineries that use closed circuit cooling water systems and that are located in temperate regions of North America. Refineries that use once-through cooling or that are located in areas with extremes of temperature or humidity have different rates.

Typical Refinery Water Uses

The flow of water through a typical refinery is shown in Figure 7.1-1.

Consumptive uses

Consumptive use of water means water that is drawn from the local source (river, lake, well, or municipal supply) and not returned. It is either put into the final products, or it is loss to the atmosphere through evaporation.

The total amount of water used in refineries in 1992 was estimated by one source to average 65 – 90 gallons of water per barrel of crude oil (Energetics, 1998). An extensive CH2M HILL study of a major refinery and petrochemical complex identified the distribution of water uses as shown in Figure 7.1-2.

Evaporative losses account for essentially all of the consumptive use in petroleum refining—representing loss of both water and energy, as process cooling constitutes rejection of energy.

In a plant where energy efficiency is maximized, heat rejected from the process at one temperature is used in another process. When no further application of low temperature energy exists, the excess heat is rejected to the atmosphere. Some heat is rejected by direct transfer to the atmosphere through air fin cooling, while the rest is rejected through a cooling water system. Conditions that favor air fin cooling are high process temperature relative to atmospheric dry bulb temperature and limited availability of water for cooling. Process and environmental conditions specific to each site determine the amount of air cooling versus water cooling used, however cooling water represents a significant water use at all sites. In a typical open cycle cooling water system, the cooling towers produce the evaporative losses. As shown in Figure 7.1-2, makeup of water to the cooling towers can represent nearly half of the water demand in a refinery. A small additional evaporative loss occurs when steam leaks from equipment or piping or is vented to remove non-condensable gases.

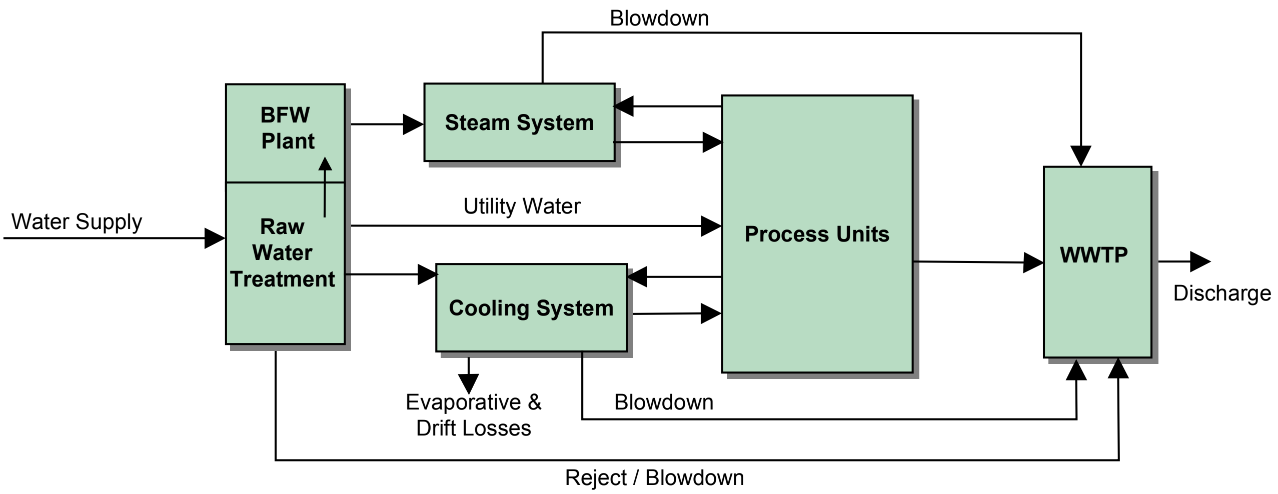


FIGURE 7.1-1
Flow diagram showing the flow of water through a typical North American refinery that uses a closed circuit cooling water system.

Return Flow

Return flow refers to water that is drawn from the local source, used in the production process or in utility functions such as heating or cooling, and then returned to the local source (river, watershed or aquifer). The net water drain on the local environment is zero; however, water quality might be affected.

Contact Water

This is water that comes into contact with the product, and has product or process residuals in it when it is returned to the environment. Contact water originates with crude desalter units and direct steam contact in steam distillation units. All wastewater from the refinery process units has contact or potential contact with the product, either as part of the process or incidentally from its use as flushing and cleaning utility water or as runoff from process areas and contact with leaked or spilled product.

Crude Desalter

Water is used to extract water soluble inorganic compounds from the crude oil to prevent catalyst poisoning later in the process. Salty wastewater is also contaminated with water soluble organic compounds.

Quench Water

Some hydrocarbon reactions require a sharp drop in temperature as part of the process, in order to achieve good selectivity for particular products of reaction. In such cases, a circulating stream of direct contact cooling water, termed “quench water,” is used to achieve the required temperature drop. This water is in direct contact with the product, and a portion

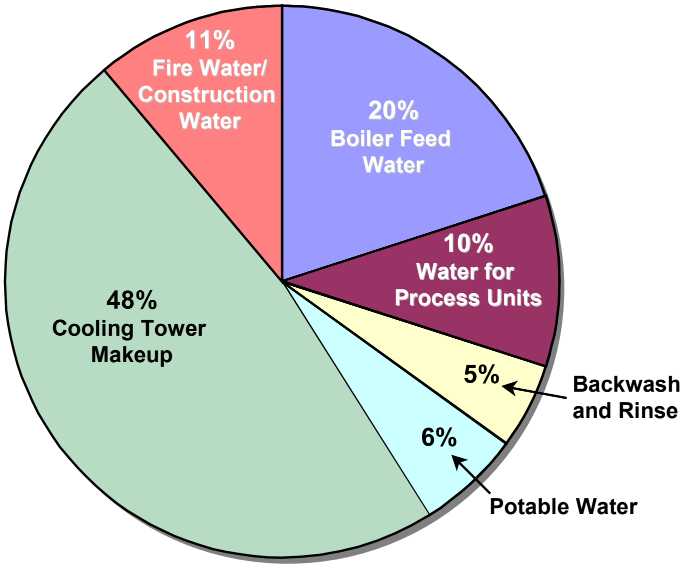


FIGURE 7.1-2
Distribution of major water uses at a large refinery and petrochemical complex (source: confidential CH2M HILL project).

of it is blown down to wastewater to maintain the quality of the circulating water.

Alkylation Wastewater

In alkylation units, a solution of potassium hydroxide is used to extract the hydrofluoric acid catalyst from the hydrocarbon stream. The spent potassium hydroxide (KOH) stream is usually neutralized and discharged, although new processes to recover the fluoride and recycle the wastewater are being implemented.

Steam Distillation

Steam is used in multi-component distillation to improve the separation of the various hydrocarbons. Water is separated from the overhead stream immediately after the overhead condenser and is discharged as process wastewater.

Cooling Water Leaks

Anytime the cooling water pressure is greater than the process pressure in a heat exchanger, internal leaks in the exchanger result in water entering the hydrocarbon stream and being discharged as process wastewater at the next separation point downstream. Leaks from the process into the cooling system will result in oily cooling water, which must be separated and would normally be diverted to the wastewater system.

Non-Contact Water

This is water that does not contact the product and does not contain product/process residuals, but it often is altered in other ways (residual heat in non-contact cooling water is common). This water could be used to aid the production process, or serve a utility function, such as plant heating or cooling.

Wastewater that has not contacted hydrocarbon product, but has nonetheless been altered significantly in composition includes boiler blowdown and cooling tower blowdown. Boiler blowdown is often used to supplement cooling tower makeup water or is discharged to the refinery wastewater treatment system. Cooling tower blowdown normally contains only the inorganic constituents of the makeup water at increased concentrations and is commonly discharged without treatment, subject to confirmation of the absence of toxicity concerns from the cooling water treatment chemicals.

Once-through Cooling Water

Refineries located close to large bodies of fresh water or to the ocean, particularly older facilities, often use water directly from the source for cooling and then discharge the heated water back to the same body of water. In theory, it is non-contact water; however; there is always a possibility of leaks from the process to the cooling water. In addition, the discharged water temperature can be a concern with respect to environmental conditions at the discharge point.

Potable and Sanitary Systems

As for any large workplace, potable water is normally supplied to the offices, control rooms, maintenance areas, locker rooms, and anywhere else personnel are expected to spend any significant time. The water balance and wastewater characteristics are similar to potable water and sanitary wastewater anywhere and the volumes involved depend on the number of staff and the time they spend at the location.

Most refineries send sanitary wastewater to the local municipality to be treated separately from process wastewater, however in some refineries, sanitary wastewater is treated together with process wastewater in a biological treatment system. From a treatment perspective, this can work well, as the treatment process is similar and refinery effluents are often too dilute to sustain the biomass. The barrier to combined treatment consists mainly of the potential for the presence of pathogens in the sanitary waste. Adding a small flow of sanitary waste to a process wastewater treatment system may make it necessary to disinfect the entire stream before discharging it to a receiving body of water or to certain reuse applications.

Quantities and Flow-through (Wastewater) Produced

A report prepared for the U.S. Department of Energy (Energetics, 1998) summarizes wastewater quantities and flow produced from various refining operations, using information from effluent limitations given by the U.S. Environmental Protection Agency (EPA) in 40 CFR, Part 419, originally promulgated in 1974. Table 7.1-1 summarizes wastewater generation by refinery unit.

7.1.2 Water Reuse Opportunities

Steam Systems

Water is used in steam systems as a heat transfer fluid and is reused within the steam system as much as is economically feasible. Most steam is used in non-contact applications, such as indirect heat transfer and turbine drives, with the resulting condensate collected and returned for use as boiler feedwater. Water is lost through steam and condensate leakage, poor steam trap maintenance, and venting to remove non-condensible gases from the steam system. In some situations, such as steam used for tank heating in large tank farms that are dispersed over a wide area, condensate return is not economically feasible because of low flows and long distances. In these situations the condensate is lost. In some situations, an imbalance between steam requirements at various pressures and process heating loads or steam condensers can result in a need to vent steam, which is lost to the atmosphere. Where steam is used in direct contact, such as steam distillation, the condensate is not returned to the boilers. Water used for steam production must be low in dissolved contaminants, with the degree of purity depending on the boiler pressure. Since removal of dissolved material from boiler feedwater is never perfect, a small flow of water (blowdown) is discharged from the boilers to maintain the boiler water within design specifications for purity.

Because of the stringent quality requirements for boiler feedwater, steam systems are one of the least attractive options for reuse of wastewater, except for the internal reuse just described. Rather, contaminated or potentially contaminated steam condensate is a good source of water with low total dissolved solids (TDS) for applications such as crude desalting. Boiler blowdown, although it is contaminated relative to boiler feedwater, is a good source of water for reuse where low to moderate levels of TDS are not a problem. Use of blowdown from high-pressure boilers as feed for medium- and low-pressure boilers in a cascade mode is also a potential reuse option.

Cooling Systems

A cooling water system typically has a high recirculation rate through the network of heat exchangers in the process units, back to the cooling towers, where the heat is removed by evaporative cooling, and then again to the heat sources. Heat is removed from the cooling water partly as sensible heat, but mainly through evaporation. The evaporative losses are by far the largest consumptive use of water in a petroleum refinery. Recent refinements to cooling tower design shift the heat balance toward a greater amount of sensible heat transfer and a smaller amount of latent heat transfer, which results in a smaller evaporative loss for the same cooling duty.

The composition of cooling water is subject to a considerable number of constraints to prevent corrosion, scale deposition, biological fouling, and solids deposition throughout the cooling system. In addition, cooling water is treated with one or more biocides and scale inhibitors for the same reasons. A portion of the cooling water (blowdown) is wasted, in order to limit the buildup of dissolved species caused by the removal of water through evaporation.

As a large net water user with relatively flexible quality specifications, cooling water makeup is a prime candidate for reusing water from other

TABLE 7.1-1
Refinery Wastewater Flows

Process	Process WW Flow (gal/bbl of oil)	Comments
Crude distillation (atmospheric and vacuum)	26.0	Largest source: oily sour water from the fractionators (hydrogen sulfide, ammonia, suspended solids, chlorides, mercaptans, phenol
Fluid catalytic cracking	15.0	Largest source: sour wastewater from the fractionator/gas concentration units and steam strippers (high levels of oil suspended solids, phenols, cyanides, H_2S, NH_3)
Catalytic reforming	6.0	Process wastewater (high levels of oils, suspended solids, low hydrogen sulfide)
Alkylation	2.6	Wastewater from water-wash of reactor hydrocarbon products (suspended solids, dissolved solids, hydrogen sulfide) and spent sulfuric acid. Spent sulfuric acid – 13-30 lbs/bbl alkylate
Crude oil desalting	2.1	Largest source: hot salty process water (hydrogen sulfide, ammonia, phenol, suspended solids, dissolved solids
Visbreaking	2.0	Largest source: sour wastewater from the fractionator (hydrogen sulfide, ammonia, phenol, suspended solids, dissolved solids)
Catalytic hydrocracking	2.0	Largest source: sour wastewater from the fractionator and hydrogen separator (suspended solids, H_2S)
Coking	1.0	Largest source: coke-laden water from decoking operations in delayed cokers (hydrogen sulfide, ammonia, suspended solids). Fluid coking produces little or no effluents.
Isomerization	1.0	Sour water (low hydrogen sulfide, ammonia), chloride salts, and caustic wash water
Ethers manufacture		Pretreatment wash water (nitrogen contaminants); cooling and alcohol wash water are recycled
Catalytic hydrotreating	1.0	Sour wastewater from the fractionator and hydrogen separator (suspended solids, H_2S, NH_3, phenols
Sweetening/Merox process		Little or no wastewater generated
Sulfur removal/Claus process		Process wastewater (hydrogen sulfide, ammonia)
Lubricating oil manufacture (deasphalting, solvent extraction, de-waxing)		Steam stripping wastewater (oil and solvents), solvent recovery wastewater (oil and propane)

Source: Energetics, 1998. "Industrial Water Use and Its Energy Implications."

sources. Boiler blowdown, treated wastewater from either the refinery wastewater treatment plant or from a municipal treatment plant, and storm water runoff are all potential sources of cooling tower makeup.

Process Operations

There are several opportunities for water reuse within the hydrocarbon processing units. Potentially oily condensate is suitable for use as desalting wash water. Stripped sour water from hydrotreating units typically has a high concentration of phenolic compounds, which are returned to the crude, if the stripped sour water is used for desalter water makeup.

7.1.3 Water Use in Exploration and Production

Overview

Water use in the exploration and production sector of the petroleum industry is negligible, with two exceptions, both in the field of enhanced oil recovery (EOR), which refers to processes used to remove more oil from the reservoir than what is possible by pumping only. Two specific EOR processes that are very water intensive are waterfloods and steamfloods.

Waterflood

A waterflood is an oil recovery technique that involves pumping water into an oil producing reservoir to replace oil that has been removed by primary production. The water serves, first, to fill the voidage and maintain the reservoir pressure, and second, once the water appears at the producing wells, to sweep unrecovered oil through the reservoir toward the producing wells.

At the surface, the produced water is separated from the oil and reinjected into the reservoir. A typical waterflood requires 100 percent makeup from other sources during the initial operation. As production proceeds, the amount of water produced increases and the demand for makeup water decreases. In some fields, the water-to-oil ratio can be as high as 10 or 20 to 1.

Water quality requirements for waterflood application are not stringent except on a few points. Suspended solids must be removed to quite low levels, depending on the permeability of the reservoir. Oxygen must be removed to prevent corrosion of the well tubing. The water must be rigorously disinfected to prevent the ingress of sulfur reducing bacteria.

Waterflood makeup water is a major opportunity for water reuse. Several floods use treated municipal effluent for makeup water. Brackish non-potable groundwater and seawater are used in a number of applications, and high TDS wastewater would be a natural fit. A major barrier to reusing wastewater is the fact that many oil producing fields are not close enough to a suitable source of wastewater.

Steamflood

A steamflood is an oil recovery technique applicable to production of heavy crude (API 15 or lower) that is too viscous for reasonable recovery by simple pumping. Other heating methods are possible, but steam injection is by far the most common. High-pressure steam is injected into the oil bearing reservoir where it heats both the reservoir rock and the oil in it. The heated oil is much less viscous. Together with the condensed steam, it flows to production wells where it is brought to the surface with pumps, gas lift, or steam lift.

At the surface, the hot fluids (produced fluids) are separated, and the water fraction (produced water) is treated and reused to produce steam. Steam (for re-injection into the formation) at some facilities is raised from water of other origins, such as treated municipal effluent and brackish groundwater. Small development projects typically dispose of the produced water and use fresh water to raise steam. At most projects, steam is produced in a once-through oil field boiler at 80 percent quality (i.e., 80 percent vapor phase, 20 percent liquid) and injected as wet steam, or separated so that only the vapor phase is injected and the liquid phase is disposed of after recovery of the associated heat. Disposal of the liquid phase is typically by subsurface injection into a brackish aquifer or depleted oil reservoir. Depending on the nature of the reservoir rock and the technique used to contact the reservoir with steam, the produced water ranges in dissolved solids concentration from 2,000-3,000 mg/L to 8,000-10,000 mg/L, or even higher. Dissolved silica is typically present in concentrations of 200-300 mg/L as SiO_2. Once through boilers are used because they can tolerate high TDS concentrations and some dissolved silica, however water treatment is still a high cost component of the production facilities. Makeup water from another source is required to start up the process, to compensate for water retained in the reservoir and for wastewater that cannot be reused.

7.1.4 Relationship of Water to Energy

Water Use and Associated Energy Costs

The major use of water in a refinery is for energy transport, either in the steam system or the cooling water system.

Steam Generation, Distribution and Use
Water is used to transfer heat from fuel or process heat sources to a wide variety of energy users. Losses occur at a number of points; wastewater from the water treatment system, leaks of water or steam throughout the system, deliberate discharge of contaminated condensate, steam vents, and at locations where recovery of steam condensate is simply not economic. In general, the amount of water lost will be in proportion to the thermal duty of the steam system. Factors other than system size that will influence the amount of water lost include:

- The quality of the water source and the treatment processes used will affect the amount lost as wastewater.
- The cost of energy will influence how much maintenance is done to prevent steam and condensate leaks and the investment made to recover small condensate flows.
- The age of the facility will influence the cost of maintenance and therefore the effectiveness of leakage control measures.

Since water and steam in a steam generation and distribution system is quite pure, steam leaks could be considered a return of clean water to the environment at the atmospheric vapor portion of the hydrologic cycle.

Cooling Water Systems
The consumptive use of water in cooling systems is tied closely to energy efficiency with an inverse relationship. Virtually all consumptive use is evaporative loss, and all cooling loads represent lost energy. The latent heat of water evaporation is approximately 1,000 BTU/lb, so in round numbers, every gallon of water evaporated is equivalent to 8,300 BTU or 2.4 kWh of lost energy.

Evaporative loss is also at return to the hydrologic cycle at the atmospheric vapor point and does not carry contamination with it. Drift loss does carry contamination with it and and is difficult to control after it leaves the tower. Cooling towers are now being designed to minimize drift loss.

7.1.5 Water Reuse Practices and Challenges in the Industry

Overview of Water Reuse Practices and Challenges

Water reuse planning in the petroleum industry is moving from water management plans that rely on consumption of raw water and discharge to the environment to plans that incorporate higher utilization efficiencies. Strategies for tightening up the water balance include:

- Internal treatment and reuse of wastewater
- Design of cooling towers to increase sensible heat transfer and thereby reduce evaporative losses
- Treatment of cooling water makeup or sidestream to minimize the amount of blowdown required
- Increased use of wastewater from external sources for water supply

The practice of using water evaporation as a final heat sink results in not only the largest net water consumption rate, but also the biggest challenge for the internal recycling of wastewater. As water evaporates, contaminants accumulate in the remaining water in the system and must be removed. Suspended material can be filtered out and calcium and magnesium salts can be removed by precipitation. However, sodium chloride and sulfate and other highly soluble salts can be removed only by very expensive and energy intensive means, such as evaporation. Membrane processes can concentrate these highly soluble salts, but not remove them. The use of evaporative cooling therefore results in the discharge of saline wastewater to the surface or to a suitable deepwell disposal formation, or in the accumulation of waste salt on the surface, no matter how thorough the treatment for other contaminants and the internal recycling of water.

Case Study

A good example of how water management strategies in petroleum refining are changing can be found in a recent refinery expansion. In this case, a refinery originally built in the 1950s was being modified to accept a higher American Petroleum Institute (API) gravity feedstock, reduce the sulfur in gasoline and diesel fuel products, and expand overall capacity. The refinery is situated near a major river and a city with a population of approximately 1 million.

Figure 7.1-3 shows the major water flows for the existing refinery, before the expansion and before a new water management plan took effect.

In addition to the usual objectives of low cost, reliable, safe operation, etc., objectives for the revised water management plan included the following, in spite of a major increase in the steam rate and cooling load.

- Remain within the existing water withdrawal licensed volume
- Remain within the capacity of the existing subsurface injection well capacity
- Be confident of being able to obtain a wastewater discharge permit

The planned expansion includes the following water management items, intended to minimize the use of river water and to limit the amount of deepwell disposal.

Demineralization of all boiler feedwater, via a system based on reverse osmosis (RO), to meet 1,500 psi specification, improve the operation, and reduce the amount of blowdown from the 600 psi boilers

- Softening of the RO reject stream from boiler feedwater treatment for use as cooling tower makeup
- Use of deepwell disposal for high TDS wastewater only.

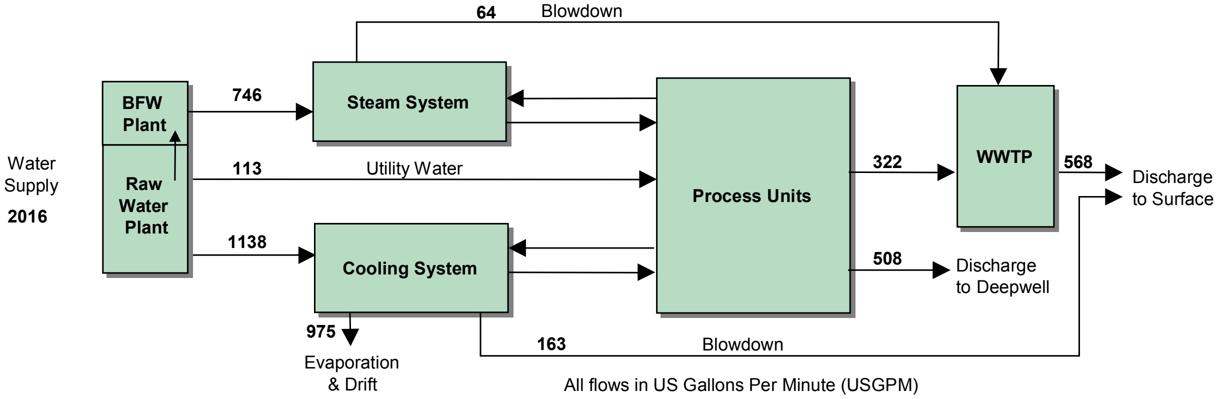


FIGURE 7.1-3
Flow diagram showing the flow of water through a typical North American refinery that uses a closed circuit cooling water system

- Major upgrade of refinery wastewater treatment system.
- Reuse of refinery effluent as cooling tower makeup water.

Figure 7.1-4 shows the major flows after the expansion and implementation of the revised water management plan. Even with a significant increase in plant capacity, and a change of product mix, the increase in total water use was minimized, and surface water discharge was reduced.

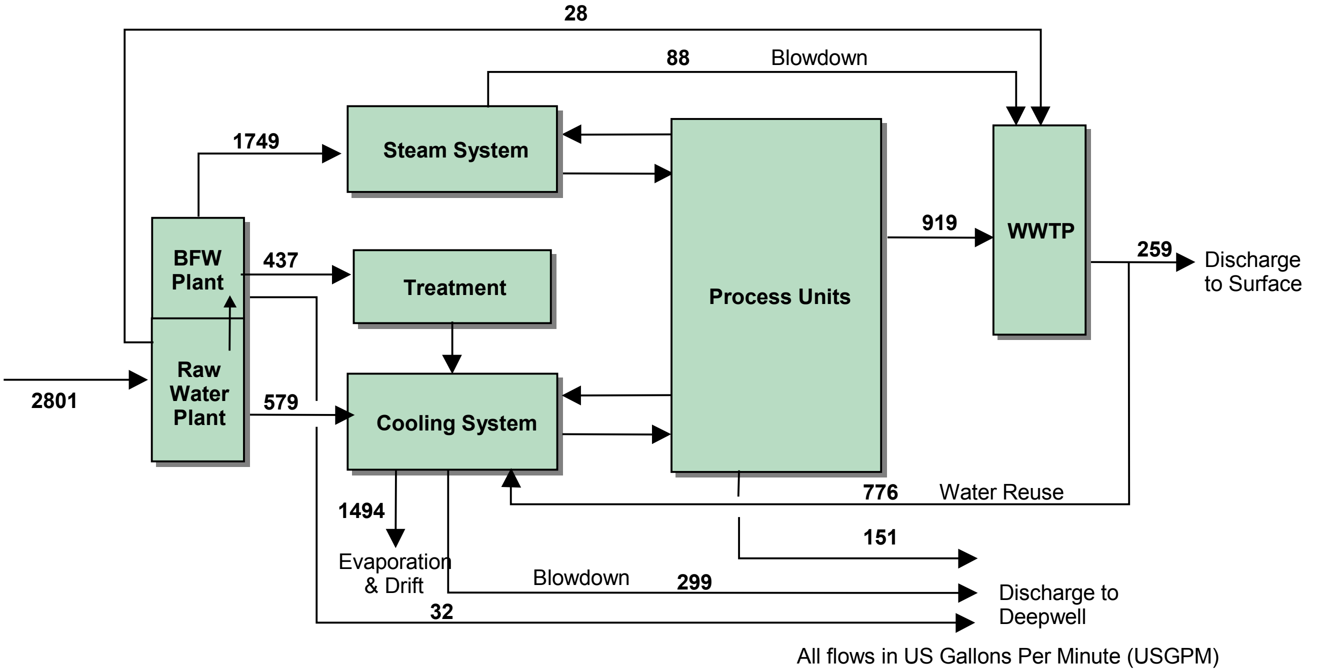


FIGURE 7.1-4
Major water flows for the expanded refinery, after implementation of a new water management plan.

8.1 Steel Industry

Contributed by Rick Johnson, in CH2M HILL's Herndon, Virginia, office

8.1.1 Steel Industry Overview

Steel is an industry in evolution from large, integrated, multiple-product facilities to smaller facilities focused on specific products or markets. The energy intensity of the steel industry has been steadily decreasing since 1950 (Stubbles, 2000). Independently, the water use intensity of the steel industry has also been decreasing, principally because water is being recycled in the production facilities (AISI, 2001). Increasing demands for water resources will make continued recycling of water a business imperative in the steel industry as well as other basic industries.

The steel industry can be categorized into three types of facilities:

- Integrated mills, which use ore, coke, limestone, energy, and water to make multiple products for a wide variety of markets
- Minimills, which use scrap steel to make a narrow list of products for multiple markets
- Finishing mills , which use intermediate steel products to make products for focused markets

8.1.2 Water Use in Various Steel Industry Operations

Table 8.1-1 shows the various unit operations that make up the steel industry universe. Integrated mills may have all of the operations listed in the table. Minimills, as constructed in the late 20th century, are built around an electric arc furnace melt shop, a caster, and rolling mills to produce plate products; structural products; bar, rod, and wire products; and flat-rolled products for the construction market. Finishing mills generally buy hot- or cold-rolled flat steel products and then form or coat products to meet market demands.

The water use patterns in these operations vary considerably, depending on process requirements. Water is used in the steel industry for three purposes:

- Material conditioning. Water is used for dust control in sinter feeds, slurrying or quenching dust and slag in blast furnaces, mill scale removal in hot- rolling operations, solvent for acid in pickling operations, or rinsing in other rolling operations.
- Air pollution control. Primary operations, particularly in integrated mills, use water in wet scrubbers for air pollution abatement. Water is also used for acid control in pickling operations and for wet scrubbers in coating operations that have caustic washing operations.
- Heat transfer. Primary iron- and steelmaking processes require heating the raw materials beyond the melting point of iron, in the range of 2,600 – 3,000 degrees Fahrenheit (°F), while hot-rolling operations require heating the materials to 2,100 - 2,300 °F. The equipment used for processing is protected by a combination of refractory linings and water-cooling of the refractory and shell of the equipment. Coke oven gas, blast furnace gas, and the offgas from basic oxygen furnaces and electric arc furnaces must be treated to remove air pollutants. In the case of coke oven gas and blast furnace gas, this is generally accomplished by using the gases as process fuels and alternatives to fossil fuels in boilers for cogeneration of steam and electricity. Heat transfer applications account for the largest use of water in integrated steel plants.

TABLE 8.1-1
Water Use for Various Unit Operations in the Steel Industry

Process Area	Material Conditioning	Air Pollution Control	Heat Transfer	Unit Energy Consumption (Stubbles, 2000)	Recycled/ Reused Fraction
Cokemaking	200 gallons per ton coke	250-300 gallons per ton coke	8,000 - 8,500 gallons per ton coke	5.1 MM BTU/ton coke	0% (newer plants may recycle cooling water)
Boilers for Converting Coke Oven Gas, Tars, and Light Oils			40,000 - 120,000 gallons per ton coke	7.5 MM BTU/ton coke exported energy in the form of gas, tars, and light oils	Varies depending on the age of the boilers
Sinter Plant	20 - 30 gallons per ton sinter	900 - 1,000 gallons per ton sinter	200 gallons per ton sinter	2.2 MM BTU/ton sinter	80%
Blast Furnace	100 - 200 gallons per ton molten iron	800 – 1,000 gallons per ton molten iron	2,500 – 3,000 gallons per ton molten iron	15.48 MM BTU/ton molten iron	90%
Boilers for Converting Blast Furnace Gas			20,000 - 60,000 gallons per ton molten iron	3.2 MM BTU/ton molten iron exported in the form of blast furnace gas	Varies depending on the age of the boilers
Basic Oxygen Furnace	100 - 200 gallons per ton liquid steel	800 - 1,000 gallons per ton liquid steel	2,500 – 3,000 gallons per ton liquid steel	1.17 MM BTU/ton liquid steel	50%
Direct Reduced Iron Processes	70 - 80 gallons per ton iron	negligible	200 - 250 gallons per ton iron	8.3 MM BTU/ton iron	~80%
Electric Arc Furnace	negligible	negligible	2,000 – 2,500 gallons per ton liquid steel	5.65 MM BTU/ ton liquid steel	80%
Continuous Caster	negligible	negligible	3,000 – 3,500 gallons per ton cast product	0.15 MM BTU/ton cast steel	70%
Plate Mill	1,000 – 2,000 gallons per ton plate	negligible	7,000 - 8,000 gallons per ton plate	3.0 MM BTU/ton plate product	30%
Hot Strip Mill	400 - 600 gallons per ton hot rolled strip	negligible	7,000 - 8,000 gallons per ton hot-rolled strip	2.2 MM BTU/ton hot-rolled strip	60%
Pickling	30 - 40 gallons per ton steel pickled	80 - 100 gallons per ton steel pickled	20 - 30 gallons per ton steel pickled	0.20 MM BTU/ton steel pickled	70%
Cold Rolling	50 - 100 gallons per ton cold- rolled strip	negligible	2,500 - 3,000 gallons per ton cold-rolled strip	4.2 MM BTU/ton cold-rolled strip	90%
Coating	60 - 70 gallons per ton coated steel	1 - 10 gallons per ton coated steel	1,200 - 1,800 gallons per ton coated steel	5 - 8 MM BTU/ton coated steel, depending on process and product	80%

MM BTU/ton = million British thermal units per ton.

Source: Compiled CH2M HILL client project data

Overall, approximately 12 percent of the water use is for material conditioning, 13 percent is for air pollution control, and 75 percent is for heat transfer, which does not include the water requirements for the boilers. The fraction of the water recycled varies from operation to operation, but it may be as much as 90 percent for some operations.

Not all integrated mills have all of the operations listed in Table 8.1-1; for instance, sinter plants have been disappearing for economic reasons.

Coke ovens produce by-product gas and liquids from the destructive distillation of coal. These by-products have considerable energy value. The liquids used to have considerable value as chemical products or raw materials for pharmaceuticals, dyestuffs, or resins. The market for the coal tars and light oils has been overtaken by the production of similar products from oil refineries (AISI, 2001). The production of coke will require that the by-products be treated or consumed as raw materials and not released to the environment. For the purposes of this study, it is assumed that the by-products are consumed in boilers for the production of electric power or steam. Similarly, blast furnaces produce a by-product gas that must be treated or consumed and not released untreated to the atmosphere. For the purposes of this study, it is assumed that this gas stream is used as low-heating value fuel in heat recovery boilers for the production of electric power or steam. This is a simplified view of energy use and recovery practices that have been at the heart of integrated steelmaking for the past 100 years.

Steel Manufacturing Processes

Figure 8.1-1 provides a graphical overview of steel manufacturing processes:

Consumptive Uses

Evaporative Losses

Water is consumed in operations where the water is evaporated. These operations include slag quenching at blast furnaces and basic oxygen furnaces, coke quenching in coke ovens, spray chamber cooling at casters, and evaporation in cooling towers.

Water in Products

Water is not a part of steel products. Water is sold or transferred with spent pickle liquors.

Return-Flow Uses

Water is supplied to the unit operations in steel plants and recycled or treated and discharged. Water supply comes from surface water sources, groundwater sources, and--in one case--as treated water from a municipal sewage treatment plant. Water is used for heat transfer from the processes, for treating and washing product, and as a solvent for electrolytic plating operations.

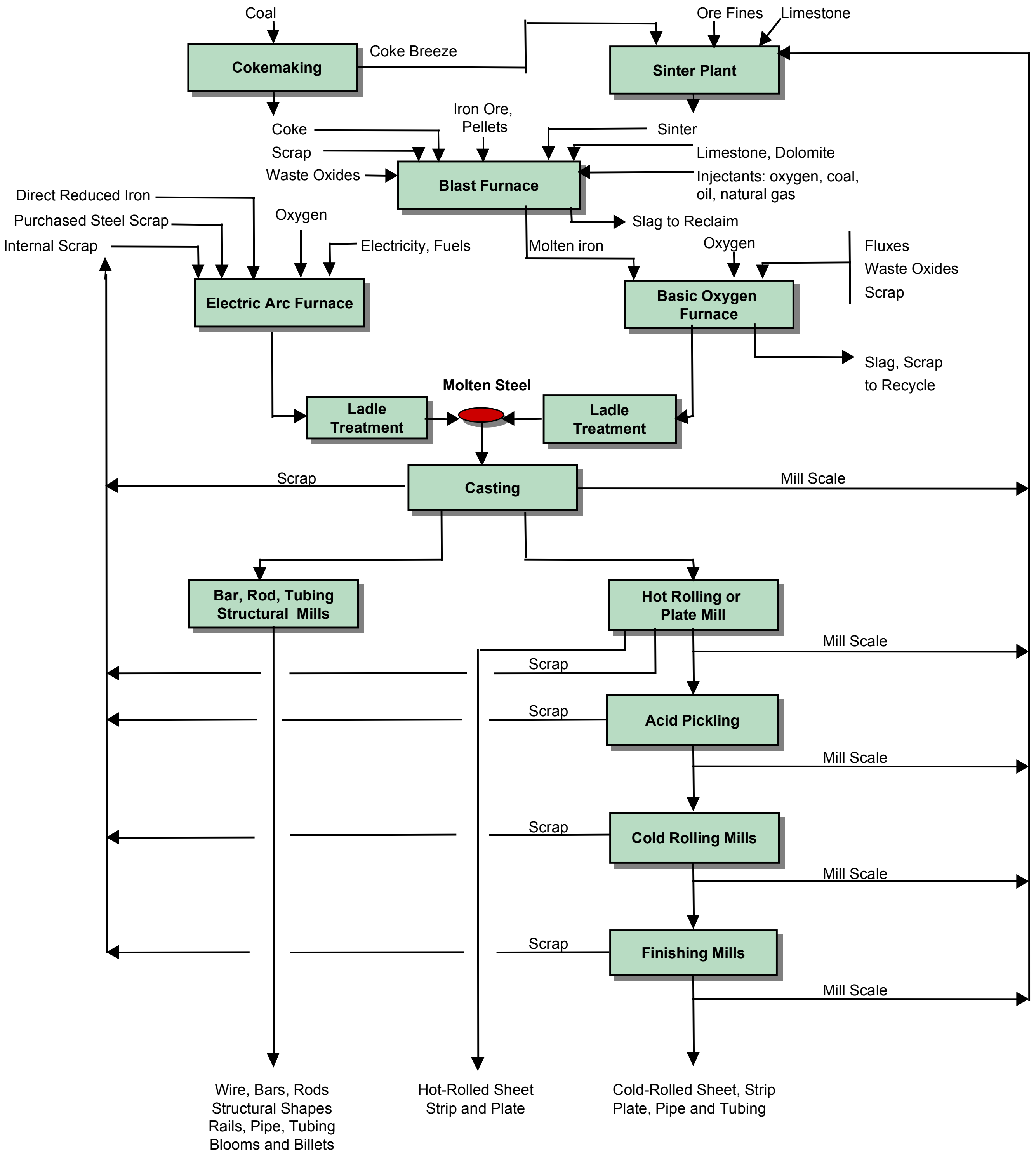
Contact Water

Water is used for contact cooling (quenching) in coke oven gas treatment, slag handling in basic oxygen furnaces, electric arc furnaces, continuous casters, scale breaking in hot-rolling operations, acid pickling, cold-rolling operations, caustic washing for coating lines, and to make up electrolytic solutions in tin-coating and chrome-coating lines. Water is also used in wet scrubbers for air pollution control in coke oven gas treatment, sinter plants, blast furnace gas treatment, basic oxygen furnaces, acid pickling, and coating operations.

Noncontact Water

Water is used in a series of heat exchangers in coke oven gas treatment, blast furnaces, basic oxygen furnaces, electric arc furnaces, hot-rolling operations, cold-rolling operations, boilers, annealing furnaces, and coating lines. This noncontact water is generally discharged separately from the process waters. Process waters require treatment before being discharged to receiving waters.

Table 8.1-2 shows a breakdown of contact and noncontact discharges and evaporative losses for steel-making operations



Source:
Adapted from U.S. Council on Wage and Price Stability, Report to the President on Prices and Costs in the United States Steel Industry, 1977 (COWPS, October 1977)
Reported in the Steel Industry Technology Roadmap, AISI, December 2001

FIGURE 8.1-1
Overview of Steelmaking Processing

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TABLE 8.1-2
Evaporation losses and discharges for various steel-making operations

Process Area	Makeup Water	Evaporation	Process Contact Water Discharge	Noncontact Water Discharge	Recycle Rate
Cokemaking	8,800 gallons per ton coke	230 gallons per ton coke	260 gallons per ton coke	8,310 gallons per ton coke	Negligible to significant, depending on the age of the plant
Sinter Plant	240 gallons per ton sinter	100 gallons per ton sinter	140 gallons per ton sinter	negligible	1,000 gallons per ton sinter
Blast Furnace	350 gallons per ton molten iron	70 gallons per ton molten iron	25 gallons per ton molten iron	260 gallons per ton molten iron	3,500 gallons per ton molten iron
Basic Oxygen Furnace	2,100 gallons per ton steel	120 gallons per ton liquid steel	140 gallons per ton liquid steel	1,840 gallons per ton liquid steel	2,050 gallons per ton liquid steel
Direct Reduced Iron Processes	290 gallons per ton iron	20 gallons per ton iron	negligible	270 gallons per ton iron	~1,000 gallons per ton iron
Electric Arc Furnace	250 gallons per ton steel	negligible	negligible	250 gallons per ton steel	2,000 gallons per ton steel
Continuous Caster	1,000 gallons per ton cast steel	10 gallons per ton cast steel	10 gallons per ton cast steel	980 gallons per ton cast steel	2,200 gallons per ton cast steel
Plate Mill	6,700 gallons per ton plate	30 gallons per ton plate	2,300 gallons per ton plate	3,000 gallons per ton plate	2,700 gallons per ton plate
Hot Strip Mill	3,100 gallons per ton hot-rolled strip	30 gallons per ton hot-rolled strip	1,750 gallons per ton hot-rolled strip	15 gallons per ton hot-rolled strip	4,700 gallons per ton hot- rolled strip
Pickling	60 gallons per ton steel pickled	15 gallons per ton steel pickled	15 gallons per ton steel pickled	30 gallons per ton steel pickled	120 gallons per ton steel pickled
Cold Rolling	80 gallons per ton cold-rolled strip	4 gallons per ton cold-rolled strip	1 gallon per ton cold-rolled strip	75 gallons per ton cold-rolled strip	3,000 gallons per ton cold- rolled strip
Coating	250 gallons per ton coated steel	10 gallons per ton coated steel	60 gallons per ton coated steel	180 gallons per ton coated steel	1,400 gallons per ton coated steel

Source: Compiled CH2M HILL client project data

Water Use by Facility Type

The integrated mills use more water than the other facility types, minimills and finishing mills. This is because integrated mills start with the most basic raw materials (ore, coal, and limestone) and convert them to steel that is then processed into products.

Minimills use more water than finishing mills do because minimills start with scrap steel and convert it into steel to be processed into intermediate and final products. The amount of water will depend on the specific mill and capacity.

Finishing mills tend to use less water than either integrated mills or minimills because (1) the technology for recycling water is more amenable to the finishing mills and (2) the finishing mills start with an intermediate product that needs processing only into a specific shape or finish for the market.

Unit Operations That Use the Most Water

Figure 8.1-2 shows a breakdown of water use in the various steel-making unit operations that use the most water.

Steel industry operations tend to fall into three ranges for water use:

- Hot rolling (plate and strip) and cokemaking use water in the range of 7,000 to 9,000 gallons per ton of product, including both makeup water and recycled water.
- Blast furnaces, basic oxygen furnaces, electric arc furnaces, casters, and cold rolling use water in the range of 2,500 to 4,000 gallons per ton of product, including both makeup water and recycled water.
- Pickling, coating, and sintering use water in the range of 200 to 1,800 gallons per ton of product, including both makeup water and recycled water.

8.1.2 Relationship of Water to Energy

Each unit operation in the steel-making process exhibits a different relationship between water use and energy consumption. In some cases, there is actually an inverse relationship. For instance, reheat furnaces for hot strip mills have progressed from three-zone furnaces with a heat rate of 5 million British thermal units per ton (MM BTU/ton) of steel heated to eight-zone furnaces with a heat rate of 1.4 MM BTU/ton. The cooling requirements increase with each zone added, however, in order to protect the internal components of the furnace. In this particular example, the energy required now is only 28 percent of the 1980 requirement, but the cooling water requirement is 230 percent of the 1980 requirement. Similar experiences occur with the blast furnaces as more cooling is added to the shell of the blast furnace to extend the life of the linings at the same time that incremental improvements are made to the energy balance with coal injection, heat recovery, oxygen addition, and burden management to increase yields.

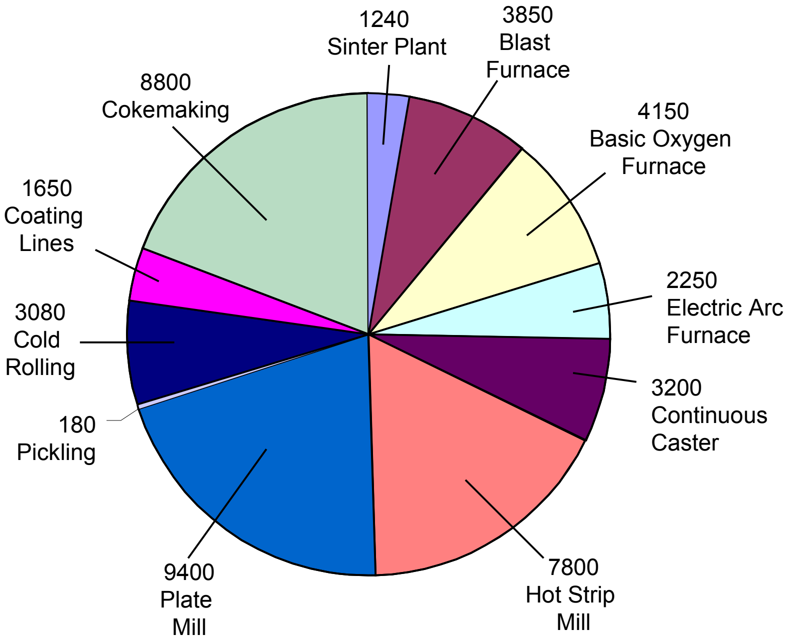

FIGURE 8.1-2
Water Use By Operation, Gallons per Ton of Production

In the transition from blast furnace and basic oxygen furnace combinations to electric arc furnaces with high scrap and supplemental supplies, the net energy and water consumption will decrease. The blast furnace - basic oxygen furnace combinations require a net use of approximately 2,400 gallons of water and 17 MM BTU/ton steel produced. the use of scrap steel in place of hot metal as feed to the basic oxygen furnace would reduce these ratios. If a direct reduced iron plant and electric arc furnace were coupled together with no scrap steel feed, the similar net usage rates would be approximately 550 gallons of water and 14 MM BTU/ton steel produced. The use of scrap steel as feed to the electric arc furnace would reduce these ratios.

The path to energy and water conservation in the steel industry is transformational in changing processes and not incremental in improving existing processes. This transformation is impeded by the current (calendar year 2002) worldwide over-capacity in steel production.

8.1.3 Water Reuse Practices and Challenges in the Steel Industry

Overview of Water Reduction and Reuse Practices and Challenges

In the steel industry, water is used primarily for heat transfer. Cooling towers minimize this water use. In some cases, closed-loop cooling systems have been used for heat removal from the process. Water has been supplied from a combination of surface water and groundwater withdrawal.

Future water supply may be in jeopardy from population pressures and competing demands. This situation may be mitigated by water reuse from treated municipal effluent or by increased internal treatment and recycling.

Process changes in steel production will reduce water demand; an example of such a change would be replacement of the cokemaking – sintering - blast furnace method with direct reduced iron processes for making iron as a raw material. Continuing replacement of the basic oxygen furnaces with electric arc furnaces has the potential to reduce water demand in the industry. This will be offset, however, by the water required for the alternative iron processes that will replace the blast furnaces and extend the scrap steel supply. Currently, the scrap steel supply is adequate for supplying minimills. This is likely to change in the future as blast furnaces are taken offline and not relined for economic reasons. Then an alternative iron supply will be required to supply the minimills.

Case Study Outline

Around 1950, the Sparrows Point Plant of the Bethlehem Steel Corporation was facing a shortage of water to support plant expansions to meet increasing market demands. The plant is located on a developed peninsula at the mouth of the Patapsco River east of Baltimore, Maryland. Water supply had been provided by a combination of groundwater wells and surface water withdrawal. The increased demands for cooling water and process water supply also required closer control of the quality and reliability of water supplied. Dissolved solids in the cooling water for new blast furnaces and hot strip mill reheat furnaces were becoming stringent limitations as these units operated hotter and with higher heat fluxes, making scale formation a more significant impediment to productivity. Increasing demand for cleanliness on the finished product as the product mix shifted from plate to hot- and cold-rolled flat, thin-section, strip was another market criterion that made dissolved solids and salts in the process water an increasing concern. The flows in the Patapsco River and Old Road Bay were not sufficient to support the increased demands for water, especially during dry years. The water from the Chesapeake Bay is brackish, with relatively high salt and carbonate concentrations. The next best choice appeared to be taking water from the rivers to the north of Baltimore, but the only river that appeared to have the capacity to supply the plant was the Susquehanna, which was also being developed for the Baltimore Department of Public Works as a drinking water supply for the expanding population of Baltimore City and Baltimore County.

Simultaneously, the Baltimore Department of Public Works was increasing treatment of the municipal water discharge plant at the Back River Waste Water Treatment Plant. The water discharge quality as designed was sufficient to provide a relatively low dissolved solids concentration. The discharged waters were filtered and disinfected sufficiently to make this water a potential source for heat transfer in the more demanding processes that were being developed at the time. The requirement for clean water for processes could be met by a combination of the effluent discharge and the treated potable water from the Baltimore Department of Public Works.

The final resolution was that the Sparrows Point Plant contracted for 160 million gallons per day of treated effluent from the Back River Waste Water Treatment Plant as a new industrial water supply. This water is monitored to meet the wastewater discharge criteria set by permits for the wastewater treatment plant. The water is delivered by pipeline to a pond where the water is inventoried and pumped to the users in the plant. Facilities are provided at the pond for bleach treatment (previously chlorine treatment) for algae control in the in-plant distribution system. This solution avoided the necessity of laying 60 miles of pipeline from the Susquehanna River and allocating water from the river, which has become a primary water supply for Maryland and Pennsylvania communities in the river basin (Mendelson and Hanson, 1996)

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