Report as of FY2006 for 2004IL56G: "Development of Water Use Benchmarks for Thermoelectric Power Generation in the United States"

Publications

- Articles in Refereed Scientific Journals:
  - Xiaoying Yang and Benedykt Dziegielewski. 2005. Water Withdrawals by Thermoelectric Power Plants in the U.S. Journal of the American Water Resources Association (Approved for publication, In press for 2006).
- Conference Proceedings:
  - Dziegielewski, Ben, 2005, "Altering Water Demands of Thermoelectric Power Generation in Proceedings of the XIIth World Congress on Water Resources, November 22-25, 2005, New Delhi, India. (Published in both hard copy book and CD-ROM proceedings).

Report Follows

EXECUTIVE SUMMARY

Water Use Benchmarks for Thermoelectric Power Generation

by
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Study Purpose

The purpose of this study was to examine water use at electric power plants in the United States and determine both the average rates of water withdrawals and consumptive use as well as the levels of water-conserving usage in the most water-efficient plants and cooling systems. The generalized water-use parameters represent benchmark measures of the quantities of water used by the different types of cooling systems and power plants. This was accomplished by exploring publicly-accessible thermoelectric water use data from the U.S. Department of Energy, Energy Information Administration (EIA), as well as by conducting on-site visits at power plants and completing a questionnaire survey of plant water managers.

Significance of Thermoelectric Water Use

Generation of electricity requires large quantities of water either for turning water turbines to generate hydroelectric power or for cooling and condensing steam in thermoelectric generation. Nearly 90 percent of generation capacity in the U.S. is in thermoelectric plants.

Precise estimates of the actual volume of water that is used to generate electricity at the national level are difficult to obtain. The U.S. Geological Survey's National Water Use Information Program (NWUIP) prepares nationwide compilations of all reported water uses, which are published every five years (Hudson et al., 2004).

The most recent USGS compilation reported that the combined country-wide water withdrawals by all sectors had increased since 1995 and in the year 2000 had reached an average daily volume of 408 billion gallons per day or 1,432 gallons per capita per day. Nearly 48 percent of all withdrawals, or 195.5 billion gallons per day, were for thermoelectric power generation, primarily to satisfy cooling requirements of power plants. Total utility-based generation of electricity in the year 2000 (not counting hydroelectric power) reached 2,762,200 million kWh, and required approximately 26 gallons per each kWh of generation. In per capita terms, total withdrawals for thermoelectric generation in the year 2000 amounted to 686 gallons per capita per day – more than four and a half times the per capita amount of all publicly supplied water for domestic, commercial and industrial uses.

Nearly 85 percent of all water withdrawals and nearly 70 percent of all thermoelectric withdrawals are obtained from the country's limited supplies of fresh water. In 2000, thermoelectric use accounted for nearly 40 percent of all freshwater withdrawals in the country, with the total freshwater withdrawals for the thermoelectric sector approximately

equal to those of the irrigation sector. Despite these high annual withdrawals for thermoelectric power generation, only a few studies of thermoelectric water demands have been conducted. The reason may be that unlike irrigated agriculture where most of the water is evaporated or lost, approximately 98 percent of water withdrawn by thermoelectric sector is returned back to the source.

However, even the "non-consumptive" withdrawals of water for thermoelectric power plants can have significant impacts on water resources. Power plants are the largest dischargers of thermal pollution that affects both aquatic ecosystems and evaporation rates. Also, the large quantities of water required for power generation must be continuously available for power utilities to provide reliable service to their customers. This quantity of water is therefore "reserved" for power generation and is not available to other user such as irrigators or public water suppliers

Average Rates of Water Use

The database used in the statistical analysis was developed primarily from the information in the Department of Energy's Form EIA-767, and contained 7,365 observations of estimated thermoelectric water withdrawals and consumptive use, for cooling systems in fossil-fuel plants, during the nine-year period from 1996 to 2004. A smaller number of observations was available for nuclear-powered plants because the annual EIA data reporting for this type of plants was discontinued after 2000, and the data were only available from 1996 to 2000.

In addition to the data on water withdrawals and consumptive use, five categories of likely determinants of cooling water withdrawals were included in the analysis: (1) cooling systems type; (2) fuel type; (3) operational conditions; (4) water sources; and (5) other relevant variables. Additional information about thermoelectric water use was obtained from site visits and interviews at five power generation facilities and questionnaire survey responses from 40 power plants.

Water withdrawals per unit of net generation of electricity were estimated from the EIA-767 data, and the average unit-use was calculated for ten different types or combinations of cooling systems. A review of the distribution of unit-use estimates determined that these calculated averages were significantly influenced by outlier values. The outliers were removed from the analysis and the mean values of water withdrawals for each cooling system type were recalculated (see Figure ES-1).

Unit withdrawals for once-through systems were estimated to range from approximately 50 to 65 gal./kWh; for closed-loop systems with cooling towers from 1.0 to 2.0 gal/kWh; and for recirculating systems with cooling ponds or canals and other mixed recirculating systems from 14 to 24 gal/kWh. Net generation weighted averages were also calculated for three general aggregations of the ten cooling system types for both fossil-fuel and nuclear plants. The resultant weighted average water use rates represent water use benchmark measures for these categories of cooling systems (see Table ES-1). Because of

the weighing by total (net) generation the resultant estimates tend to reflect water usage rates in larger plants.

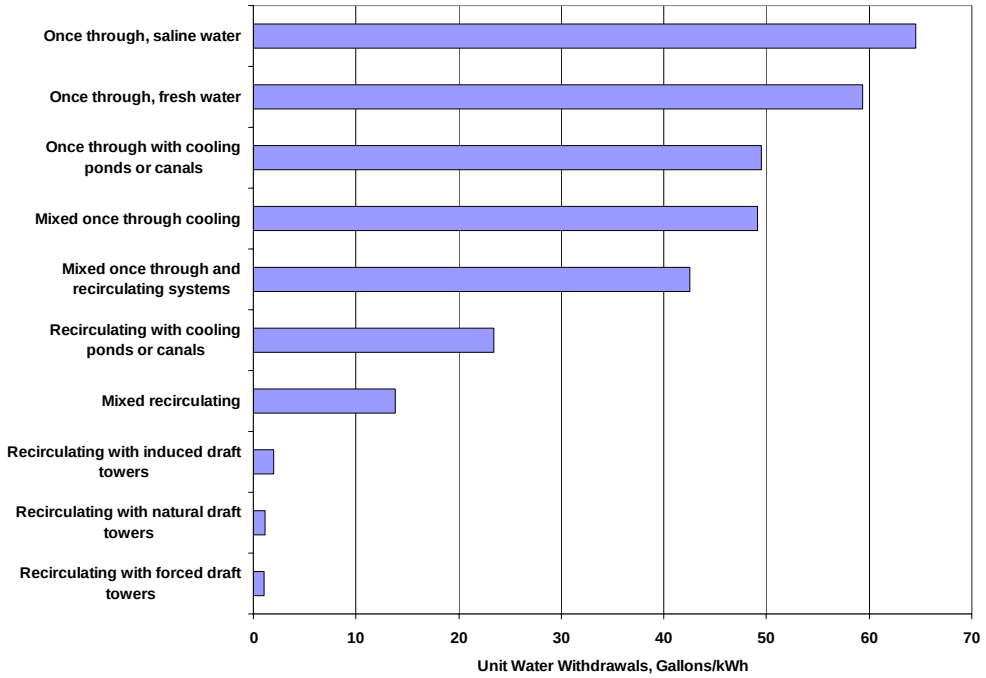

Figure ES-1. Average Rates of Unit Water Withdrawals in Different Types of Cooling Systems in Fossil-Fuel Plants

Table ES-1. Benchmarks of Weighted-average Use Rates of Cooling Water

Description	Withdrawals per unit (gallons/kWh)	Consumptive use (gallons/kWh)	Percent consumptive use (%)
Fossil fuel plants:			
Once-through systems	44.0	0.2	0.5
Recirculating systems with ponds	24.0	0.7	3.0
Closed-loop w/ cooling towers	1.0	0.7	70.0
Nuclear plants:			
Once-through systems	48.0	0.4	0.7
Recirculating systems with ponds	13.0	0.5	4.0
Closed-loop w/ cooling towers	2.6	0.8	30.0

Regressions of Water Use on Explanatory Variables

Ordinary least-squares regression procedures were used to identify the relationship between water withdrawals and various plant and cooling system characteristics. The resulting regression models demonstrated that unit water withdrawals are primarily a function of the operational efficiency (i.e., percent of capacity utilization), maximum temperature rise at the condenser, and, to a lesser extent, the age of the cooling system and thermal efficiency of the generators. The observed rates of water withdrawals were also found to depend on the type of water source and the type of fuel.

The estimated regression equations were used to calculate low, average, and high water rates for different types of cooling systems. The average water withdrawals and consumptive use were calculated by substituting the mean values of the continuous explanatory variables into the estimated regression equation (Table ES-2). The lowest value was calculated by combining the 90 percentile values for variables with negative coefficients and 10 percentile values for variables with positive coefficients. The reversed 10 and 90 percentile values were used to calculate the maximum value. Also, because some regression equations included binary indicator variables, the values in Table ES-2 apply to systems with only some water sources and fuel types as indicated in the footnotes under the table.

Table ES-2. Regression-based Benchmarks of Average Water Withdrawal Rates

Description	Minimum (gallons/kWh)	Average (gallons/kWh)	Maximum (gallons/kWh)
WATER WITHDRAWALS			
Fossil fuel plants:			
Once-through systems[a]	--	78	181
Recirculating systems with ponds[b]	19	53	91
Closed-loop w/ cooling towers[c]	0.4	1.2	2.4
Nuclear plants:			
Once-through systems	30	49	56
Recirculating systems with ponds[d]	--	0.8	2.2
Closed-loop w/ cooling towers[e]	0.9	1.5	2.3
CONSUMPTIVE USE			
Fossil fuel plants			
Once-through systems[f]	1.7	3.1	4.1
Closed-loop w/ cooling towers[g]	0.5	0.9	1.5

[a] Other than public water delivery or mixed water sources; [b] Other than recirculating systems w/ponds; [c] Other than mixed fuels with coal, petroleum as fuel, fresh groundwater source, or saline surface water source; [d] Other than surface freshwater source; [e] Other than saline surface water supply or induced air-flow tower; [f] Other than once-through freshwater systems or petroleum as fuel; [g] Other than mixed fuel w/ coal, or fresh groundwater source

The regression-based benchmarks for average water use in Table ES-2 differ from the weighted estimates in Table ES-1 (and are generally higher) because no weights were applied during the regression procedure, and because of the added regression effects of the fuel types

and water supply source. However, the estimates are generally consistent across the different types of cooling systems.

Technical Efficiency Estimates

The stochastic production frontier analysis of the data demonstrated that the estimated technical efficiencies of cooling system water use vary significantly, and are lower (on average) in fossil fuel plants than in nuclear power plants (Table ES-3).

Table ES-3. Technical Efficiency Estimates for Cooling Systems Based on Stochastic Production Frontier

Description	Minimum (%)	Average (%)	Maximum (%)
Fossil fuel plants:			
Once-through systems	22.5	52.9	91.6
Closed-loop w/ cooling towers	40.0	67.2	93.0
Nuclear plants:			
Once-through systems	44.0	69.6	100.0
Closed-loop w/ cooling towers	55.8	80.8	100.0

The mean technical efficiency in once-through systems is 52.9 percent for fossil-fuel plants and 69.6 percent for nuclear plants. Closed-loop systems with cooling towers were estimated to have mean efficiencies of 67.2 and 80.8 percent, respectively. This result suggests that nuclear plants tend to use cooling water more efficiently than fossil-fuel plants. Nevertheless, there is still a 20 to 30 percent theoretical potential for reducing water withdrawals at nuclear plants, and a 30 to 50 percent potential for reductions at fossil-fuel plants.

Recommendations

The results of this study indicate that the reported average rates of water withdrawals and consumptive use in thermoelectric power plants exhibit very high variability within the same cooling system type at different power generation facilities. While a part of this variability can be explained in terms of the system design parameters and operational conditions, a significant portion of the variability cannot be explained and can be attributed to inefficiency of using cooling water. The results of the stochastic frontier analysis conducted in this study indicate that water intake by thermoelectric power plants could be reduced on average between 20 and 50 percent depending on the type of plant and cooling system.

Further development and refinement of water-use benchmarks should be undertaken to facilitate the improvement of water-use efficiency in thermoelectric generation. Further studies should include the collection of data from a sample of “best performing” plants, which could be identified using the analysis presented in this study. The benchmark practices

at these facilities could serve as standards in the design and operation of wet cooling systems, and guide the process of gradual elimination of inefficient use of water in thermoelectric power generation.