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Technical Report

Consumptive Water Use for U.S. Power Production

P. Torcellini, N. Long, and R. Judkoff

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393

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Executive Summary

Evaporative cooling systems in buildings have been criticized for their water use and acclaimed for their low energy consumption, especially when compared to typical cooling systems. In order to determine the overall effectiveness of cooling systems in buildings, both water and energy need to be considered; however, there must be a metric to compare the amount of energy used at the site to the amount of water used at the power plant.

A study of power plants and their respective water consumption was completed to effectively analyze evaporative cooling systems. Eighty-nine percent of electricity in the United States is produced with thermally driven water-cooled energy conversion cycles. Thermoelectric power plants withdraw a tremendous amount of water, but only a small percentage is evaporated. The evaporative or consumptive use1 is approximately 2.5% or 3,310 million gal per day (MGD) (12,530 x 10^6 L/d). Moreover, hydroelectric plants produce approximately 9% of the nation's electricity. Evaporative water loss from the reservoir surfaces also results in water being evaporated for electrical production.

In thermoelectric plants, 0.47 gal (1.8 L) of fresh water is evaporated per kWh of electricity consumed at the point of end use. Hydroelectric plants evaporate an average of 18 gal (68 L) of fresh water per kWh used by the consumer. The national weighted average for thermoelectric and hydroelectric water use is 2.0 gal (7.6 L) of evaporated water per kWh of electricity consumed at the point of end use. From this information, different types of building cooling systems can be compared for relative water consumption.

This paper will aid in High Performance Building research by providing a metric in determining water efficiency in building cooling systems. Further analysis is planned to determine the overall water efficiency of evaporative cooling systems compared to conventional direct expansion systems and chiller systems with cooling towers.

[1] Water consumption or consumptive water use is water lost to the environment by evaporation, transpiration, or incorporation into the product.

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1 Introduction

In the United States there is a regional trade-off between energy consumption and water consumption when comparing evaporative and nonevaporative cooling systems. In most regions of the United States, evaporative cooling systems are used for large HVAC applications because they have lower capital and operating costs than nonevaporative systems. In some cases, direct and indirect evaporative systems are used for directly cooling buildings, especially in hot and dry desert climates but with a trade-off of consuming a portion of the finite water supply. Ultimately, there is a trade-off between water consumption and energy consumption used at the site. Direct expansion systems consume no water to produce cooling, but use more electricity than evaporative cooling systems. In many chiller systems, cooling towers are added to increase the efficiency of heat removal from the condenser, thereby increasing energy efficiency. The water consumption at the power plant and the building must be studied and documented to evaluate the overall water efficiency of different types of building cooling systems.

Building researchers at NREL performed a literature search of water use for thermal and hydroelectric power plants. Combining the research resulted in an aggregated U.S. total of water evaporated by power plants per kWh of energy consumed by the end user (site energy). The analysis accounts for evaporation at the power plant, and is adjusted to incorporate transmission and distribution losses. Hydroelectric systems were also evaluated based on evaporative losses from the reservoir per kWh of energy consumed by the end user. These numbers apply only to the location where the electricity is produced, not to the location of use. Because of the nature of power distribution, it is currently impossible to “tag” electrons from production to consumption. As a result, only aggregated totals are presented. The total amount of water evaporated seems insignificant compared the total amount of water passing through the power plant, but when compared to the amount of energy and water consumed in a typical commercial building or residential home, these values are significant. The energy-water relationship needs to be considered when designing for building cooling systems.

This paper focuses on water consumption at power plants to provide the data needed to make accurate comparisons between water uses of building cooling systems. The paper does not answer the question of which system consumes more water, but merely provides the metric for determining the amount of water used at the power plant when the amount of energy consumed at the site is known. Subsequent analysis will be completed to determine the water effectiveness of cooling systems. All values reported are for fresh water, which includes lakes, rivers, ponds, and domestic water.

2 Water Consumption for Power Generation

In the United States, approximately 89% of the energy produced in power plants is generated by thermoelectric systems, which evaporate water during the cooling of the condenser water (EIA 1999). Hydroelectric plants evaporate water off the surface of the reservoirs and represent approximately 9% of the total power generated in the United States. The remaining electricity is produced by wind and solar.

2.1 Water Consumption in Thermoelectric Power Plants

In a typical thermoelectric power plant, heat is removed from the cycle with a condenser. In order to remove the heat, cooling water is used. The cooling water (and related heat) can be discharged to a river, a reservoir, or an ocean. This practice is being replaced with evaporating a portion of the cooling tower water and transferring heat into the air by evaporating water. The reason cooling towers are being pursued more is to minimize the environmental impacts from withdrawing the abundant amount of water and quickly dumping it back into the stream. Values of total power plant water withdrawals were obtained from the U.S. Geological Survey (USGS) (Solley et al. 1998). These values were reported in both fresh and saline water withdrawals, but this analysis will focus on fresh water only.

The USGS also calculated the consumptive use of water (amount of water evaporated, transpired, or incorporated into products) for thermoelectric power plants. According to the USGS, these values were calculated by multiplying the water withdrawals by a coefficient of water loss, approximated for each cooling design. If the cooling water was recycled through cooling towers or cooling ponds, the consumptive use was high. Conversely, if the water was used once from a nearby river then returned to the flow, the evaporation at the site was low, but the added heat to the stream increased the evaporation rate of the river, thus increasing the overall evaporation. According to the USGS the total amount of fresh water used at U.S. thermoelectric power plants in 1995 was 132,000 MGD (500 x 10^9 L/d), of which 2.5%, or 3,310 MGD (12.5 x 10^9 L/d), was evaporated (Solley et al. 1998).

2.2 Water Consumption for Mining Water

The amount of water that is used to mine and process the fossil fuels that are sent to the power plants also needs to be considered for an accurate analysis. Unfortunately, the data available for mining water use are for all types of mining, including coal and ore. This analysis did not attempt to break down the percentages of water that each mining process used.

2.3 Water Consumption in Hydroelectric Power Plants

Reservoirs and dams are built for many reasons, including electric power production, flood control, water storage, and recreation. Most dams currently provide more than one function. The discussion of hydroelectric dams brings up many difficult issues related to the value of the dam, and the values of different individuals. This paper does not make statements or judgments regarding the ecological impacts or the human value of the dams, but merely provides the amount of water evaporated off the reservoirs as a function of the amount of energy produced. There is no easy way to disaggregate on a national level the end uses for hydroelectric dam water into irrigation, flood control, municipal water, and thermoelectric power plant cooling. Development of hydroelectric facilities was integral to providing reliable power in the United States and reliable water supplies over the last century. Reliable water supplies enabled thermoelectric power plant development. These plants not only consume water, but also need the consistent flow of cooling water. The analysis will assume that consumptive use of water in hydroelectric facilities should be considered, but the values reported contain aggregate totals with and without hydroelectric water use to allow for individual interpretations. Also, the data are broken up into the different geographic regions to allow for analysis and interpretation of regional hydroelectric power water use.

Water flowing through the turbines and into the river is not considered consumptive because it is still immediately available for other uses. However, the increased surface area of the reservoir, when compared to the free flowing stream, results in additional water evaporation from the surface. A Free Water Surface Evaporation (FWSE) map was used to calculate the amount of water evaporated off the reservoirs (Farnsworth et al. 1982). The map contains isopleths[2] with values of evaporation in inches per year. FWSE is calculated by the NWS by multiplying the class A pan evaporation rates by a pan coefficient. The class A pan evaporation rates were measured by placing an open cylindrical container in the area of interest and filling it with water two inches from the top. At specific time intervals water was added to bring the container back up to the original level. The amount of water added is recorded as the amount of water evaporated and the process was repeated for a fixed time period. A pan coefficient was used to compensate for the heat conducted through the sides of the pan and other losses that were unique for each location. Using the FWSE map for estimating the amount of water evaporated off a reservoir or lake was a good approximation as long as the following assumptions held: there has to be negligible change in heat storage, and the heat content of inflow waters is essentially the same as that for outflow waters. These assumptions hold if annual evaporation rates are calculated. The reference also indicates that this is an appropriate method for calculating the amount of water evaporated from a lake surface.

The map was used to approximate the average evaporation per year by location in the United States. Based on the latitude and longitude of the dam given by the Army Corp of Engineers (ACE), the amount

[2] Isopleths are lines of constant values on a map that represent the third dimension.

of water evaporated could be approximated by estimating the average value of the isopleths covering the reservoir (ACE 2001). Isopleths are lines of constant yearly evaporation rates that are drawn on maps to represent the third dimension. The surface areas of the reservoirs were measured in acres at a normal height as defined by the National Inventory of Dams (ACE 2001). With this information the volume of water evaporated can be calculated from each reservoir.

This analysis was completed on a collection of hydroelectric dams, most of which produced more than 1 TWh/yr (10^{12} Wh/yr) or the 120 largest hydroelectric facilities in the United States. These hydroelectric facilities represent approximately 65% of the total electricity produced by hydroelectric facilities in 1999. There are approximately 2,300 hydroelectric dams currently in the United States (Corso 1998). Using this analysis, it was estimated that the U.S. reservoirs used for hydroelectric evaporate an average of 9,063 MGD (34.3×10^9 L/d).

Compared with the river without the reservoir, the increase in evaporation is significant. The length of the river was approximated as the present length of the reservoir. The average width of the river and its winding were estimated. The evaporation rate was assumed to be the same as the free-water surface evaporation rate, even though most rivers have significant shaded areas, either from vegetation or canyon walls. The analysis was done for Glen Canyon Dam (Lake Powell) and Hoover Dam (Lake Mead), both located in high evaporation areas. For the two dams the evaporation from "the river" was only 3.2% of that of the reservoir that replaced it (see Table 1). This value was considered negligible and was not included in the overall numbers or calculated for other dams.

Table 1. Water Evaporation of Reservoirs Compared with Free-Running River

		Reservoir		River		
Dam	Evaporation in/year	Surface Area Acres	Evaporation Gal/year	Surface Area[1] Acres	Evaporation Gal/year	Percentage Difference
Hoover	80	164,000	3.6E+11	4,000	8.7E+09	2.4%
Glen Canyon	76	169,700	3.5E+11	6,764	1.4E+10	4.0%
Totals			7.1E+11		2.3E+10	
Average						3.2%

[1]Surface area was calculated by multiplying the current reservoir length by an overestimated width of the river. The river was overestimated to compensate for its winding and water thrown into air.

3 Net Power Production in the United States

Using the above data it is possible to determine a useful metric for relating water to energy use; however, the energy use needs to be the energy use at the site and not at the energy production at the power plant. Therefore, it is necessary to adjust the gross power produced by power used in the generation process and by distribution losses. The Energy Information Administration (EIA 1996) tabulates the amount of power generated in the United States. Thermoelectric power plants use approximately 5% of their gross generation to power equipment. This power is used to crush and transport coal, excitation for generators, and power other machinery within the plant. The EIA estimates the transmission and distribution losses for the United States as 9% of the gross generation. Figure 1 details the power flow from the power plant to the site.

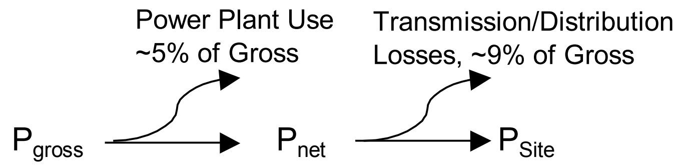

Figure 1. Thermoelectric power flow diagram detailing where power was consumed and lost before reaching consumer

Using the flow chart it was possible to write a simple equation to account for distribution and line losses (see Equation 1).

$$P_{Site} = P_{Net}(1 - LineLosses) \tag{1}$$

The transmission and distribution losses for hydroelectric power plants must also be considered. The calculation was slightly different from the thermoelectric power plants because hydroelectric facilities use little internal energy to power their machinery. As a result, another assumption was made stating that the gross generation was approximately equal to the net generation in a hydroelectric power plant.

4 Water Consumption and Power Generation in U.S. Power Plants

Using the information above, it was possible to calculate the amount of water consumed by electricity production for each kWh of end-use energy for the entire United States. The metric was calculated by taking the total consumptive water use divided by the total power output. The values were broken down into three categories: thermoelectric, hydroelectric, and a combined aggregate (see Table 2). Also, the values were broken down into three regions in the United States, based on the three main electrical grid interconnects: Western, Eastern, and Texas. The assumption that the regions did not import or export power was made.

Table 2. Total Consumptive Use of Water for U.S. Power Plants

Power Provider	Gallons Evaporated per kWh at Thermoelectric Plants	Gallons Evaporated per kWh at Hydroelectric Plants	Weighted Gallons Evaporated per kWh of Site Energy
Western Interconnect	0.38 (1.4 L)	12.4 (47.0 L)	4.42 (16.7 L)
Eastern Interconnect	0.49 (1.9 L)	55.1 (208.5 L)	2.33 (8.8 L)
Texas Interconnect	0.44 (1.7 L)	0.0 (0.0 L)	0.43 (1.6 L)
U.S. Aggregate	0.47 (1.8 L)	18.0 (68.0 L)	2.00 (7.6 L)

The initial interest was a U.S. aggregated average; however, it was possible to break down the values per state, assuming that states did not import or export power—a poor assumption, but typically used when reporting other power generation numbers. The state values were calculated and reported as seen in Table 3. The hydroelectric power production reported in the table is not the net production for the state over the year. The values reported are only for the analyzed hydroelectric dams.

Table 3. United States Water Consumption per kWh of Energy Consumed by State

State	Thermoelectric Site Power million kWh/Year	Hydroelectric[1] Site Power million kWh/Year	Thermoelectric Site Water Gallons/kWh	Hydroelectric Site Water Gallons/kWh	Weighted Total Site Water Gallons/kWh
Alabama	81,708	3,459	0.14	37.00	2.50
Alaska	3,611	0	0.31	N/A	0.27
Arizona	62,551	8,763	0.32	64.85	7.85
Arkansas	35,825	0	0.29	N/A	0.26
California	72,800	9,130	0.05	20.87	4.64
Colorado	29,312	1,176	0.51	17.91	1.20
Connecticut	26,342	0	0.08	N/A	0.07
Delaware	5,805	0	0.01	N/A	0.01
D.C.	181	0	1.61	N/A	1.61
Florida	142,726	0	0.14	N/A	0.14
Georgia	88,797	41	0.60	47.42	1.65
Hawaii	6,102	0	0.04	N/A	0.04
Idaho	0	6,093	0.00	8.51	7.85
Illinois	140,811	0	1.05	N/A	1.05
Indiana	100,579	0	0.41	N/A	0.41
Iowa	31,227	0	0.12	N/A	0.11
Kansas	36,496	0	0.58	N/A	0.58
Kentucky	67,627	892	1.10	154.34	5.32
Louisiana	51,918	0	1.56	N/A	1.47
Maine	4,406	0	0.29	N/A	0.12
Maryland	41,381	1,281	0.03	6.72	0.21
Massachusetts	32,568	0	0.00	N/A	0.00
Michigan	92,628	0	0.50	N/A	0.48
Minnesota	39,561	0	0.44	N/A	0.41
Mississippi	25,001	0	0.39	N/A	0.37
Missouri	60,922	0	0.31	N/A	0.30
Montana	8,401	8,172	0.96	36.77	16.74
Nebraska	22,798	346	0.19	2.18	0.30
Nevada	18,104	2,510	0.56	73.33	7.25
New Hampshire	13,411	0	0.12	N/A	0.10
New Jersey	22,606	0	0.07	N/A	0.07
New Mexico	27,875	94	0.63	68.00	1.13
New York	72,896	5,487	0.85	5.57	1.62
North Carolina	89,467	875	0.23	10.37	0.55
North Dakota	25,193	2,374	0.36	57.80	5.13
Ohio	129,316	0	0.95	N/A	0.94
Oklahoma	42,818	415	0.51	136.96	8.39
Oregon	3,468	27,803	0.82	4.41	3.71
Pennsylvania	160,926	0	0.54	N/A	0.53
Rhode Island	266	0	0.00	N/A	0.00
South Carolina	71,076	0	0.26	N/A	0.25
South Dakota	2,682	6,076	0.01	114.84	72.64
Tennessee	70,693	3,261	0.00	43.35	3.60
Texas	248,095	0	0.44	N/A	0.43
Utah	30,269	717	0.57	73.34	3.05
Vermont	4,215	0	0.35	N/A	0.25
Virginia	48,757	0	0.07	N/A	0.06
Washington	12,740	89,094	0.29	3.19	2.70
West Virginia	75,769	0	0.59	N/A	0.58
Wisconsin	42,818	0	0.49	N/A	0.46
Wyoming	36,975	1,022	0.49	136.96	4.15
U.S. Totals	2,562,519	179,082	--	--	--
Weighted Averages			0.47	18.27	2.00

[1]Amount of power generated by analyzed hydroelectric facilities.

5 Summary and Conclusions

The United States uses several methods to produce power, many of which evaporate water. The number of evaporative power plants significantly outweighs the number of nonevaporative power plants; therefore, it is important to consider water use at power plants when concerned about water conservation.

Nonetheless, a detailed search of consumptive water use for thermal and hydroelectric systems was performed and evaluated. For thermoelectric plants, the analysis accounts for water evaporation at the power plant. All power numbers were adjusted to incorporate transmission and distribution losses so the values related to the end use. The final result for typical thermoelectric power plants was 0.47 gal (1.8 L) of fresh water evaporated per kWh of end-use electricity. Hydroelectric power plants evaporated 18 gal (68 L) of fresh water per kWh consumed by the end user. Combined, these values give an aggregate total for the United States of 2.0 gal/kWh (7.6 L/kWh). These values can be used to compare building cooling systems by the amount of water that is evaporated, both at the site and indirectly at the power plant. The reported values are broken up into region and type of power generation to allow for individual interpretation of the results.

There are substantial regional differences in the use of hydroelectric power, and therefore a thorough understanding of local conditions is necessary to properly interpret these data. There are river basins where evaporation is a substantial percentage of the total river flow, and this evaporation reduces the available supply both for downstream human consumption as well as having environmental consequences for coastal ecosystems that depend on fresh water supply. On the other hand, consider the case of a hydroelectric project on a relatively small river, which provides the fresh water supply to a major metropolitan area. In this case, the reservoir may be a valuable fresh water resource, especially if evaporation as a percentage of the river flow rate is low. If the downstream consequences for human consumption and coastal ecosystems are low, then the water consumption from hydroelectric projects would be irrelevant—whether or not electric generation occurs, the evaporation will still happen as a necessary consequence of providing fresh water supply to the region. These issues are beyond the scope of this paper, but must be considered when interpreting these results.

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Appendix A – Percentage of Water Withdrawals in United States

The percentage of water used by power plants to make electricity is a significant amount. In fact, thermoelectric power plants make up 39% of all water withdrawals in the U.S. from rivers, lakes, ponds, and reservoirs, only to be passed by irrigation and livestock, which has a withdrawal percentage of 41% (Solley et al. 1998). In a survey done by the EPA, the average power plant withdraws anywhere from 100 to 250 million gallons per day (MGD), see Figure A-2 (EPA 2001).

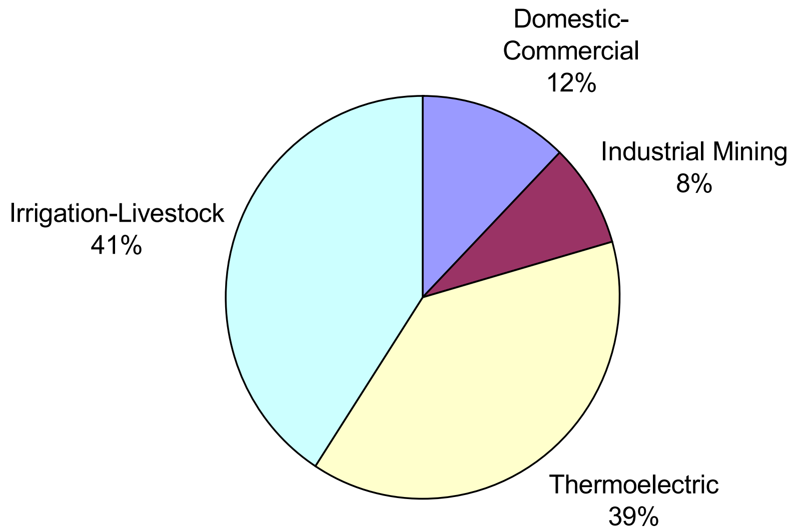

Figure A-1. Percentage of total water withdrawals in the United States

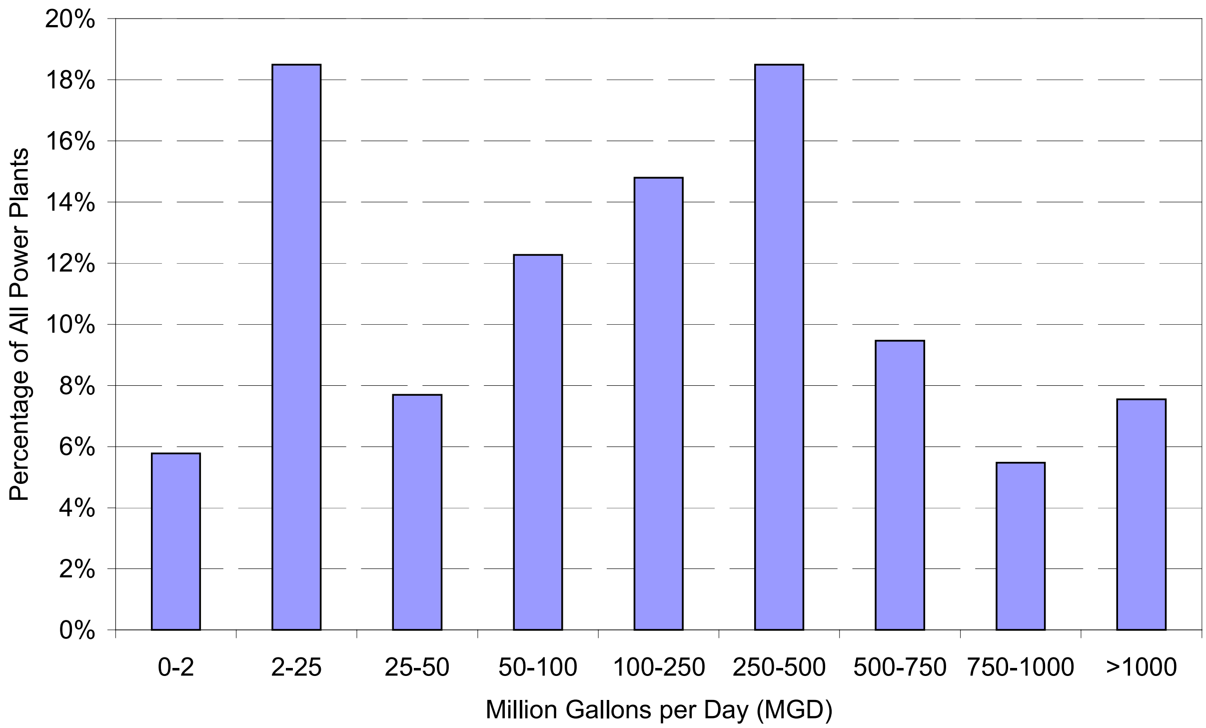

Figure A-2. Distribution of water withdrawal as percent

Although thermoelectric power plants withdraw large amounts of water, only a small percentage is evaporated, approximately 2.5% or 3,310 MGD (12,530 x 10^6 L/d). This constitutes 3.3% of all consumptive use in the United States or 41% of the total domestic and commercial consumptive use. Irrigation is the largest contributor to water consumption, with a consumption of 85% of the total water withdrawn in the United States. Finally, of the total amount of water returned to waterways, power plants make up the most with a 53% return. The amount of return water is significant when discussing thermal pollution of rivers, which is beyond the scope of this analysis.

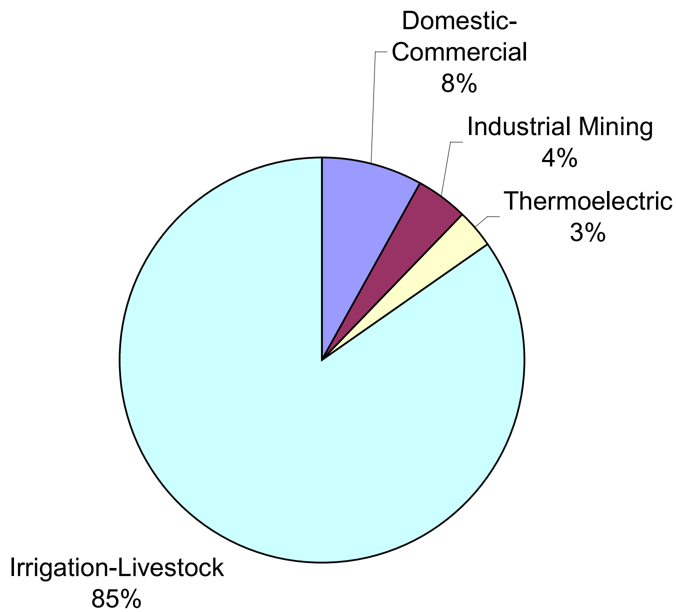

Figure A-3. Percentage of total water consumption in the United States

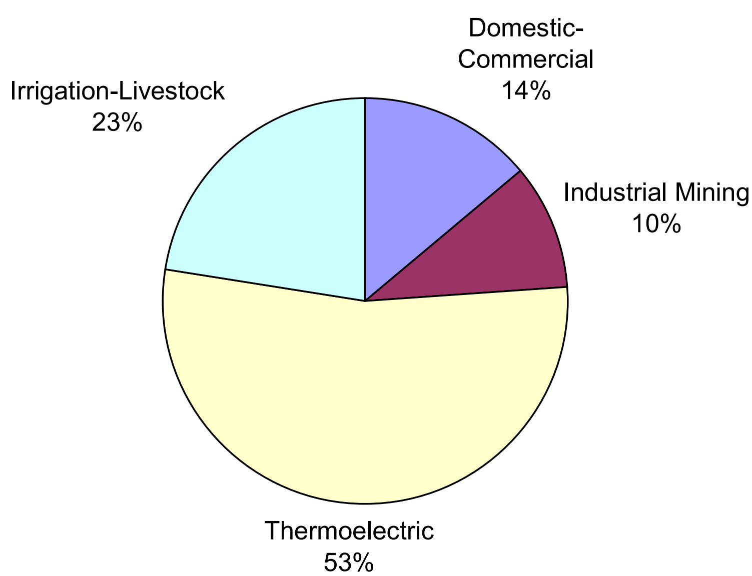

Figure A-4. Percentage of total water returns in the United States

Appendix B – Cooling Technologies

Power plants either consume water or do not consume water to produce power. Some examples of waterless power plants are gas turbine facilities, wind turbine, and most solar photovoltaic systems. These plants make up about 1% of the total energy produced in the United States (EPA 2001).

The two major types of power plants that consume water for cooling are hydroelectric and thermoelectric (powered by fossil fuels, nuclear, or geothermal energy). Hydroelectric facilities use a significant amount of water by evaporation from the reservoir surface. Many thermoelectric plants withdraw water and evaporate it to condense the steam back to a liquid for pumping and efficiency purposes.

There are two widely implemented types and one seldom used type of cooling for power production. The two major types are once-through cooling and closed-loop cooling; the minor type is termed dry cooling. Dry cooling is typically more water efficient, both from a capital cost and an operational cost because dry cooling uses little or no water and needs less maintenance than cooling towers that require water.

Once-Through Cooling

Once-through cooling systems use the nearby water to help cool the condenser water. The river or lake water is passed through a heat exchanger to condense the steam. The exiting condenser water is pumped back through the cycle and the river water is returned to the stream (Figure B-1). (Condensers and Cooling Systems 2002.) The water consumption at the power plant is minimal, if not zero, because the water does not directly contact the air. However, the temperature increase of the river water increases the evaporation rate, thus indirectly increasing the amount of water consumption. Although the consumptive water use is minimal, the amount of water withdrawn from the river is significant because the water is only used for a short time before it is returned to the stream.

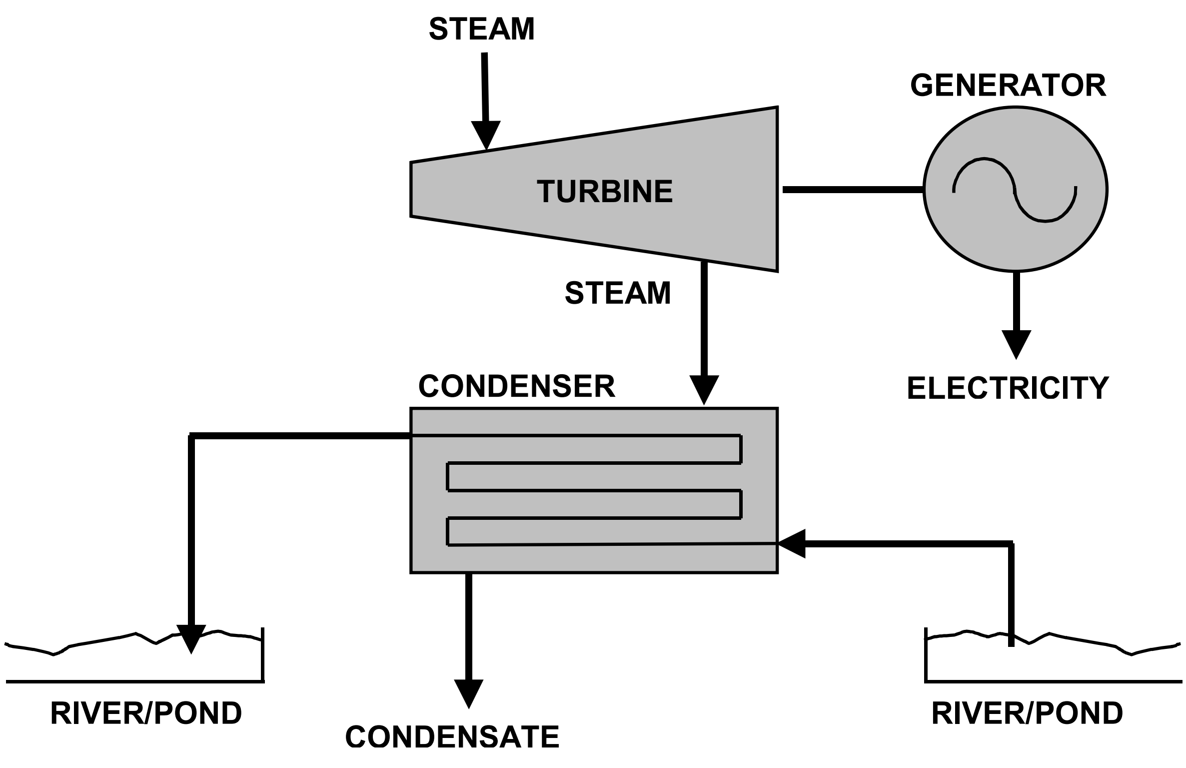

Figure B-1. Diagram of once-through cooling system

Closed-Loop Cooling

A closed-loop cooling system was designed to minimize the amount of water withdrawn from the river. In this system, the condenser water still exchanges heat with water in a heat exchanger, but the cooling water is recycled between a cooling tower and a heat exchanger (Figure B-2). In this system, the cooling water is cooled by evaporating a percentage of the water to the environment. Because the water is evaporated, there has to be a make-up water supply to account for the consumed water. The make-up water typically comes from the nearby water source. This system consumes much more water than once-through types because the entire energy exchange is through evaporation of the water—a consumptive use. These systems withdraw less water because the only water used is to make up the evaporated portion; however, they consume more water.

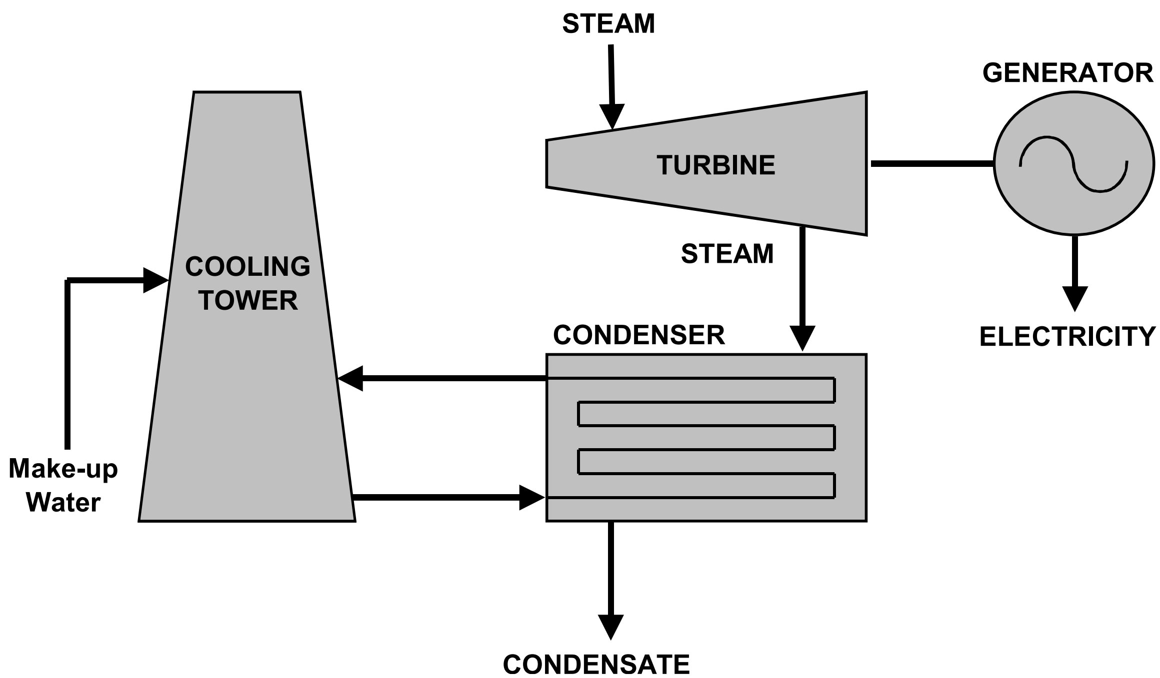

Figure B-2. Diagram of a closed-loop system

Dry Cooling

Dry cooling is the most attractive cooling system when considering water withdrawals and water consumption for power production. Dry-cooling systems function without having the water contact the air. The hot condenser water is passed through a liquid-to-air heat exchanger. The heat exchanger has many fins on the pipes to increase the area, thus increasing the amount of heat removal (Figure B-3). Dry cooling typically requires a fan to aid in heat removal. The advantage to dry cooling is the water withdrawals and consumptions are zero. Basically, no water is needed for dry cooling.

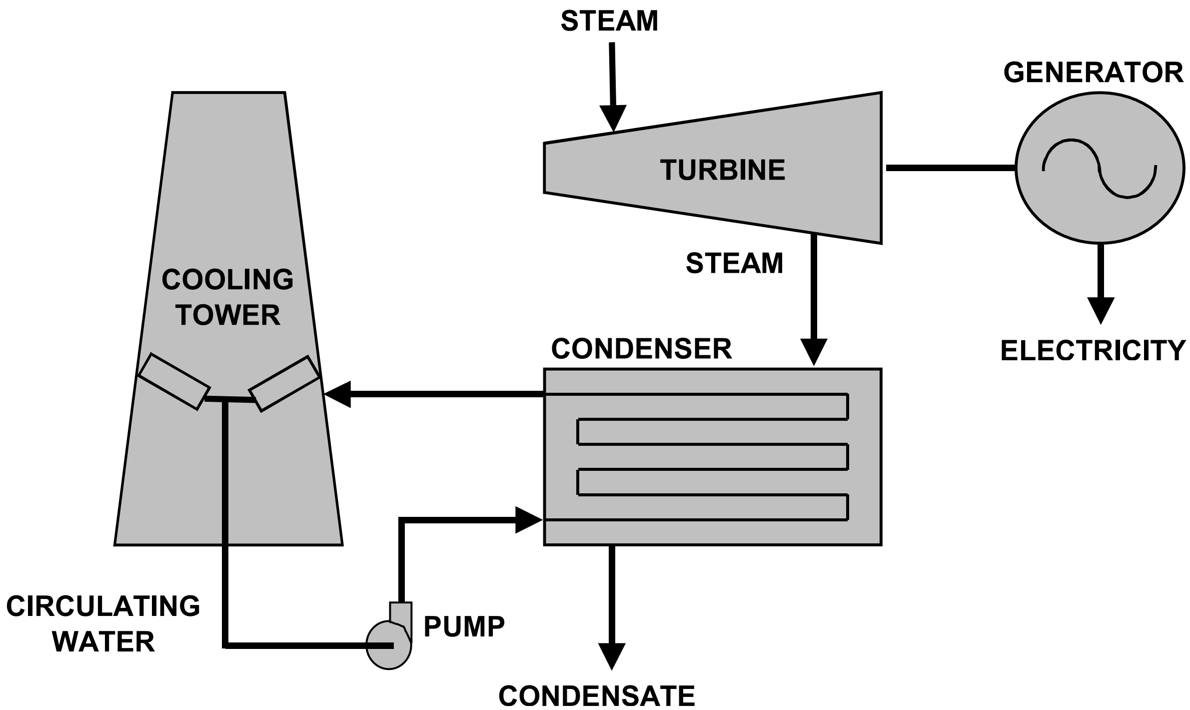

Figure B-3. Diagram of a dry-cooling system

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P. Torcellini, N. Long, and R. Judkoff

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1617 Cole Blvd.
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A study of power plants and their respective water consumption was completed to effectively analyze evaporative cooling systems. This technical paper will aid the High Performance Buildings Research Program by providing a metric in determining water efficiency in building cooling systems. Further analysis is planned to determine the overall water efficiency of evaporative cooling systems compared to conventional direct expansion systems and chiller systems with cooling towers.

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