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ANL/ESD/11-2 – Update

Developing a Tool to Estimate Water Use in Electric Power Generation in the United States

Energy Systems Division

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Developing a Tool to Estimate Water Use in Electric Power Generation in the United States

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ACRONYMS AND ABBREVIATIONS

Argonne	Argonne National Laboratory
BM	biomass
CHP	combined heat and power
DOE	U.S. Department of Energy
EIA	Energy Information Administration
EISA	Energy Independence and Security Act of 2007
EV	electric vehicle
FGD	fluid gas desulfurization
GT	gas turbine
IGCC	integrated gasification combined cycle
LFG	landfill gas
MSW	municipal solid waste
NETL	National Energy Technology Laboratory
NG	natural gas
NGCC	natural gas combined cycle
OBP	Office of Biomass Program
PHEV	plug-in hybrid electric vehicle
RFS2	renewable fuels standard (federal)
RPS	renewable portfolio standard
ST	steam turbine

ABBREVIATIONS

B	billion
Btu	British thermal units
gal	gallon(s)
kWh	kilowatt-hour(s)
MW	megawatt(s)
W	watt(s)

EXECUTIVE SUMMARY

A spreadsheet-based tool has been developed to characterize water use in electricity generation from nonrenewable and renewable sources for the 50 states in the United States. The tool is built upon a data inventory that analyzes water requirements by fuel source, generation technology, and cooling system. A total of 13 fuel sources and their 19 subcategories and eight electricity generation technologies are included in the inventory. It also incorporates four types of cooling systems: for each type, water withdrawal and consumption factors were determined. The data inventory and the tool cover the 50 states in the nation which enable users to generate scenarios at national level and for individual state. As such, the tool allows decision makers to perform quick estimates of water consumption in electricity generation. It enables the projection of future water use in electricity generation from various fuel sources at state and national levels. Further analysis can be conducted to examine how changes in fuel source mix and cooling system mix impact water use. Decision makers can use the tool to compare options among fuel sources and technologies from the perspective of impacts to water use (i.e., withdrawal and consumption), to evaluate the conservation of water resources associated with renewable sources, and to address environmental sustainability issues in renewable energy development.

Analysis performed by using the tool shows that nuclear and coal plants with once-through cooling systems demand the largest share of freshwater withdrawal among all of the cooling system and fuel combinations. At present, approximately one-third of the electricity was generated by once-through cooling systems located at coal and nuclear plants. The largest contributors of power generation — accounting for 38.5% of total U.S. electricity generation — are plants with wet-recirculating cooling systems. A set of fuel source/technology-based national water withdrawal and consumption factors has been derived from the share of various fuel sources in the electricity mix, the generation technology, and the cooling system mix. Based on these mixes, on average, 13.9 gal of freshwater withdrawal and 0.39 gal of freshwater consumption are required to generate one kilowatt-hour (kWh) of electricity in the United States.

Total water use in power generation for each state is influenced strongly by total power generated, fuel mix, and major type of cooling systems employed. The top five water-use states — Illinois, Michigan, Ohio, Tennessee, and Texas — account for one-third of the freshwater withdrawal to generate 25% of the total power in the United States. The power industry has been exploring saline and brackish water use in recent years, particularly in California and Florida, where a larger portion of freshwater is allocated to food and feed production; each also contains a large saline water supply. As of 2005, these two states used the lowest amounts of freshwater to produce one unit of electricity.

We further developed two cases based on projections to 2035 by the U.S. Department of Commerce (Tracy 2011) to assess impacts on water use for the projected power generation. Results indicated that fuel mix projections with current cooling mix will have a significant impact on projected freshwater use. Moving away from use of withdrawal-intensive cooling systems can further reduce freshwater requirements per kWh of electricity generated. If the DOC's fuel mix projections can be realized, substantial benefits to water conservation efforts for the nation could result.

An assessment of the blue water footprint[1] of electricity generation associated with various fuel sources, generation technologies, and cooling systems indicates that upstream resource recovery and fuel production require a minimal amount of blue freshwater in comparison with the cooling water requirements in conventional power plants. As a result, the blue water footprint of electricity produced from fossil, non-fossil, and solar, wind, geothermal, hydro sources is primarily shaped by the power plants. When considering the total water footprint by including green water, it turns out that biomass-derived power generation has a larger freshwater footprint. Although the power plant still holds a major portion of the freshwater footprint in power generated via a once-through cooling system, the water footprint in the fuel recovery and production stage becomes equally important in power generated from a recirculating cooling system. As use of recirculating cooling systems tends to increase in new, planned, and refurbished power generation plants, water management and conservation for both upstream fuel production and downstream power production should be addressed.

[1] "Blue water" is water from surface and groundwater sources. A "blue water footprint" refers to the blue water consumed during the production of a product.

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DEVELOPING A TOOL TO ESTIMATE WATER WITHDRAWAL AND CONSUMPTION IN ELECTRICITY GENERATION IN THE UNITED STATES

May Wu and Michael J. Peng

ABSTRACT

Freshwater consumption for electricity generation is projected to increase dramatically in the next couple of decades in the United States. The increased demand is likely to further strain freshwater resources in regions where water has already become scarce. Meanwhile, the automotive industry has stepped up its research, development, and deployment efforts on electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs). Large-scale, escalated production of EVs and PHEVs nationwide would require increased electricity production, and so meeting the water demand becomes an even greater challenge. The goal of this study is to provide a baseline assessment of freshwater use in electricity generation in the United States and at the state level. Freshwater withdrawal and consumption requirements for power generated from fossil, nonfossil, and renewable sources via various technologies and by use of different cooling systems are examined. A data inventory has been developed that compiles data from government statistics, reports, and literature issued by major research institutes. A spreadsheet-based model has been developed to conduct the estimates by means of a transparent and interactive process. The model further allows us to project future water withdrawal and consumption in electricity production under the forecasted increases in demand. This tool is intended to provide decision makers with the means to make a quick comparison among various fuel, technology, and cooling system options. The model output can be used to address water resource sustainability when considering new projects or expansion of existing plants.

1 INTRODUCTION

To address energy security concerns and reduce the carbon intensity of transportation fuels, renewable energy sources are being promoted globally. At present, the source of about 19% of the total global energy consumption is renewable, 13% of which is traditional biomass (BM, which is mainly used for heating), and 3.2% of which was hydroelectricity in 2008 (REN21 2008). New renewable sources (small hydro, modern biomass, wind, solar, geothermal, and biofuels) accounted for another 2.7%, and these sources are growing very rapidly. The share of renewable sources in electricity generation is around 18%, with 15% of global electricity coming from hydroelectricity and 3% from wind, solar sources, geothermal sources, and biomass (REN21 2008; REN21 2010).

In the United States, renewable energy production is limited at present — about 10% of total energy production in 2008 was represented by renewable energy (EIA 2010), about 9.1% of electricity generation was represented by renewable energy (EIA 2010), and 3.4% of motor vehicle fuel consumption was represented by renewable energy (EIA 2009). However, we are anticipating robust growth in the use of renewable fuel. Rapid expansion is primarily a result of federal and state programs — including the production of 36 billion gallons of renewable fuels by 2022 — as mandated by the U.S. Congress in the Energy Independence and Security Act (EISA) of 2007 and corresponding rules in the federal renewable fuels standard (RFS2), various state renewable portfolio standard (RPS) programs, and funds in American Recovery and Reinvestment Act of 2009 — together with rising prices for fossil fuels. The renewable energy sector is expected to grow despite the economic downturn .The renewable share of total energy use is projected to increase from 10% in 2008 to 14% in 2035 (EIA 2010). Among the types of renewable energy, EIA (2010) forecasts the strongest growth in fuel use for the renewable fuels used to generate electricity and to produce liquid fuels for the transportation sector. Renewable generation is expected to account for 45% of the increase in total generation from 2008 to 2035 (EIA 2010).

In the transportation sector, recent development shifts toward an emphasis on electricity-fueled vehicles to ease the demand on liquid fuel. For the past few years, extensive research and development and funding have been invested in the development of technology and feedstock resources for electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs). Hence, demand for power is likely to increase even more with the adoption of the EVs and PHEVs. A sizable amount of that demand would be met by the production of renewable power.

According to a U.S. Geological Survey (USGS) report (Kenny et al. 2009), thermoelectric power plants are the largest category of entities making water withdrawals in the United States (49%), followed by water withdrawn for irrigation (31%) and public supply (11%). Water use for electric power plants increased fourfold from 40 billion gallons per day in 1950 to 201 billion gallons per day in 2005 (Kenny et al. 2009). As indicated by recent statistics, demand for electricity will continue to increase, which will require more water withdrawal. Electricity generation increased by 6.7% between 2000 and 2005 (EIA 2010). Water use for thermoelectric-power generation in 2005 had increased by about 3% over such use in 2000 (Kenny et al. 2009). Nearly all of the water withdrawn for thermoelectric power was used to support the once-through cooling process at power plants. A majority of these plants are fueled by coal, nuclear, and natural gas (NG). Electricity produced by coal power plants accounts for one-half of the total energy produced in the United States, followed by electricity produced by nuclear power plants (19.3%) and natural gas plants (18.7%) (Figure 1). Depending on the fuel source and technology, increased electric power generation could require substantial water input.

Among the major causes for such an increase in electricity demand, population growth is considered the dominant factor and, consequently, drives the need for water for electricity generation. Figure 2 shows the growing production of electricity from 2000 to 2005. It is expected that this trend will continue. Since 2005, the issue of water resources required in the production of both renewable energy and energy in general has sparked extensive discussion and debate among scientists and other experts in research institutes, fuel industries, and government agencies in the United States and abroad. Large-scale renewable fuel or electricity production may compete on a regional basis with other existing industries for water supply. In areas where water supply is limited, it could further strain local freshwater resources. Therefore, the key issue to be addressed is the sustainability of renewable energy production from a water use perspective.

A number of studies have been conducted to analyze the water requirements of renewable energy production technologies (CEC 2006; Berndes 2002; DeMeo and Galdo 1997, EPRI 2002) and to address projected future freshwater demand for electric power (Feeley et al. 2008; NETL 2006, 2008; EPRI 2002). The increased energy demand is likely to further strain freshwater resources in regions where water has already been scarce, such as in Arizona, Georgia, California, Colorado, New Mexico, Missouri, and Massachusetts, among others (Sovacool and Sovacool 2009). Furthermore, the accelerated use of EVs and PHEVs on a nationwide basis will necessitate increased electricity production and therefore could bring the significance of the water issue to the forefront of energy discussion. The life cycle assessment of water consumption for EVs and PHEVs, which is based on available aggregated upstream production data, indicates significant variations in water withdrawal among a range of fuel sources (King and Webber 2008). Biofuel development requires the use of irrigation water, which, together with water withdrawal related to power generation, accounts for a majority of freshwater use in the United States. Therefore, water resources and consumption remain a key issue in developing sustainable energy.

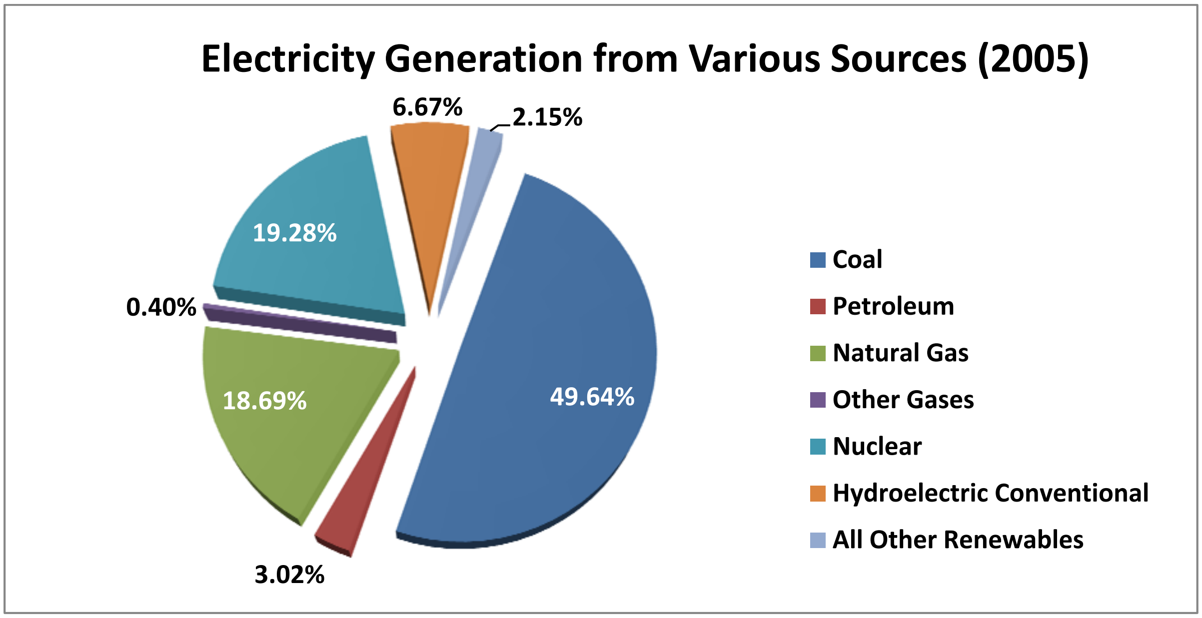

FIGURE 1 Fuel Sources and Shares in Electricity Generation in the United States in 2005 (Data source: EIA 2010)

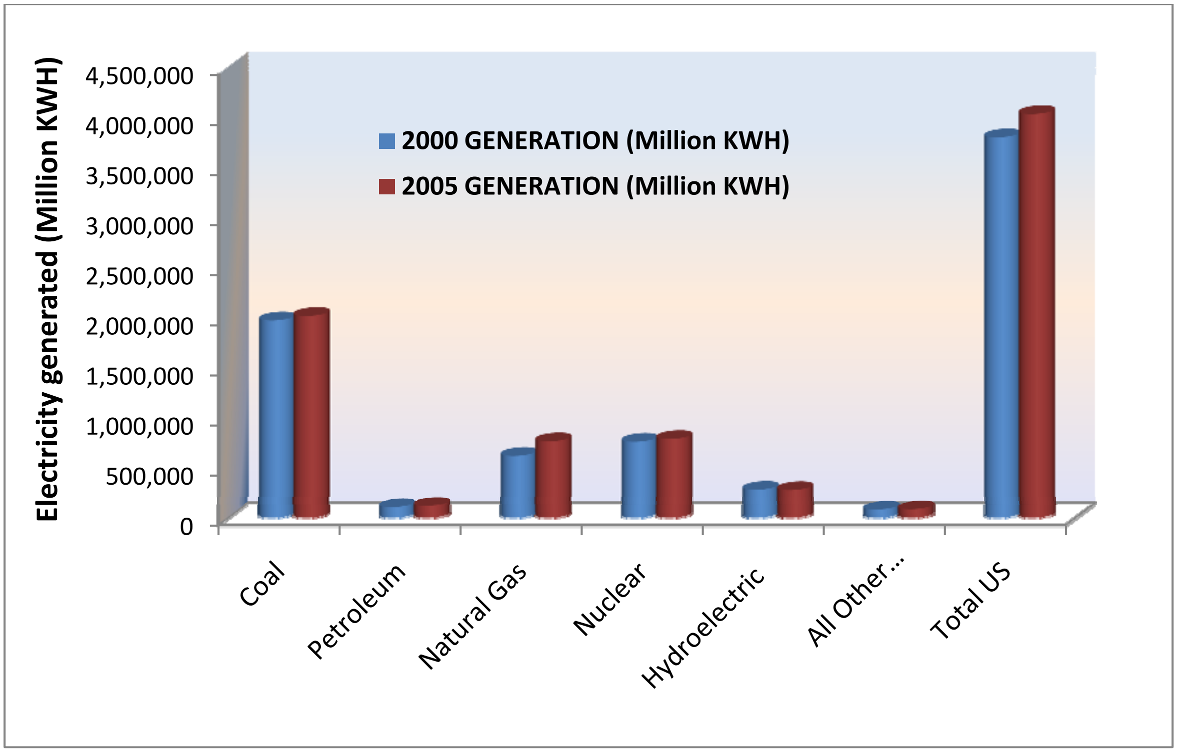

FIGURE 2 Change in Electricity Generation from 2000 to 2005 by Fuel Source (Data source: EIA 2010)

2 PROJECT BACKGROUND

This study is part of a water analysis project funded by the U.S. Department of Energy's (DOE's) Energy Efficiency and Renewable Energy, Office of Biomass Program (OBP) and conducted by the Center for Transportation Research in the Energy Systems Division of Argonne National Laboratory (Argonne). A previous study that was documented in a peer-reviewed journal publication (Wu et al. 2009a) addressed consumptive water use for irrigation and production processes that were associated with (1) biofuel production from conventional and cellulosic feedstock, and (2) petroleum oil production from conventional and oil sands–based crude. The water consumption factors of two major life-cycle stages have been evaluated, and the results have been further converted to highlight the volumes of water consumed per mile driven when a vehicle is fueled with either petroleum or biofuel (Wu et al. 2009b). To have a broader view of the impact of water use on renewable energy production, we need to examine electric power generation that could be used by EVs and PHEVs in the transportation sector. Thus, the study focuses on freshwater withdrawal and consumption for electric power generation from conventional and nonconventional and renewable sources. The results of the analysis are expected to (1) provide OBP with a tool for analyzing electricity produced from various renewable sources and the implications on freshwater demand at the state and national levels, (2) assist in comparing between options for fuel sources and technologies, and (3) estimate freshwater-saving benefits. Furthermore, this tool can assist decision makers in the planning and siting of renewable fuel and energy production facilities. The outcomes of such planning and consideration would be maximized resource utilization and minimized competition among different industries for freshwater resources.

2.1 OBJECTIVES AND SCOPE

The primary objective of this study is to develop a data inventory and modeling tool to establish a baseline of current U.S. water withdrawal and consumption levels for electricity generation. The modeling tool will be used to analyze trade-offs among different fuel types and technologies. It covers freshwater and saline water use. Specific goals are to:

- Assemble a data inventory of electric power generation at the state and national scales, including data on:

  - Conventional, nonconventional, and renewable fuel sources;
  - Existing generation technologies;
  - Major cooling types for power production;
  - Water withdrawal and consumption factors for technologies and fuel sources;
  - Freshwater and saline water use for electric power production;

- Determine metric

- Develop a simple and user-friendly interactive tool to:
  - Compare water use among fuel sources, technologies, and cooling systems;
  - Estimate implications of freshwater withdrawal and consumption as a result of changes in fuel sources, technology advances , and choice of cooling systems for individual states and for the nation; and
  - Identify areas with intensive freshwater use in electric power generation.

This study does not include boiler water and fluid gas desulfurization because of their relatively small contribution to total water use.

3 METHODOLOGY

A comprehensive data inventory would be needed for the modeling of water use in electricity generation. Electricity production is routinely reported by the Energy Information Administration (EIA) (e.g., EIA 2007). A thermal electric power plant database has been maintained by the National Energy Technology Laboratory (NETL). The unit water use factor that is applicable to different fuel sources and generation technologies and cooling systems has been reported in a variety of literature and government reports dating from the 1990s to 2008. Therefore, an extensive literature search was conducted, relevant data were identified and organized, and results were analyzed and interpreted. This process required us to identify, compare, and assemble sources; extract and organize data by fuel source, generation technology, and cooling system type; and synthesize results by relevant parameters. We have also consulted with power generation experts at the Electric Power Research Institute (EPRI) during the process. The assembled data inventory serves as a base for the modeling process. This section discusses approaches for inventory development and modeling.

3.1 DATA COLLECTION AND PROCESSING

3.1.1 Freshwater Withdrawal

Total water withdrawal and consumption for thermoelectricity generation in the United States was reported by the U.S. Geological Survey (USGS) every five years until 1995. Since then, USGS has reported only water withdrawal by major sectors (Hutson et al. 2004; Kenny et al. 2009), and data on consumptive water use are no longer collected. The total water withdrawal is further broken down by water type to freshwater and saline water. On the basis of USGS reporting, we calculated the share of freshwater use and saline water use for electricity generation for each state. The state freshwater share is then used to calculate fuel source- and technology-specific total freshwater use in the generation of electricity. The total state freshwater withdrawal for power production that was calculated from the water use factors in various technologies is then calibrated against USGS withdrawal data in 2005. Because the USGS last published data in 2005, that year is considered as the current baseline year.

3.1.2 Electricity Production

On an annual basis, the EIA reports electricity production from various conventional and renewable sources for the United States and for each state. The EIA reports further categorize electricity production by sector (e.g., utility, industrial), by plant type (e.g., combined heat and power [CHP], non-CHP), and by fuel source (e.g., coal, natural gas, petroleum, hydroelectric). For this study, total electricity generation data are based on EIA statistics. To be consistent with USGS water withdrawal data, we used electricity generation in 2005 as a baseline.

Electricity produced through various generation technologies and their corresponding fuel sources is documented in EIA forms 906, 759, and 920 (EIA 2001, 2006). Form EIA-906 and EIA-920 each collect plant-level data on generation, fuel consumption, stocks, and fuel heat content from electric utilities and non-utilities. Form EIA-906 contains monthly data from approximately 1,600 power plants and annual statistics from another 2,689 plants (>1 megawatt [MW]). Form EIA-920 reports data from CHP plants, including monthly reporting from a total of 300 plants and annual statistics for about 600 plants. Form EIA-759 had been used for the same purpose as form EIA-906 until 2001, when form EIA-906 superseded form EIA-759. These data sets are used to determine the production shares of fuel source and generation technology for each state and for the United States overall. In this study, year 2000 data are based on data collected in form EIA-759 (which was replaced by EIA-906 in 2001), and year 2005 data are based on data collected in forms EIA-906 and EIA-920. The results are incorporated into the modeling logic. Table 1 presents the sources of fuel for electricity that are covered in this work. Table 2 lists the electricity generation technologies included in this report.

TABLE 1 Fuel Sources for Electric Power Generation

Category[1]	Subcategory
Coal	Anthracite/Bituminous Coal
	Lignite Coal
	Sub-bituminous Coal
	Waste/Other Coal
	Coal-based Synfuel
Petroleum	Distillate Fuel Oil
	Jet Fuel
	Kerosene
	Residual Fuel Oil
	Oil-Other and Waste Oil
	Petroleum Coke
Natural Gas	
Blast Furnace Gas (BFG)[2]	
Other Gas[2]	
Propane[2]	
Nuclear	
Hydroelectric	
Biomass	Agriculture Crop By-products
	Black Liquor
	Landfill Gas
	Biomass Solid (Municipal solid waste [MSW] and other BM solid waste)
	Other Biomass Liquid
	Other Biomass Gases
	Wood/Wood Waste Solids
	Wood Waste Liquids
Geothermal	

TABLE 1 (Cont.)

Category[1]	Subcategory
Solar	
Wind	
Tires	

[1] Other sources of electricity generation included in EIA data but not listed here are purchased steam, pumped storage hydroelectric, and others (e.g., chemicals).

[2] BFG, propane, and other gases (e.g., petroleum) are combined into the natural gas in the estimate.

3.1.3 Cooling Technology

The type of cooling system is the primary determinant of the amount of consumptive use relative to water withdrawals. Once-through (also known as open-loop) cooling refers to cooling systems in which water is withdrawn from a source, circulated through heat exchangers, and then returned to a surface-water body. Large amounts of water are needed for once-through cooling, but consumptive use is a small percentage of the total withdrawn. Recirculation (also known as closed-loop) cooling refers to cooling systems in which water is withdrawn from a source, circulated through heat exchangers, cooled by using ponds or towers, and then recirculated. Subsequent water withdrawals for a recirculation system are used to replace water lost to evaporation, blow down, drift, and leakage. Although smaller amounts of water are withdrawn for recirculation cooling than for once-through cooling, the consumptive use during recirculation cooling is a larger percentage of the amount withdrawn. Four major types of cooling technologies were considered in this study: once-through cooling, wet recirculating tower cooling, recirculating tower with pond cooling, and air cooling (dry cooling).

TABLE 2 List of Electricity Generation Technologies Used in the Inventory

Generation Technologies
Steam Turbine (ST)
Gas Turbine (GT)
Internal Combustion Engine
Combined Cycle
Hydraulic Turbine
Binary Cycle Turbines
Photovoltaic
Wind Turbine

Coal, Natural Gas, Oil, and Nuclear Power

A benchmark study of thermoelectricity generation that was conducted by Southern Illinois University (SIU) analyzed data from more than 2,000 power plants from 1996 to 2004 and provides excellent statistics for different types of cooling processes and their water use factors (SIU 2006). Although the analysis covers a broad range of types of cooling processes, its representation of fuel sources is limited to the aggregated level: fossil (includes natural gas, coal, and petroleum oil) and nuclear. Historically, NETL has collected and maintained a power plant database for EIA and has performed thermoelectricity production analysis. A comprehensive report (NETL 2006, update issued in 2008) documented cooling technologies used in thermoelectricity generation in the United States and projected future changes in electricity generation and the accompanying levels of water use. The shares by cooling type of electricity generation for coal, petroleum, NG, and nuclear power plants in the NETL report are used in this study.

Biomass Power

Reports on the current share by cooling type for biomass-based power production are scarce. Although some existing plants produce power from black liquor (e.g., pulp and paper industry) and agriculture crop residues (e.g., sugar production), information on dedicated biomass power plants using wood/wood waste solids, municipal solid waste (MSW), and other biomass solids has not been reported to date. An earlier study assumed that the cooling water needs of common biomass-based power generation are comparable to those of a coal-fired power plant (EPRI 2002). Recent developments in biomass energy production showed that feedstock requirements and associated logistics could limit the scale of power production in biomass-fired plants. Further, with increased freshwater conservation efforts in the power sector, the selection of a once-through cooling system for a new biopower project is not likely (Sovacool and Sovacool 2009). Rather, recirculating cooling towers would have increased representation, as projected by NETL (2008). According to the available literature, the most common biomass-based power generation would be direct-fired (stoker, fluid-bed) with steam turbine (ST) (Rankine cycle), co-firing, and gasification based (DeMeo and Galdo 1997). With such system, cooling is not required. We considered the direct-fired system using the boiler water use factor reported by DeMeo and Galdo (1997).

Geothermal Power

Although both steam turbine and binary cycle turbine production exist, historically, ST-based production is the predominant technology in the United States. In particular, the dry steam system employed by the Geysers power plant accounts for 58% of total geothermal electricity production capacity. In terms of the number of plants, a majority of electricity-generating geothermal plants within the United States are binary, mostly in small units. This model uses a steam turbine for estimating water use. In terms of cooling system, there is a mix of dry cooling and wet recirculating systems. We assumed 100% wet recirculating for cooling in geothermal generation.

Other Renewable Sources

For power production based on landfill gas (LFG), biomass gases, and other gases (e.g., blast furnace gas), we assume the cooling type split would be similar to that of an NG-fired (excluding combined cycle) power plant. Solar and wind power generation do not require cooling. Cooling systems for black liquor, MSW, and tire-derived power were assumed to be wet-recirculating systems. Cooling types and their representation in electricity generation from various fuel sources are presented in Table 3. These cooling system mixes were adjusted to match actual statistical data during model calibration.

TABLE 3 Representation of Types of Cooling Systems in Electricity Generation by Various Fuel Sources

Fuel Source	Wet Recirculating (%)	Once-Through (%)	Dry Cooling (%)	Recirculating Tower with Cooling Pond (%)
Coal (Pulverized Coal)[1]	48.0	39.1	0.2	12.7
Fossil Non-coal[1]	23.7	59.2	0.0	17.1
Natural Gas, or Coal Combined Cycle[1]	30.7	8.6	59.0	1.7
Nuclear[1]	43.6	38.1	0.0	18.3
Blast Furnace Gas and Other Gases[2]	23.7	59.2	0.0	17.1
Landfill Gas[2]	23.7	59.2	0.0	17.1
Other Biomass Gases[2]	23.7	59.2	0.0	17.1
Black Liquor[3]		0.0	0.0	0.0
Wood/Wood Waste Solids[3]		0.0	0.0	0.0
Agriculture Crop By-products[3]		0.0	0.0	0.0
Municipal Solid Waste[3]		0.0	0.0	0.0
Other Biomass Solid[3]		0.0	0.0	0.0
Tires[3]	100.0	0.0	0.0	0.0
Waste Heat[4]	23.7	59.2	0.0	17.1
Solar	0.0	0.0	0.0	0.0
Wind	0.0	0.0	0.0	0.0
Purchased Steam[5]	23.7	59.2	0.0	17.1
Geothermal[6]	0.0	0.0	0.0	0.0
Others[7]	23.7	59.2	0.0	17.1
U.S. Total	41.9	42.7	0.9	14.5

Source: Platts (2005), quoted in NETL (2008).

[1] Including petroleum coke, jet fuel, diesel fuel oil, residual oil, waste oil, kerosene, and NG steam turbine.

[2] Cooling type split data for LFG, BFG, and other gases are not available. We assume that they are comparable with NG cooling types in the Fossil Non-coal category.

[3] Cooling type split data for black liquor, wood/wood waste solids, agriculture crop residues, municipal solid waste, tires, and other biomass solid are not available. Process analysis showed current practice for biomass power does not require cooling (DeMeo and Galdo 1997), see section 3.1.4.

[4] Waste heat data are not available. We assume systems similar to those used for BFG and LFG.

[5] Power generated through a steam turbine with purchased steam; we assume same cooling type split as that of non-coal steam turbine.

[6] Cooling type data for geothermal are not available; we assume it uses wet recirculating tower for cooling.

[7] Others include batteries, chemicals, coke breeze, hydrogen, pitch, sulfur, tar coal, and miscellaneous technologies that generate power through steam turbine. We assume same cooling split as that of non-coal fossil.

3.1.4 Unit Cooling Water Withdrawal and Consumption Factors

Water withdrawal and consumption factors in electricity generation and water withdrawn or consumed were collected from the open literature and assembled into a data inventory by fuel source, generation technology, cooling type, and boiling type. As may be expected, there are significant variations among data from several sources. Some are from plant surveys; others are a collection of aggregated literature values (or even from model simulation). To have consistent base data that closely reflect a majority of current power plants, we emphasized original statistics that are specific to fuel source and technology whenever possible during the data-screening process. Unit water factors (gal/kWh) of a particular category of electricity generation from a source/technology/cooling system combination were identified and then compared, and representative factors were then selected as model parameters. When there was a discrepancy among the data, we chose a value within the range that represents the agreement by a majority of researchers, as reported in the literature. The metric used to characterize water withdrawn or consumed are gallons of water per kWh produced.

The SIU study (SIU 2006) provides extensive analysis of the cooling water use factors of seven types of cooling systems for an aggregate of plants producing power from fossil fuels. Nevertheless, these estimates offer a reasonable basis for comparison with other reported values. Because a majority of the fossil-energy-based plants analyzed by SIU were coal-fired power plants, the water withdrawal and consumption factors from that study were used for coal and nuclear plants with once-through cooling, recirculation with natural draft cooling towers, and recirculation with cooling ponds or canals.

On the basis of forecasts by EIA of increases in population and associated increases in energy demand, NETL conducted a series of studies projecting freshwater needs to meet future thermoelectric generation requirements (NETL 2006, 2008). Thermoelectric power plant water use at different plants and production processes was also analyzed in great detail in a 2005 report (Klett et al. 2005). Another major data source is EPRI's report on water and sustainability (EPRI 2002). Unit water withdrawal and consumption factors for natural-gas-fired plants (steam turbine or natural gas combined cycle [NGCC]) and nuclear plants are based on these sources.

During the data screening, we noticed marked differences (i.e., by factors of 60) among several studies in the recirculating cooling pond water factor for conventional coal, oil, natural gas, and nuclear power plants. For example, some reported the water withdrawal factor of a recirculating cooling pond for a conventional coal plant that is close to the value for a wet recirculating tower (0.45 gal/kWh withdrawal [EPRI 2002]), while others estimated a factor close to that of once-through cooling, 24–27 gal/kWh (Yang and Dziegielewski 2007; SIU 2006). More recent estimates by NETL (2008) lean toward the latter value. Because the cooling pond more closely resembles a once-through system rather than a closed-loop recirculation system, we used 24 gal/kWh as a water withdrawal factor for a conventional coal plant with a recirculating cooling pond. A similar approach was used for a nuclear power plant with a cooling pond. We used the NETL (2008) estimate for natural-gas– and oil-fired power plants.

Geothermal water use factors are from a collection of four sources (Gleick 1994; SNL 2006; Larson et al. 2007). Geothermal power generation does require a large amount of water as a heat (energy) carrier (DeMeo and Galdo 1997) during operation. It was estimated that 2,000 gal/MWh for water withdrawal and 1,400 gal/MWh for consumption are required for the dry steam cooling in the Geysers plant (SNL 2006). Within the context of plant operations, water use is often reported as a total of geofluids use; such reporting does not distinguish between makeup water for geofluids and makeup water for use in cooling systems. The data range in Table 4 includes both types of water use.

A hydropower system generally has high consumptive water use as a result of evaporation. Literature data gathered from more than 100 facilities from California and Pennsylvania showed that average evaporative loss is about 2 gal/kWh (Gleick 1992).

Literature values of the water use factor for biomass-fired power plants are incomplete. An EPRI study assumes that it is comparable to the water use factors in coal-fired power plants (EPRI 2002). Another source relies on process analysis (DeMeo and Galdo 1997). We adopt the process analysis approach for determining the water consumption factor associated with direct-fired biomass power production and focus on the direct-fired plant, which is the dominant technology at present. Because water withdrawal data for biomass-fired power generation are not available, we approximate it by using a ratio of water consumption to water withdrawal for biomass power proposed by EPRI’s 2002 study. Table 4 provides a list of water use factors and data ranges of each factor obtained from the literature review.

During the process to synthesize collected literature value of water use factors for each fuel source by generation technology and by cooling system, we rely on mostly the original survey data if all possible. Representative data points were selected. When there is a range of data available for a particular fuel/generation technology/cooling system, a value that is close to the most of the reported data points was used for the model.

3.1.5 Boiler and Fluid Gas Desulfurization

Existing coal-fired power plants use either super-critical or subcritical boilers and flue gas desulfurization for sulfur removal. The amount of freshwater required for boiler operation in thermoelectricity generation is well documented by NETL (2008). In the United States, current majority types of boilers are subcritical boilers (73%), and the remaining 27% are supercritical boilers in coal-fired power plants. In typical coal-fired generation plants, an estimated 32.5% are equipped with fluid gas desulfurization (FGD) (EIA 2007); 67.5% of plants have no scrubbers. Of those with FGDs, 90% use the wet FGD type and 10% use the dry (NETL 2008); this ratio translates to 29.25% of all coal-fired generation plants use wet FGD, and 3.25% use dry (to reach the 32.5% FGD total). Freshwater use for the boiler and FGD, however, is rather small compared to cooling water use (NETL 2008). Thus, boiler water withdrawal and consumption data are included in the inventory but are not factored into the modeling.

3.1.6 Other Technology Assumptions

Saline and Freshwater Use by Generation Technology

Saline water use is reported as a total, which does not distinguish among types of plants, fuel sources, and generation technologies. Saline water use is excluded from the freshwater estimate by using the saline water fraction in total water withdrawal as reported by USGS. However, adopting the aggregated fraction in the model implies the assumption that the freshwater use factor, cooling system mix, and fuel source in freshwater use are in proportions similar to that of saline water use. This assumption will be updated when the relevant data become publicly available.

Future Shares of Cooling System and Generation Technology

It is generally agreed that use of wet recirculation and air cooling systems would increase in newly planned thermoelectric generation plants because of their relatively lower or nil water withdrawal and consumption factors (NETL 2008). It has also been demonstrated that the combined cycle process can significantly reduce freshwater requirements in electric power generation. However, quantitative projections of future shares of cooling systems and integrated gasification combined cycle (IGCC) or NGCC for each state were not available at the time of this study. This model assumes a baseline share for both the generation technology and cooling systems in future simulations.

State Cooling System Share

The relative share of the number of cooling systems (i.e., once-through, wet recirculating, cooling pond, and air cooling) in this inventory represents national averages that were collected from a literature review. The national average was applied to the state estimate because the shares of state-specific cooling systems are not available. In addition, the four cooling systems that were chosen are the major systems. During the model calibration phase, we adjusted state cooling mix to match freshwater withdrawal value recorded by USGS for major production states. Nevertheless, the estimate for some states may depart from the actual value if a state’s share of a particular cooling system is very different from the national average.

TABLE 4 Literature Value of Water Withdrawal and Consumption Factors in Electricity Generation

Fuel Source	Cooling Type	Withdrawal Factor (gal/kWh)	Consumption Factor (gal/kWh)	Reference
Coal — Conventional Pulverized Coal	Once-through	22.55–50.50	0.06–0.39	NETL 2008; Gleick 1994; EPRI 2002; Yang and Dziegielewski 2007; SIU 2006; Knipping 2009
	Wet recirculating	0.46–1.20	0.39–1.04	
	Cooling pond	0.45–27.4	0.00–0.80	NETL 2008; EPRI 2002; Yang and Dziegielewski 2007; SIU 2006; Knipping 2009
Coal — IGCC	Once-through	11.67–22.81	0.10–0.25	EPRI 2002
	Wet recirculating	0.23–0.75	0.17–0.69	NETL 2008; SNL 2006; EPRI 2002; Klett et al. 2005
	Cooling pond	0.20–0.39	0.20–0.31	Knipping 2009
Oil Combustion	Once-through	22.74–35.00	0.09–0.30	NETL 2008; Gleick 1994; EPRI 2002
	Wet recirculating	0.25–0.55	0.16–0.69	
	Cooling pond	0.45–7.89	0.11–0.39	NETL 2008; EPRI 2002
Natural Gas — Steam Turbine	Once-through	22.74–35.00	0.09–0.30	NETL 2008; Gleick 1994; EPRI 2002
	Wet recirculating	0.25–0.55	0.16–0.69	
	Cooling pond	0.45–7.89	0.11–0.39	NETL 2008; EPRI 2002
Natural Gas — NGCC	Once-through	9.01–11.67	0.02–0.11	NETL 2008; SNL 2006; EPRI 2002
	Wet recirculating	0.15–0.50	0.13–0.50	NETL 2008; SNL 2006; Klett et al. 2005; EPRI 2002
	Cooling pond	5.95	0.24	NETL 2008
	Air (dry) cooling	0.00	0.00	EPRI 2002
Nuclear	Once-through	31.50–48.00	0.14–0.40	NETL 2008; SNL 2006; EPRI 2002; SIU 2006
	Wet recirculating	0.95–2.60	0.59–0.85	NETL 2008; SNL 2006; SIU 2006; EPRI 2002; Gleick 1994
	Cooling pond	0.80–13.0	0.50–0.75	SIU 2006; SNL 2006; EPRI 2002

TABLE 4 (Cont.)

Fuel Source	Cooling Type	Withdrawal Factor (gal/kWh)	Consumption Factor (gal/kWh)	Reference
Geothermal[1] — Steam Turbine	Once-through	NA[2]	3.43	Gleick 1994
	Wet recirculating	2.00	0.38[6]–1.80	Gleick 1994; SNL 2006; Adee and Moore (2010)
Geothermal[1] — Binary Turbine	Once-through	15.00	NA[2]	Larson et al. 2007
	Once-through		4.65[6]	Adee and Moore 2010
	Wet recirculating	6.00	3.96	Gleick 1994; Larson et al. 2007
	Air (dry) cooling	2.00	NA[2]	Larson et al. 2007
Solar — Luz System	Wet recirculating	0.84	0.84–1.06	Gleick 1994; SNL 2006
Solar — Photovoltaics	Wet recirculating		0.03	Gleick 1994
Biomass — Direct Combustion, Steam Turbine[7]		0.61	0.61	DeMeo and Galdo, 1997
Biomass — Gasification			0.04[3]	DeMeo and Galdo, 1997
Biomass/Agricultural Residue/Wood/MSW/ Biosolid/Waste Steam/Tire	Once-through	35.00	0.30	EPRI 2002
	Wet recirculating	0.55	0.48–0.61	EPRI 2002; Gleick 1994
Biogas/LFG[4]/Other Gases, Steam	Once-through	35.00	0.3	EPRI 2002
	Wet recirculating	0.25	0.16	NETL 2008
	Cooling pond	7.89	0.11	NETL 2008
Hydro Power			2.00–4.49	Gleick 1992, 1994
Wind		0	0	Gleick 1994
Others[5]	Wet recirculating	0.55	0.48	EPRI 2002

[1] Drilling water for geothermal power during construction period is not used in this estimate.

[2] NA = not available.

[3] Boiler water consumption in biomass gasification is not used in this estimate.

[4] LFG = landfill gases.

[5] Others include batteries, other chemicals. We assume recirculating cooling, where water use is comparable to that used in oil combustion.

[6] Values of 0.38 gal/kWh and 4.65 gal/kWh are from Adee and Moore (2010) and are provided as “water use.” No information is provided on whether the values are for withdrawal or consumption; we assume consumption.

[7] Stokers and fluid-bed combustion. No cooling requirement. Value shown are boiler water use factors.

3.2 MODEL DEVELOPMENT

On the basis of the data inventory described in Section 3.1, an interactive tool has been developed that calculates the requirements for freshwater withdrawal and consumption to meet the demand for electricity generation in the 50 states of the United States. It covers energy sources, generation technology, and major cooling systems for the existing power sector. This section details steps involved in tool development.

3.2.1 Framework and Algorithm

The tool framework was structured to allow a quick estimate of freshwater use in electric power generation. The estimate will be specific to fuel source, generation technology, and cooling system. Users will be able to compare water withdrawal and consumption among generation technologies for the same fuel, cooling systems for the same fuel and generation technology, and different fuel sources for generating the same amount of electricity to meet the demand in a particular state or region. In addition, users can examine changes or improvements made or that would be expected in water use over time by simulating the historical trend and developing future projections for individual states and for the entire nation. The algorithm begins with user selections followed by an interface with the data inventory and subsequent calculations to deliver the final estimates. Figure 3 illustrates the logic and calculation steps for finding freshwater withdrawal and consumption levels in electricity production.

The calculation logic in Figure 3 is carried out further through calculations described in equations 1–4. Equations 1 and 2 present total freshwater withdrawal and consumption associated with power generation on the basis of technology share and cooling share for various fuel sources in each state. Equations 3 and 4 summarize state estimates to derive a national value of water withdrawal and consumption.

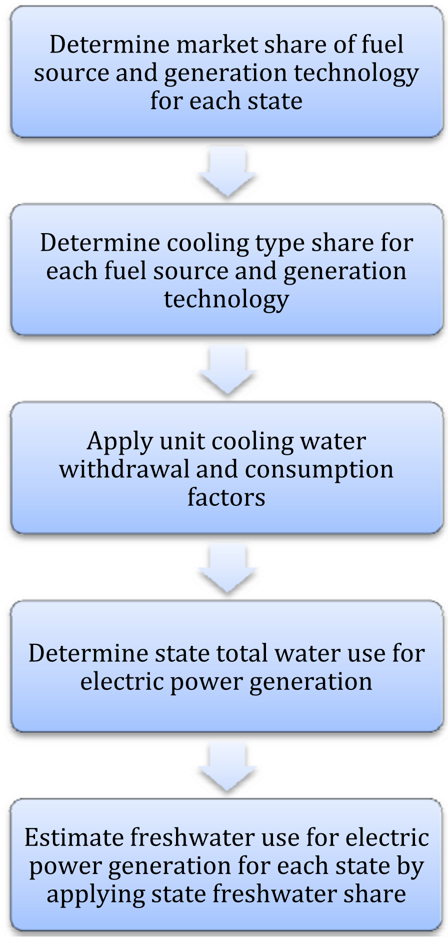

FIGURE 3 Steps to Estimate Freshwater Withdrawal and Consumption in Electricity Production

$$TFWW_i = EG_i \times \left\{ \sum_j S\&T\ share_{ij} \times \left(\sum_k CT\ share_k \times WWF_{kj} \right) \right\} \times FWshare_i \cdots [Equation\ 1]$$

$$TFWC_i = EG_i \times \left\{ \sum_j S\&T\ share_{ij} \times \left(\sum_k CT\ share_k \times WCF_{kj} \right) \right\} \times FWshare_i \cdots [Equation\ 2]$$

$$TFWW_{US} = \left\{ \sum_i TFWW_i \right\} \cdots [Equation\ 3]$$

$$TFWC_{US} = \left\{ \sum_i TFWC_i \right\} \cdots [Equation\ 4]$$

where:

TFWW = total freshwater withdrawal
TFWC = total freshwater consumption
$TFWW_{US}$ = total freshwater withdrawal in the United States
$TFWC_{US}$ = total freshwater consumption in the United States
EG = electricity generation
i = state
j = type of generation technology for a fuel source
k = type of cooling technology
S&T share = fuel source and generation technology share
CT share = cooling type share for a generation technology for a fuel source
WWF = water withdrawal factor
WCF = water consumption factor
FW share = freshwater use share

3.2.2 Modules

A Visual Basic A program is developed for the interactive simulation. The program consists of three modules: Current, Historic, and Future. The Current module provides a baseline estimate using 2005 data. In this module, users are able to select key input parameters, including state and cooling types (i.e., once-through, wet recirculating, cooling pond, and air cooling), and the tool will compute total freshwater withdrawal and consumption on the basis of the fuel source, generation technology share, and cooling types of the selected state for power generation.

The Historic module estimates freshwater withdrawal and consumption in electric power generation at the state and national levels. Freshwater withdrawal and power generation data from 2000 (Hutson et al. 2004; EIA 2001) and 2005 (Kenny et al. 2009; EIA 2006) were gathered. Fuel sources, generation shares, and cooling shares have been incorporated into the model. Freshwater withdrawal and consumption for electricity production by different fuel sources and generation technologies in 2000 and 2005 are estimated. Finally, a comparison can be made in water withdrawal and consumption between 2000 and 2005. This module is expandable to include additional historical data.

In the Future projection module, the user is given options to choose a state or the entire United States, input incremental changes in total electricity demand, and input shares of fuel sources desired. The model will calculate total water withdrawal and consumption levels for projected power generation changes. Although we expect an emphasis on air cooling (dry cooling) for power production in geothermal areas and on wet recirculation (cooling) towers in general, recent projections of future cooling systems for the entire power sector and a quantitative estimate of future cooling shares are limited in this study, and so the baseline shares are used for future estimates. Cooling share values for the future can be updated once such data become available. Similarly, we assume a comparable technology split with the baseline for each type of fuel source.

3.2.3 Model Calibration

As indicated in previous sections, the cooling technology shares we obtained are national survey values, which may or may not apply to individual states. Using the national average cooling share to estimate state-level cooling shares would lead either to over- or underestimating total water use. Therefore, a rigorous model calibration was conducted. Freshwater withdrawal was calibrated against observed water withdrawal data in 2005 (Kenny et al. 2009) by adjusting the cooling type shares of individual states. We selected the 20 major power-producing states and freshwater use states for power generation — Alabama, Arizona, California, Florida, Georgia, Illinois, Indiana, Louisiana, Michigan, Missouri, Nebraska, New York, North Carolina, Ohio, Pennsylvania, South Carolina, Tennessee, Texas, Virginia, and Wisconsin, — for the model calibration. Additional states were added during calibration as needed. These states are: Colorado, Kansas, Nevada, New Mexico, Oklahoma, Utah, and Wyoming. Because coal power with once-through cooling systems contributes to a majority of water use, during the calibration, the adjustment in cooling share was made in the following sequence: (1) once-through cooling for coal power, (2) once-through and pond cooling for nuclear sources, (3) natural gas sources, and (4) others. The freshwater withdrawal from model estimation and actual data are then compared. The model prediction for water withdrawal for 2005 was quite satisfactory. Figure 4 shows that the predicted values match well (R^2=0.99) with observed values for the calibrated states. Differences between model prediction and observed values for the calibrated states are 2.2% and for the United States are 0.6%. The model is then used to estimate water consumption during power generation for the selected scenarios.

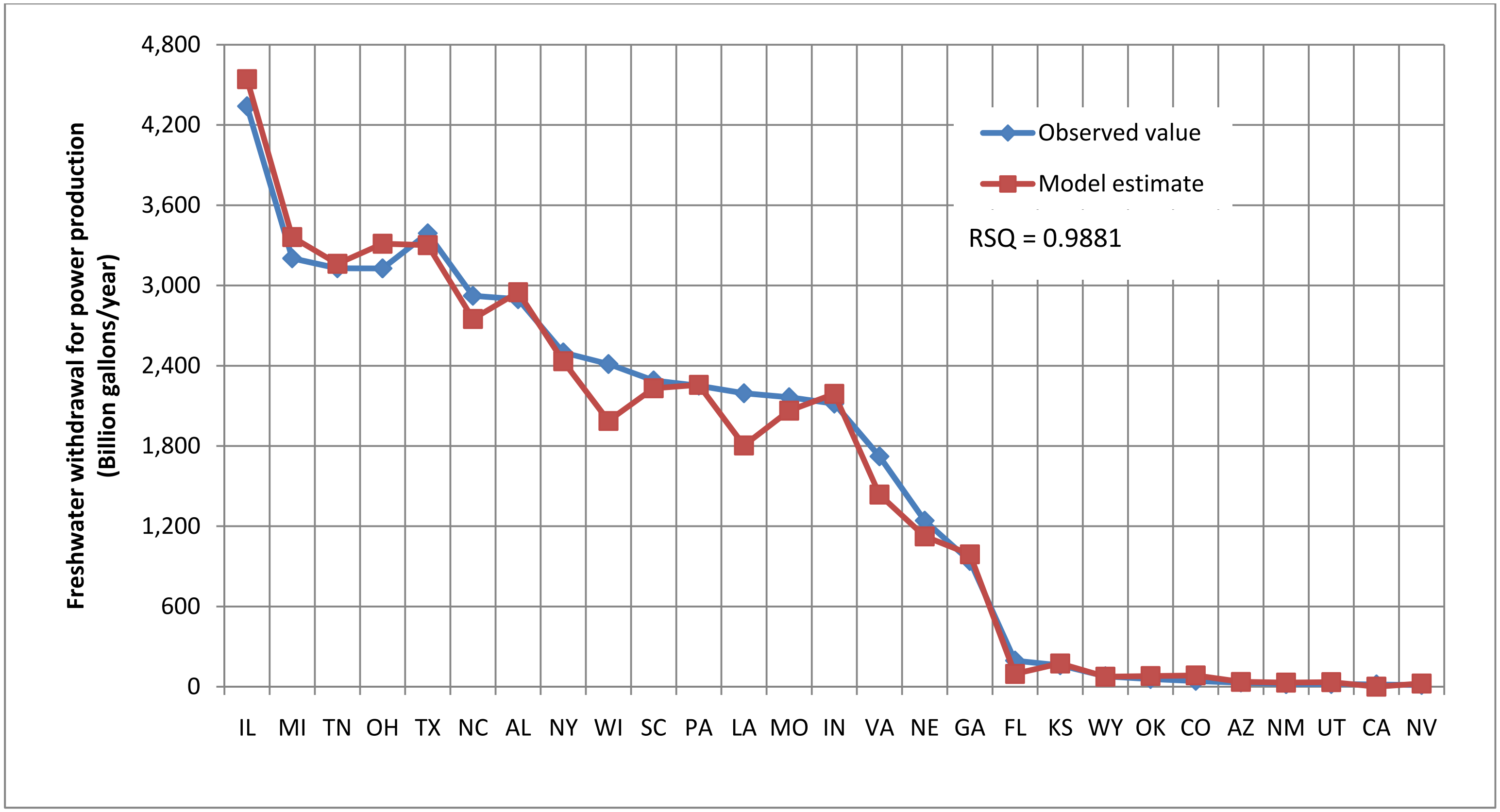

FIGURE 4 Model Calibration Results for Freshwater Withdrawal in Major Power-Producing and/or Water-Using States in 2005. Observed Values are from USGS (Kenny et al. 2009)

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4 RESULTS

4.1 ANALYSIS OF WATER WITHDRAWAL AND CONSUMPTION FACTORS

4.1.1 Fuel Source and Technology

Table 5 presents modeled electricity generation breakdown by major fuel source and then by cooling technology. In 2005, nearly 91% of electricity production in the United States was generated by conventional fossil and nonfossil fuels (EIA 2006). Among this group of fuels, approximately one-third of electricity production was generated by coal and nuclear plants using once-through cooling systems (Table 5). However, the largest contributor of power generation is from wet-recirculating cooling systems, which account for 38.5% of total U.S. electricity generation (Table 5). With its low water requirements for withdrawal, incorporation of wet-recirculating cooling will likely continue to grow. Air cooling or dry cooling is almost exclusively used in the NGCC plant. Its production share at current is still limited (9%).

Figure 5 shows the estimated water withdrawal factors of the top 12 fuel/generation/cooling system combinations that were responsible for 91% of electricity generation in the United States in 2005. From a water use viewpoint, the once-through cooling system is still the dominant water user in power generation by the major fuel sources, followed by the cooling pond. NGCC plants use the lowest amounts of water by fuel source: NGCC plants generated approximately 14% of electricity in the United States while requiring only 1.2 gallons for water withdrawal and consuming 0.1 gal per kWh, which is the net water use. In fact, natural gas–based power generation has led the growth in recent years (Figure 2). In particular, NGCC with wet recirculating cooling is most promising from a water conservation perspective.

On the basis of a weighted average by cooling types and then by major fuel sources (fossil and non-renewables), 14.7 gal of cooling water must be withdrawn and 0.42 gal consumed to generate one kilowatt-hour of electricity in the case of 91% of electricity production (Table 5). Without NGCC plants, 17–22 gal of cooling water are withdrawn and 0.3–0.6 gal are consumed to generate one kilowatt-hour of electricity for a majority (77%) of the electricity production in the United States, which includes coal, nuclear, oil, and conventional natural gas plants (Table 5). The unit water use factor (gallons per kWh of electricity) provides a basis for analysis and comparison.

Power generated by renewable resources — in particular from biomass, agricultural waste, landfill gas, geothermal, solar, and wind — is still small, accounting for 2.15% of total U.S. generation. Hydropower is the dominant renewable power source, with reportedly 6.8% of production shares. Most of the biomass-based power generation plants use wet recirculating cooling systems, whereas renewable gas-based power generation plants rely on both once-through and wet recirculating. Table 6 presents modeled cooling water requirements for electricity generated from use of renewable sources — solar, wind, biomass, agricultural residue, landfill gas, waste sludge, wood waste, biogas, black liquor, and hydropower. Individual water

TABLE 5 Modeled Cooling Requirements for Electricity Generation from Major Sources (Fossil and Non-renewable)

Cooling Type	Withdrawal (gal/kWh)	Consumption (gal/kWh)	Cooling Share (%)	Water Withdrawal Factor by Source[1] (gal/kWh)	Water Consumption Factor by Source[1] (gal/kWh)	Percent in Total Generation by Fuel Source (%)
Conventional coal						
Once-through	35.00	0.30	39	17.2	0.5	49.60
Recirculating	1.00	0.70	48			
Cooling Pond	24.00	0.70	13			
Dry Cooling	0.00	0.00	0.2			
Nuclear						
Once-through	48.00	0.40	38	21.8	0.6	19.28
Recirculating	2.60	0.80	44			
Cooling Pond	13.00	0.50	18			
Dry Cooling	0.00	0.00	0			
NGCC						
Once-through	11.67	0.10	9	1.2	0.1	14.10
Recirculating	0.18	0.16	31			
Cooling Pond	5.95	0.24	2			
Dry Cooling	0.00	0.00	59			
NG and Oil						
Once-through	35.00	0.30	59	22.2	0.3	8.10
Recirculating	0.55	0.48	24			
Cooling Pond	7.89	0.11	17			
Dry Cooling	0.00	0.00	0			
Total				14.70[2]	0.42[2]	91

1 Average weighted by power generation in 2005.

2 Sum of factors that are weighted by fuel mix in the United States.

use factors were aggregated by cooling type share within each fuel source and then by fuel mix in the United States to calculate a weighted average. As shown in Table 6, renewable sources required only 0.09 gal of freshwater withdrawal and 0.14 gal of freshwater consumption to produce one kilowatt of electricity. Note that hydropower consumes freshwater, which is included in the 0.14 gal/kWh. The water withdrawal factor for renewables is less than one-tenth of that required for nonrenewable fuels (14.7 gal/kWh as shown in Table 5). By combining the nonrenewable and renewable fuel sources together, we aggregated the electricity mix, generation technology, and cooling system mix to determine a set of national water withdrawal and consumption factors. On average, 14.79 gal of water withdrawal and 0.56 gal of water consumption are required to generate one kilowatt hour of electricity in the United States. Note that the technology-based analysis does not differentiate between freshwater and saline water used for power generation. Therefore, this set of figures includes saline water use.

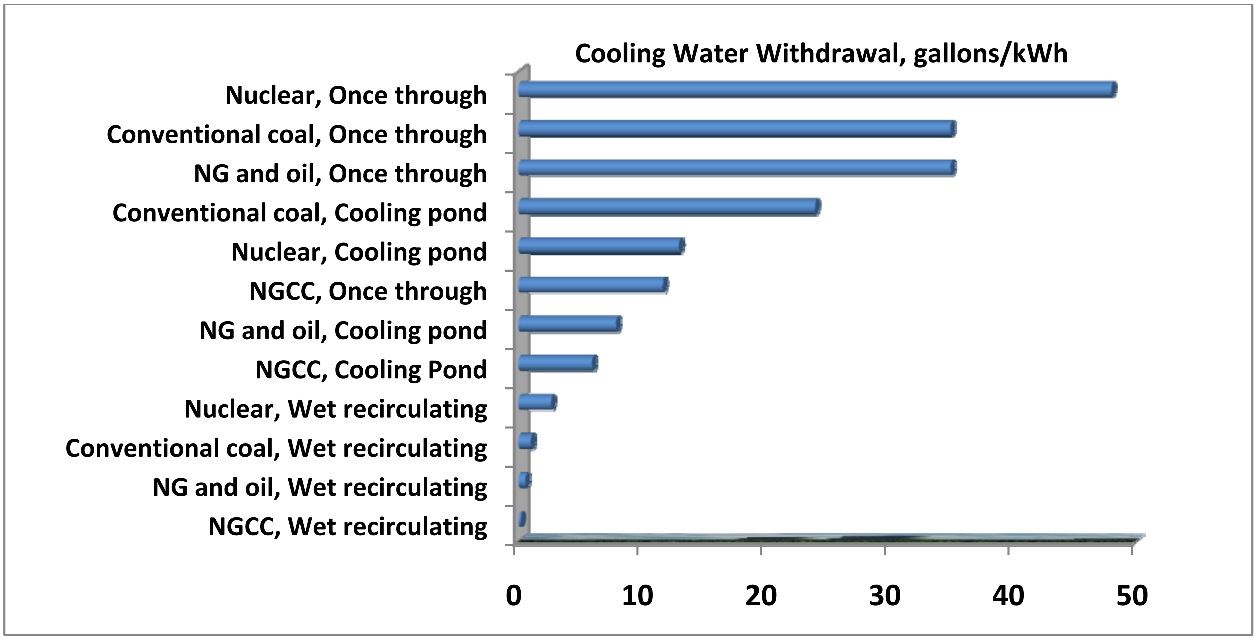

FIGURE 5 Water Withdrawal Factors of Top 12 Cooling Systems

Although renewable sources (especially biopower) at present contributes only a small fraction of power to the entire U.S. electricity mix, with the projected EISA target and rapid development of biorefinery and renewable natural gas, its share is likely to grow. From the perspective of freshwater conservation, wet recirculating cooling systems will likely continue to be an acceptable option for such facilities. Increased share of renewables in the national electricity mix would benefit in terms of both greenhouse gas emissions and freshwater use. If renewable electricity plants with existing cooling system mix displace coal-based facilities with a once-through cooling system, the average water withdrawal per kWh of electricity production is likely to decrease. If all new renewable facilities are built with wet recirculating cooling systems, water use can be reduced even further.

In addition, it is planned that new fossil power plants will be mostly wet circulating NG plants. Coal plants with recirculating cooling would still be an attractive option because of their relatively modest water withdrawal requirements. As old plants are retired, we expect to see a shift toward reduced use of once-through cooling systems and an increased use of recirculating tower systems and, perhaps, even dry cooling systems, which would result in reduced water withdrawal and water consumption on the whole. Recent developments in renewable power production indicate increased interest in a dry cooling system for a geothermal plant in California. However, the plant could still have a large land footprint because of the significantly increased land requirement for the dry cooling system to meet the plant's cooling needs.

TABLE 6 Modeled Water Use for Electricity Production by Type of Renewable Source

Fuel Sources	Cooling Type	Withdrawal, gal/kWh	Consumption, gal/kWh	Cooling Share within the Source/ Technology[1] (%)	Weighted Average Water Withdrawal Factor by Source (gal/kWh)	Weighted Average Water Consumption Factor by Source (gal/kWh)	Total Generation by Fuel Source (%)
Geothermal – Steam	Recirculating	2.00	1.40	100	2.0	1.4	0.35
Geothermal – Binary	Recirculating	6.00	3.96	100	6.0	4.0	0.02
Solar Thermal –- Luz System	Recirculating	0.84	0.84	100	0.8	0.8	0.01
Biomass/Agricultural Residue/Wood/MSW/ Biosolid	—[4]	0.61	0.61	100	0.6	0.6	0.99
Biogas/LFG/Other Gases	Once-through	35.00	0.30	59	22.1	0.2	0.35
	Recirculating	0.25	0.16	24			
	Cooling Pond	7.89	0.11	17			
	Dry Cooling	0.00	0.00	0			
Wind		0.00	0.00	0	0.0	0.0	0.44
Hydro			2.00			2.0[2]	6.67
Weighted Average					0.09	0.14[3]	Total: 8.8

[1] National average. Sources: NETL (2008); Platts (2005). Note: Cooling type split data are not available for black liquor, wood/wood waste solids, agriculture crop residues, municipal solid waste, tires, and other biomass solid; thus, we assume wet-recirculating cooling. Cooling type split data are not available for LFG, BFG, and other gases; we assume the data are comparable to NG cooling types in the Fossil Non-coal category. Cooling type data are not available for geothermal; we assume this source requires no external water for cooling (Gleick 1994). Waste heat data are not available; we assume the data are similar to that of BFG and LFG.

[2] Hydropower does not require cooling. The value indicates a net water consumption factor.

[3] The aggregated consumption factor value is higher than the withdrawal value because it includes net water consumption in hydropower.

[4] Most biomass power generation unit employs direct combustion with a steam turbine (Table 4) where cooling system is not used. The value in this table is boiler water requirement.

4.1.2 State Water Use

The weighted average of the water withdrawal factor for each state was further calculated on the basis of state electricity production and fuel source mix as reported by the USGS (Kenny et al. 2009) and EIA (2010). Figures 6, 7, and 8 present average water withdrawal factors by state, electricity production by state , and total freshwater withdrawals by state in 2005. Data for 2005 show that Texas is the largest power producer, and Illinois withdraws the largest amounts of water for power. Total water use in power generation for each state is influenced strongly by total power generated, fuel mix, and major type of cooling systems employed. For example, Wisconsin and Nebraska withdraw the most freshwater for each kilowatt of electricity produced in 2005 (Figure 6). However, because their levels of annual power generation are relatively small as seen in Figure 7, the total amounts of freshwater withdrawn for the two states remain modest (Figure 8). Missouri and Illinois, on the other hand, have similar per-kWh water withdrawal rates; however, the electricity generated in Illinois is almost twice as much as that generated in Missouri (Figure 7). Therefore, total water use in Illinois becomes much larger (Figure 8). In contrast, Texas has a much smaller withdrawal factor compare to that of Pennsylvania, although the two states withdraw comparable total amounts of water as a result of the considerable power generation occurring in Texas. As indicated in Section 4.1.1, once-through cooling systems constitute a significant portion of total water withdrawal (Figure 5). Figure 9 presents the states in which once-through cooling water systems predominate. Not surprisingly, a majority of these are also among the top water users (Figures 6 and 9).

4.2 ANALYSIS OF MAJOR POWER-PRODUCING AND WATER-USING STATES

Analysis has been conducted to estimate current water use in electricity generation for the top electricity-generating and water-using states. As of 2005, 17 states — Alabama, Arizona, California, Florida, Georgia, Illinois, Indiana, Louisiana, Michigan, New York, North Carolina, Ohio, Pennsylvania, South Carolina, Tennessee, Texas, and Wisconsin — withdrew 76% of the total freshwater withdrawn for thermal power generation (Figure 10). These states together generated 2,645,202 million kWh in 2005, which is 65% of the electricity generated in the United States (EIA 2006). Texas stands out as the largest power-producing state — it holds nearly 10% of the generation share while using 7.2% of freshwater withdrawal. The top five water-use states — Illinois, Texas, Michigan, Ohio, and Tennessee — account for one-third of the freshwater withdrawal to generate only one-fourth of the total power in the United States. Of these 17 states, California and Florida withdraw among the lowest amounts of freshwater to produce power. During the five-year period from 2000 to 2005, a trend toward water conservation emerged in southern states. Thus, compared to 2000, the top five water-use states have changed. The state of Tennessee moved down from being the third-largest water user in 2000 to the fifth-largest in 2005. The state of Alabama also moved down from fifth- to seventh-largest, while the state of Michigan moved up from the seventh- to the third-largest.

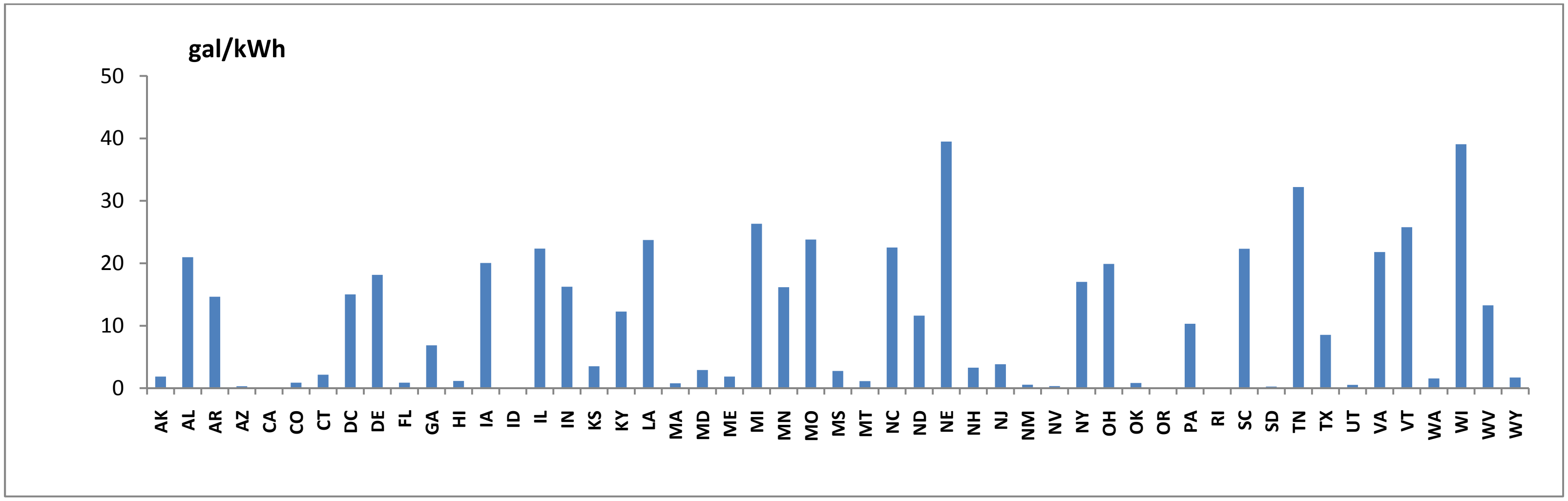

FIGURE 6 Freshwater Withdrawal Factor (gal per kWh) for Electricity Generation in the 50 States and Washington, D.C. (Sources: Kenny et al. 2009; EIA 2006)

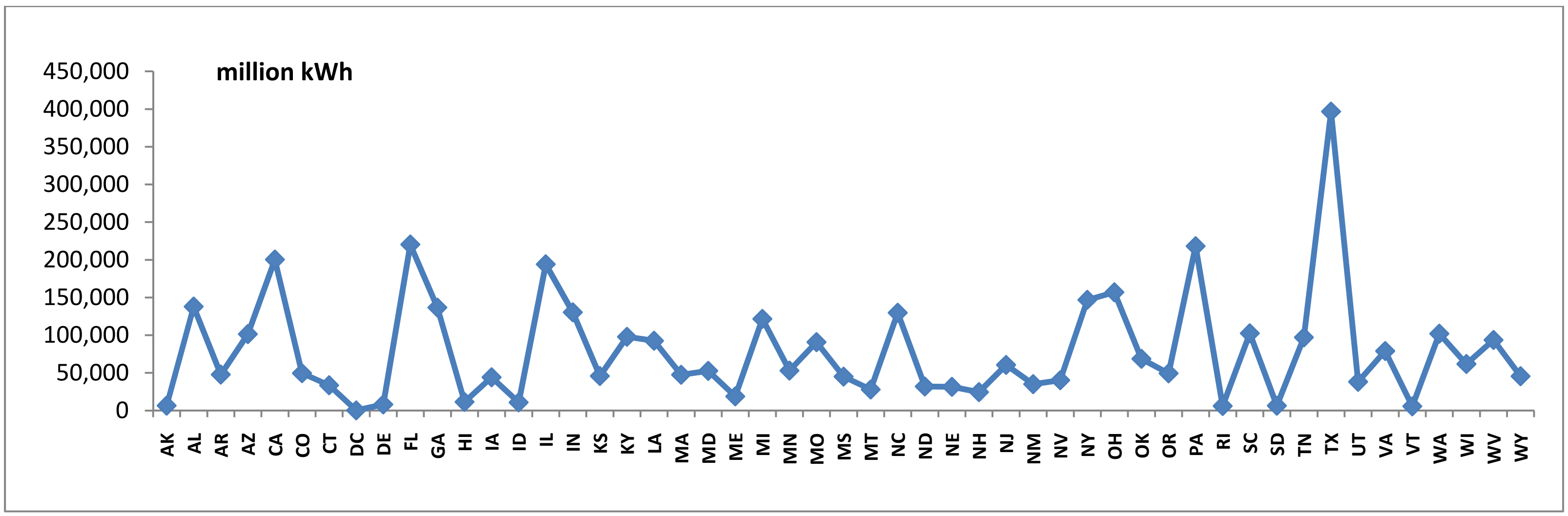

FIGURE 7 Electricity Generated in the 50 States and Washington, D.C., in 2005 (Source: EIA 2006)

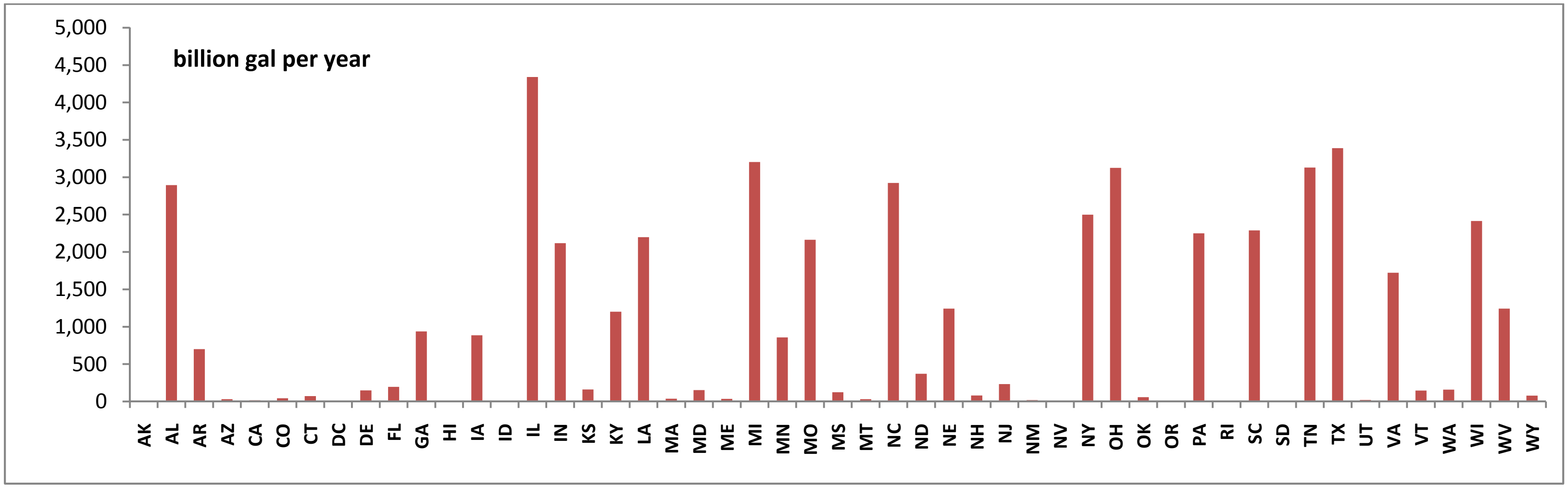

FIGURE 8 Total Freshwater Withdrawal for Electricity Generation in the 50 States and Washington, D.C., in 2005 (Source: Kenny et al. 2010)

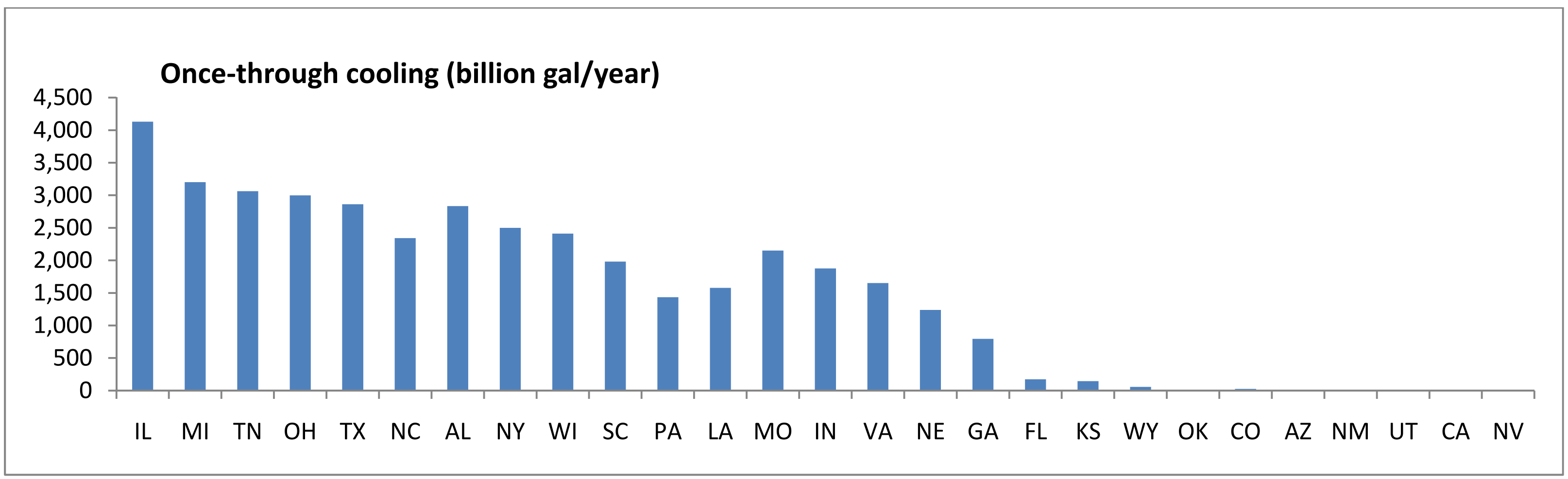

FIGURE 9 Amount of Freshwater Withdrawal from Once-Through Cooling Plants in Major Power-Producing — and Major Water-Using — States in 2005 (Source: Kenny et al. 2009)

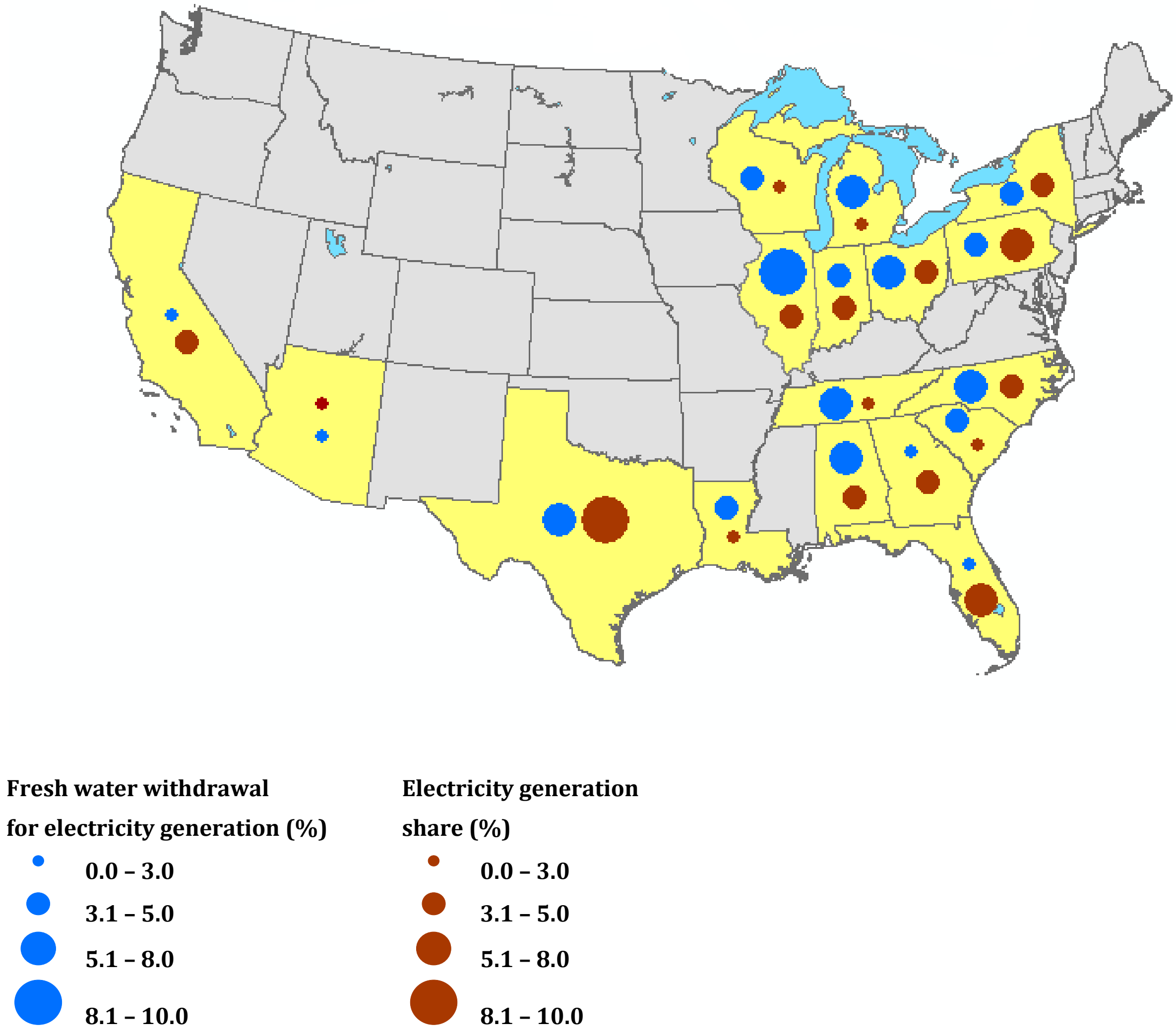

FIGURE 10 Comparison of Freshwater Withdrawal for Electricity Generation by the 17 States that are Responsible for 65% of Electricity Production in the United States

Depending on the fuel source, geographic location, and availability of other water sources, freshwater use can vary significantly in the major electricity-producing and water-using states (Figure 11a). Historically, Illinois has had several nuclear power facilities, as well as coal-based plants. Together, the nuclear and coal power plants provide nearly 95% of the state's electricity generation. This electricity mix is primarily the result of sizable coal reserves in the state and an abundance of surface freshwater available for use in once-through cooling. In regions with freshwater scarcity, such as in the west of Texas, cooling water has become an important consideration in power plant design. Texas produces about half of its total electricity from natural gas–based plants; most of them are equipped with recirculating cooling systems that have a lower water withdrawal requirement. Such a fuel source mix for electricity reduces total water withdrawal demand.

In contrast to water withdrawal, freshwater consumption is rather small, typically less than 1 gal per kilowatt of electricity produced. Alabama, Georgia, Illinois, Pennsylvania, and Texas are among the top consumers of freshwater for power generation (Figure 11b). It is noted that even though Texas withdrew less freshwater than Illinois, the amount of freshwater consumed by Texas for power is slightly higher (Figure 11b). This result could be attributable to a higher water consumption ratio (gal per kWh) in wet recirculating cooling towers relative to that of once-through cooling systems. For example, a conventional coal plant with once-through cooling consumes 0.06–0.39 gal of freshwater, whereas recirculating cooling for a conventional coal plant requires 0.39–1.04 gal of freshwater to produce one kilowatt of electricity (Table 4). A large number of generation facilities with wet recirculating cooling towers in Texas could increase the net consumption relative to withdrawal. Nevertheless, the wet circulating system is water efficient such that with its slightly higher water consumption, Texas nevertheless almost doubled its electricity generation over that of Illinois (Figure 11b).

Figure 12 presents freshwater withdrawal and consumption per kWh of electricity generated for the 17 major states. According to this metric, Wisconsin, Tennessee, Michigan, and Louisiana were ranked in the top four in water withdrawal, whereas Georgia, Pennsylvania, South Carolina, and Tennessee are the top unit water consumers in power generation in 2005. In the 17 states, three states — California, Florida, and Arizona — are not major water users (Figures 8 and 11a). Without including these three states, water factors ranged from 6.9–39.1 gal/kWh for withdrawal and from 0.26–0.64 gal/kWh for consumption. The water-use factors above translate to a power generation weighted average of 14.3 gal freshwater withdrawal and 0.37 gal freshwater consumption per kWh of electricity generated. Nationally, the average withdrawal figure is at the lower end of the range — 12.3 gal/kWh for freshwater withdrawal — but is right in the middle of the range — 0.43 gal/kWh — for freshwater consumption.

4.3 SALINE WATER USE

In regions where saline and brackish water is available, extensive effort has been made to use these resources, such as selecting saline water for thermal power production. Currently, saline water use is about one-third of the total. Figure 13 presents saline water use for thermal power generation in 2000 and 2005. In 2005, Florida and California — both major power-producing states containing large saline water supplies — withdrew less than 1,000 million gal/day of freshwater while taking 24,100 million gal/day of saline water for power generation. Hawaii and Utah were the latest states to join the pool of users of saline water for power. Nationwide, a total of 29% of the water withdrawals for thermal electric power production in 2005 were of saline water from oceans and brackish coastal water bodies (Kenny et al. 2009). When compared with data for 2000, power generation increased by 6.7% and total water withdrawal increased by 3% — which is a clear sign of an overall trend of water conservation in the power sector. Saline water use in power generation is likely to continue to increase. It is particularly likely in states with limited freshwater resources and rich saline sources. A similar approach can also be adopted for renewable energy generation, such as saline water use in the production of advanced biofuel from algae and generation of power from geothermal source. For

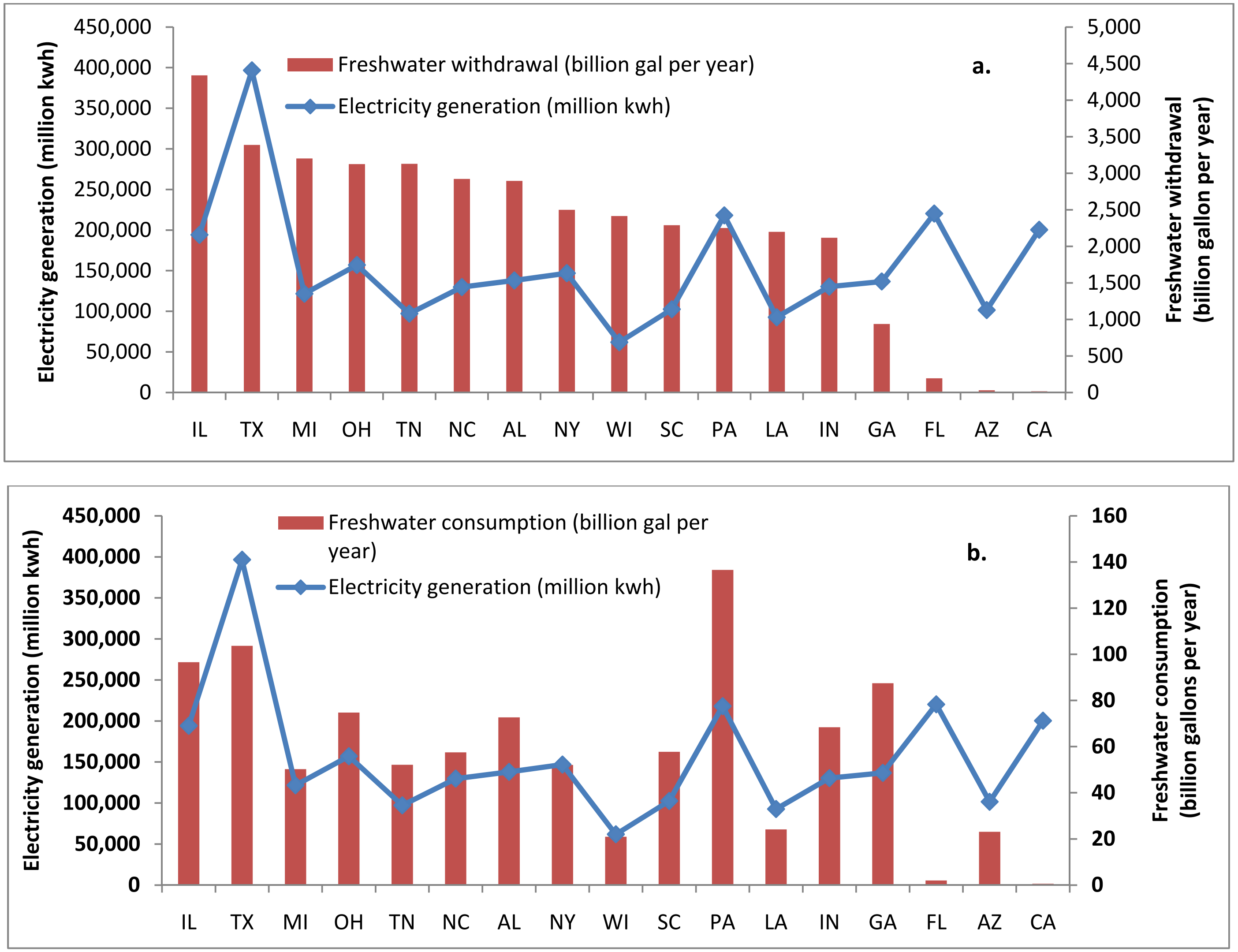

FIGURE 11a (top) and 11b (bottom). Freshwater Withdrawal (a) and Consumption (b) for Thermal Electricity Generation by Major States in 2005 (Water withdrawal data source: Kenny et al. 2009). Note: Water consumption rates are model estimates.

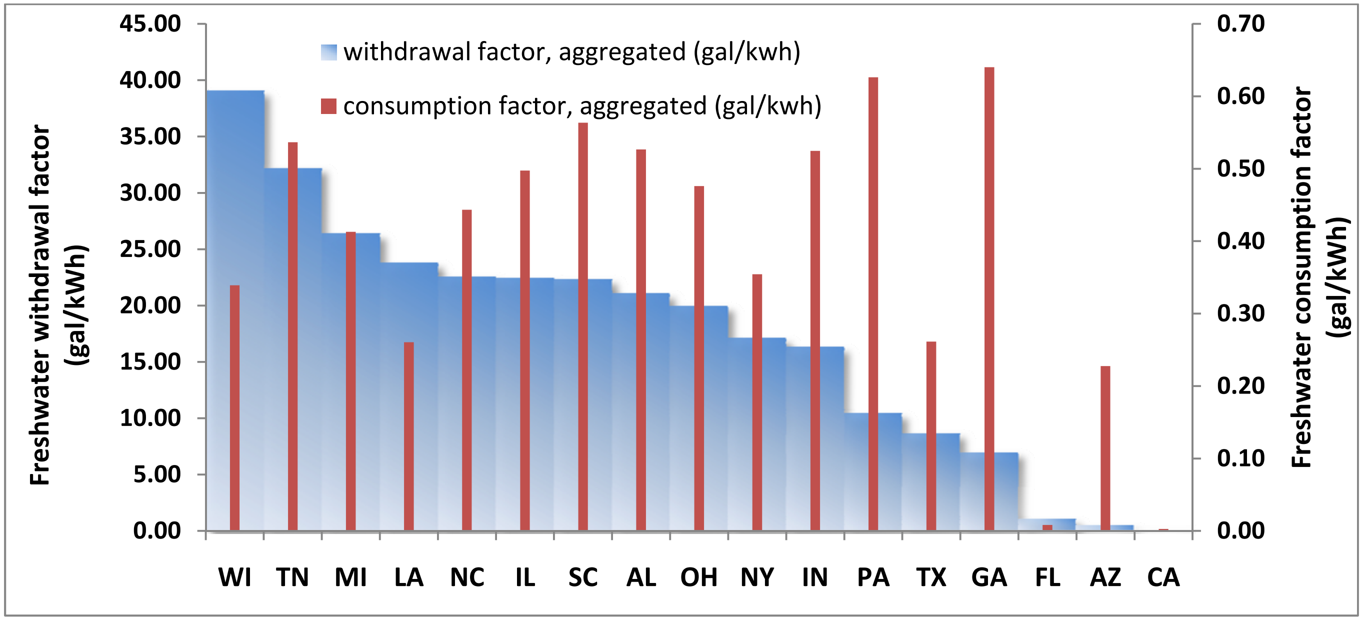

FIGURE 12 Freshwater Withdrawal and Consumption per Kilowatt-hour of Electricity Produced for the Major Power-Producing and Water-Using States (Sources: water withdrawal – Kenny et al. 2009; water consumption – modeling results; power generation – EIA 2006)

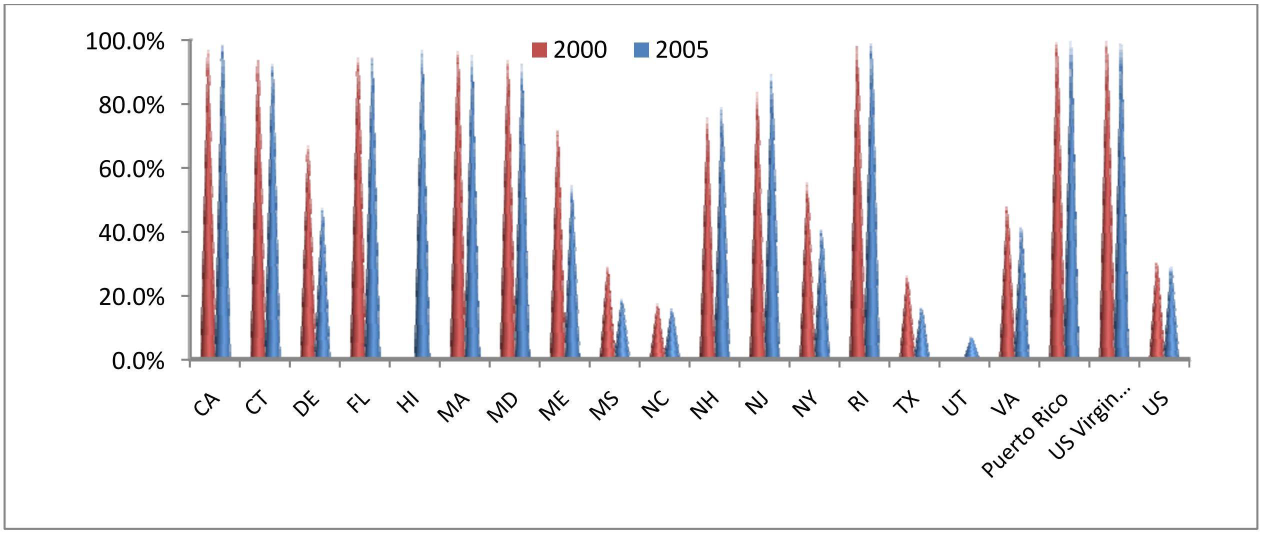

FIGURE 13 Saline Water Use for Electricity Generation by Various U.S. States, Puerto Rico, and U.S. Virgin Islands (Source: Hutson et al. 2004, Kenny et al. 2009)

algae biofuel, alternative water sources under investigation cover a much broader range: sea water, brackish water, coal mine water, animal feedlot wastewater, and wastewater from municipalities.

4.4 THERMAL POWER COOLING AND IRRIGATION

The two largest uses for which freshwater withdrawals are made are for thermoelectric power generation and irrigation. In 2005, freshwater withdrawals for thermoelectric power generation were estimated to be 201 billion gal/day (Bgal/d), which accounted for 41% of all withdrawals. Withdrawals for crop irrigation were 128 Bgal/d, which was approximately 37% of the total (Kenny et al. 2009). These withdrawals have been stabilized or even reduced since the peak withdrawals of 1980, according to the USGS (Kenny et al. 2009). The splits of the freshwater withdrawal between the two major uses can vary from state to state (Figure 14). Freshwater tends to be allocated for food and feed production in the areas where freshwater resources are limited. Florida, California, and Arizona allocated considerably more freshwater to irrigating needs than to power production. In particular, California dedicates 24,400 million gal/day to irrigation, which is almost its entire amount of freshwater withdrawal in the state (Kenny et al. 2009). This amount is also equivalent to 125% of the sum of the irrigation water withdrawn in the rest of the major water-using and power-producing states (Figure 14). Texas withdrew similar amounts of freshwater for both uses. The rest of the major states spent much smaller portions of their freshwater withdrawals on irrigation as compared to cooling. Because agricultural production for food requires freshwater in general, irrigation will continue to be a priority for freshwater allocation. Alternative water sources of lower quality should therefore be used for energy production whenever feasible, including for conventional and renewable energies. Such freshwater conservation thinking has been incorporated into renewable fuels

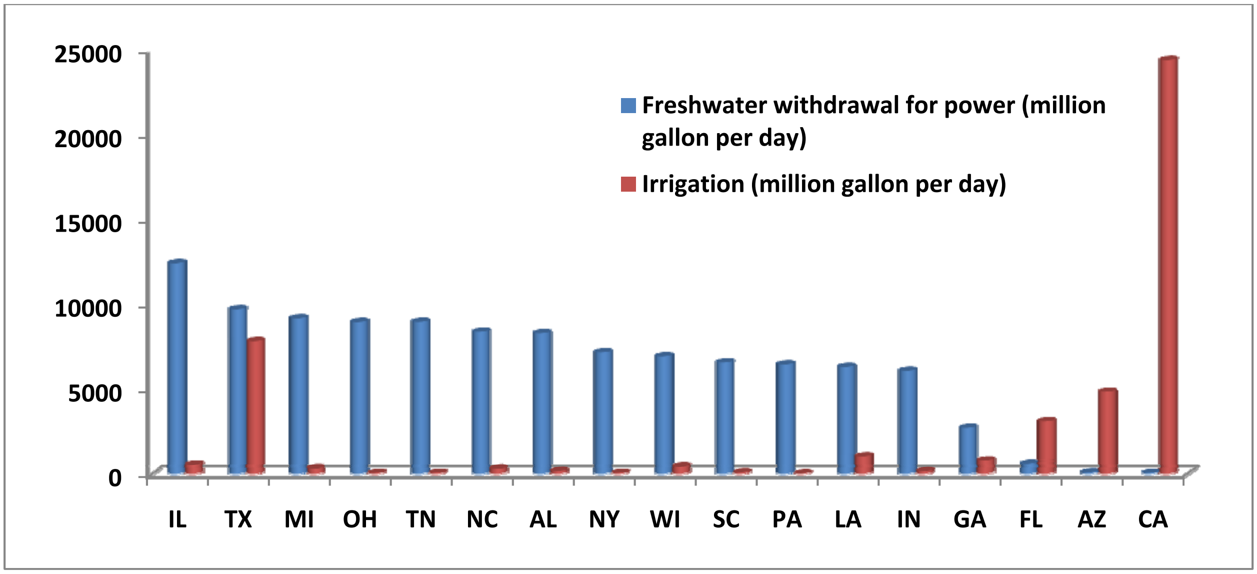

FIGURE 14 Freshwater Withdrawal for Electricity Generation and Irrigation in 2005 for the 17 Major States (Source: Kenny et al. 2009)

development. A typical example is recent research and development that addresses using wastewater from municipal wastewater treatment plants or animal facilities to support algae growth for biofuel production. (Energy production associated with using saline water sources is discussed in Section 4.3.)

4.5 FUTURE CASES

EIA (2010) has projected an 18% increase in electricity production capacity by 2035 to meet growing power demand. If the power industry remains at its current mix of cooling systems and electricity sources and split between freshwater and saline water, we could expect an 18% increase in levels of freshwater withdrawal and consumption to satisfy the power demand by 2035, which would significantly strain our water resources. Most recently, analysis from the U.S. Department of Commerce (DOC) projected a 78% reduction in use of coal power in 24 years by 2035 (Tracy 2011). In the DOC's projections, the U.S. electricity mix has changed as follows: 37.1% nuclear, 30.6% renewables, 24.8% natural gas, and 7.6% from coal to achieve the extremely aggressive goal of generating 80% of U.S. power from clean sources by 2035. The projected fuel mix can lead to a change to the fuel/technology aggregated water use factors (gal/kWh), as shown in Table 5. We developed two cases on the basis of the 2035 projection to assess its impact on water use for power generation in the United States, as follows: (1) electricity mix change and other factors remain the same as in 2005; and (2) electricity mix change and once-through cooling in coal plants drop to 19% and are replaced by wet recirculating cooling. Results presented in Table 7 illustrated the significant impact that the fuel mix has on water use. With the new fuel mix, we will likely see a substantial 41% reduction in freshwater withdrawal and 37% reduction in freshwater consumption per kWh generated. When

TABLE 7 Impact of Fuel and Cooling System Mix on Unit Water Use: Future Cases

	Case (1)			Case (2)			2005		
	With-drawal Factor[1]	**Consumption Factor[1]**	**Electricity Mix (%)**	**With-drawal Factor[1]**	**Consumption Factor[1]**	**Electricity Mix (%)**	**With-drawal Factor[1]**	**Consumption Factor[1]**	**Electricity Mix (%)**
Non-renewable	11.38	0.296	69%	10.87	0.302	69%	14.70	0.42	91%
Renewable	0.09	0.14	30.7%	0.09	0.14	30.7%	0.09	0.14	8.8%
Weighted Average[2]	7.87	0.25		7.52	0.25		13.40	0.39	
Reduction from 2005 (%)	–41.3%	–36.7%		–43.9%	–35.6%				

[1] Unit: gallons of freshwater/kWh electricity generated.

[2] Fuel source and technology weighted average.

the cooling system mix also changed such that once-through cooling in coal-fired plants decreased to 19% from 38% and wet recirculating cooling increased from 48% to 68%, there will be an additional 3% reduction in freshwater withdrawal, although the consumption factor increased slightly (1%) from Case (1). These remarkable water savings are caused by the displacement of the conventional coal plant, which has one of the highest cooling water requirements, by renewable power production (from 8.8% in 2005 to 30.6% in 2035). As shown in Figure 5, coal and nuclear once-through cooling systems are very water intensive. The share of water-consuming nuclear power increased by about 18% from its current level of 19.3% (Figure 1), which canceled out some of the water saving benefits from the 42% reduction in use of coal power. The coal power is displaced in part by nuclear and in the majority by renewable power. As indicated in Table 6, renewable power generation today requires very small amounts of water withdrawal; therefore, if the future mix can be realized, it can bring substantial benefits in water conservation to the nation.

4.6 FRESHWATER FOOTPRINT IN POWER GENERATION

The concept of “water footprint” analysis is to understand and address freshwater consumptive use by considering production and supply chains as a whole. In this framework, the total water footprint accounts for three types of water: *blue water*, which is the freshwater from surface and groundwater sources; *green water*, which represents water from precipitation; and *grey water*, which stands for the used water with a water quality change. The blue and green water footprints together represent a net freshwater use through various processes in which the water is evaporated, evapotranspirated, or incorporated into another form (i.e., a product, solid). Through such analysis, researchers, policy makers, and industries would be able to promote wise water governance and resource conservation while maintaining sustainable development. The water footprint of a product covers the entire supply chain: in particular, the feedstock production, feedstock processing and conversion, and product use stage. Historically, the water footprint of food has been analyzed extensively by the water footprint network at the University of Twente (Water Footprint Network 2011) that was pioneered by Hoekstra and colleagues (Hoekstra and Chapagain 2007). In the past few years, the footprints of conventional biofuel (e.g., sugar cane ethanol, corn ethanol) produced from several regions have been established (Gerbens-Leenes et al. 2009a; Fraiture et al. 2008), and the impacts of increased production were assessed (Gerbens-Leenes et al. 2009b). From a life-cycle standpoint, researchers also emphasize the life-cycle use of blue water (withdrawal or consumption) for biofuels produced from conventional and cellulosic feedstock (Chiu et al. 2009; Wu et al. 2009a; Mishra and Yeh 2010) and major transportation fuels (King and Webber 2008; Wu et al. 2009a).) In this analysis, the water footprint of electricity generated from various sources is estimated for major production stages — resource extraction/feedstock production/processing and electricity generation. This estimate focuses on blue water because water withdrawal from surface and groundwater sources constitutes a majority of the water use in electricity generation.

Data on freshwater use in fuel resource extraction/recovery and production/processing stages were gathered from the available literature and are presented as gallon of water used per gallon of fuel produced (Table 8). Results from the upstream resource recovery were then summed with the unit water use factors (gal/kWh) during power generation from nonfossil and fossil sources by using the tool described in Section 3. Because the water use factors for each fuel source vary with the cooling system mix (which also changes from year to year), this estimate assumes the national cooling system mix estimated by NETL (2008) as presented in Tables 5 and 6. Water use factors for each fuel and each cooling system in power plants are synthesized by using the cooling mix. Resultant values provide a baseline estimate for future comparison. Finally, the blue water footprint (withdrawal and consumption) were determined.

As can be seen in Table 8, upstream resource recovery and fuel production require a minimal amount of freshwater in comparison with the cooling water requirements in power plants. As a result, the blue water footprint of electricity is strongly influenced by the cooling system of choice and fuel source. On the basis of the 2005 estimate of the cooling system mix in the United States, electricity generated from wind, solar, and water sources has a relatively small blue water footprint. Because these sources do not require the consumptive use of green water (precipitation), they tend to have the smallest overall water footprint. The blue water footprint of natural gas power via NGCC and geothermal power is slightly higher than are the wind, solar, and hydropower footprints but are still in the low range.

Biomass-based power has a small blue water footprint because there is a predominant portion in the current biomass mix for power sourced from forest wood residue, which does not require irrigation. When considering power sourced from crop residues, however, currently crop residue is regarded as agricultural waste and therefore does not have a water credit. If irrigation water is allocated to the agricultural residue, the blue water use could be extensive, depending on where the crop is grown. For example, corn stover that is used as a fuel source for power production could require from 0.19 gal, 0.29 gal, or up to 8.9 gal of blue water in the upstream resource recovery stage when the stover is grown in Midwest states corresponding to U.S. Department of Agriculture (USDA) regions 5, 6, and 7, respectively.[2] To date, a majority (70%) of the corn stover grown in the United State is at the low end of the range (i.e., 0.19 gal–0.29 gal) (Wu et al. 2009a).[3] Even without irrigation, biomass would still require green water for growth, which was not included in Table 8. The freshwater footprint (including blue and green water) for biomass-based power from wood, grass, and agricultural residue would therefore be much larger.

As far as water consumption is concerned, the blue water footprint of electricity is generally small at less than 2 gal/kWh. Nevertheless, during power plant operation, withdrawn water — even if it is not consumed — is often not available to others in the region. The freshwater footprint of water withdrawal becomes a key factor in the siting of new plants and in water resource planning.

[2] A range of 7–321 gal of blue water are consumed to produce a gallon of corn ethanol with a yield of 2.7 gal/bushel in USDA regions 5, 6, and 7 (Wu et al. 2009a). A harvest index of 0.55 and 15% moisture are assumed for the stover. Use of a biomass boiler for electricity generation assumes a 32.1% rate of efficiency for the boiler; thus, 3,115,265 British thermal units (Btu) of biomass are needed to generate 1 million Btu (mmbtu) of electricity generation (Argonne 2009). This calculation assumes a corn stover heating value of 392,000 Btu/bushel. Conversion factors are as follows: 3,400 Btu/kWh electricity, 1 bushel = 56 lbs, and 1 kg = 2.2 lbs.

TABLE 8 Blue Water Footprint in Electricity Generation[1]

Fuel Source	Upstream Fuel Recovery and Production (gal/kWh)	Electricity Generation, Withdrawal (gal/kWh)	Electricity Generation, Consumption (gal/kWh)	Total Blue Water Footprint, Withdrawal (gal/kWh)	Total Blue Water Footprint, Consumption (gal/kWh)
Coal	0.13–0.56 [2,3]	17.2	0.5	17.33–17.76	0.63–1.06
Oil	0.13–0.33 [3,4,5]	22.2	0.3	22.33–22.53	0.43–0.63
Natural Gas – Steam Turbine	0.02 [2]	22.2	0.3	22.22	0.32
Natural Gas – NGCC	0.02 [2]	1.2	0.1	1.22	0.12
Nuclear	0.09 [2]	21.8	0.6	21.89	0.69
Geothermal	-	2–6	0.38–4.0	2–6	4.0
Solar	-	0.84	0.84	0.84	0.84
Biomass/Agricultural Residue/Wood/MSW/ Biosolid [6]	-[7]	0.6	0.5	0.60	0.50
Biogas/LFG[3]	NA[8]	22.1	0.2	22.10	0.20
Hydro power	-	0	2	0.00	2.00
Wind	-	0	0	0.00	0.00

1 The table includes blue water only (water retrieved from surface water and ground water bodies).

2 Source: Gleick (1994).

3 Source: Younos et al. 2009.

4 Source: Wu et al. (2009a). Total water use of 2.2–6.6 gal per gal oil is adjusted to exclude saline water. We assume 30% of the total water use in oil recovery is saline/brackish water.

5 Source for electricity generation efficiency: GREET 1.8c (Argonne 2009). Electricity is generated by residue oil from utility oil boiler in oil-fired power plant. 2.99 mmBtu oil required/mmBtu electricity produced (million British thermal at the wall-outlet. Residual oil heating value 140,353 Btu/gal. Electricity unit conversion 3,400 Btu/kWh. Power plant electricity generation efficiency: 33.4% for oil, 34.1% for coal, 40% for NG, 53% for NGCC, and 100% for nuclear. Electricity transmission was not included.

6 We assume rain-fed cellulosic biomass from perennial grass. No irrigation was required.

7 Irrigation water for crops was allocated to grain, assuming that the primary purpose for the production is to harvest grain and residue is regarded as an agricultural waste. If irrigation water is allocated to agricultural residue, the water consumption value could be much larger, depending on where the crop is grown, as indicated in the text.

8 NA = not available.

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5 CONCLUSIONS

Water withdrawal and consumption for electricity generated from various conventional and renewable sources can be simulated for the United States and for each individual state by using the modeling tool developed in this research effort. Based on the inventory of data that was collected and synthesized, the modeling tool projects impacts of freshwater use under future power generation scenarios and compares that with the current baseline. Total water use in power generation for each state is strongly influenced by total power generated, fuel mix, and the predominating types of cooling systems employed. In particular, changes in fuel mix will have a significant impact on projected freshwater use. Moving away from the use of withdrawal-intensive, once-through cooling systems can further reduce freshwater requirements per kWh of electricity generated.

From a water footprint viewpoint, upstream resource recovery and fuel production require a minimal amount of freshwater withdrawal from surface and groundwater sources (blue water) in comparison with the cooling water requirements in conventional power plants. As a result, the blue water footprint of electricity produced from fossil; nonfossil; and solar, wind, geothermal, and hydro sources is affected primarily by the cooling system selected. In terms of the blue water footprint for consumption, upstream resource recovery and fuel production stages become equally important in power generated.

Finally, renewable power generation can play an important role in reducing freshwater use in power generation by the displacement of the conventional coal plant, which has one of the highest cooling water withdrawal requirements. At current cooling systems mix and projected increase in power demand, an increased share of renewable power sources in the overall electricity mix can bring substantial benefits in water conservation to the nation.

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APPENDIX A

The spreadsheet-based tool consists of six sheets:

- User Guide
- Producer Source Generation
- Cooling Boiling Technology
- Water Factor
- Water Withdrawal Data
- Input/Results

The User Guide contains an introduction and equations for the simulation. The Producer Source Generation sheet includes the electricity power generation tables for 2000 and 2005. The Water Factor sheet provides a list of water withdrawal and consumption factors per unit (kilowatt-hour [kWh]) of electricity generated in the power plant. The factors are further grouped by fuel source, technology, and cooling system combinations. Representative factors are selected from the list for model estimates. The Cooling Boiling Technology sheet includes the cooling technology share by source and the boiler and sulfur scrubber technology shares. These shares are used to calculate the water withdrawal and consumption rates for each source. In the Water Withdrawal Data tab, U.S. Geological Survey (USGS) water withdrawal data for the power industry in 2000 and 2005 are presented for the states and for the United States as a whole (USGS data for 2005 are presented in Table A-1).

On the Input/Result sheet, a selection panel allows users to select scenarios (current, historical, and future) and the state of interest. The model output displays total power generated per year, total freshwater withdrawal and consumption per year, and water use breakdown by various fuel sources and its production technologies. The model also presents the percentage change in water use from year 2000 to baseline year (2005) and from the baseline to a simulated future scenario. In the future scenario, users are able to further choose the state of interest, input expected electricity generation, and then select fuel source and cooling technologies. An example output page is shown in Table A-2.

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TABLE A-1 USGS 2005 Data on Water Withdrawal by State					
	Fresh Water (billions gal/year)	**Saline (billions gal/year)**	**Total (billions gal/year)**	**Fresh Water (%)**	**Saline Water Use (%)**
AK	12	0	12	100.00	0.0
AL	2,895	0	2,895	100.00	0.0
AR	700	0	700	100.00	0.0
AZ	31	0	31	100.00	0.0
CA	17	4,410	4,427	0.39	99.6
CO	43	0	43	100.00	0.0
CT	72	1,005	1,077	6.73	93.3
DC	3	0	3	100.00	0.0
DE	148	134	282	52.42	47.6
FL	195	4,025	4,220	4.63	95.4
GA	938	13	951	98.64	1.4
HI	13	508	521	0.00	97.5
IA	886	0	886	100.00	0.0
ID	0	0	0	0.00	0.0
IL	4,340	0	4,340	100.00	0.0
IN	2,118	0	2,118	100.00	0.0
KS	161	0	161	100.00	0.0
KY	1,201	0	1,201	100.00	0.0
LA	2,198	0	2,198	100.00	0.0
MA	37	819	856	4.37	95.6
MD	153	2,083	2,236	6.86	93.1
ME	35	42	77	45.12	54.9
MI	3,203	0	3,203	100.00	0.0
MN	858	0	858	100.00	0.0
MO	2,163	0	2,163	100.00	0.0
MS	124	29	153	81.12	18.9
MT	31	0	31	100.00	0.0
NC	2,923	543	3,465	84.34	15.7
ND	371	0	371	100.00	0.0
NE	1,243	0	1,243	100.00	0.0
NH	80	310	390	20.56	79.4
NJ	232	1,911	2,143	10.83	89.2
NM	20	0	20	100.00	0.0
NV	13	0	13	100.00	0.0
NY	2,499	1,708	4,207	59.40	40.6

TABLE A-1 (Cont.)					
	Fresh Water (billions gal/year)	**Saline (billions gal/year)**	**Total (billions gal/year)**	**Fresh Water (%)**	**Saline Water Use (%)**
OH	3,126	0	3,126	100.00	0.0
OK	57	0	57	100.00	0.0
OR	3	0	3	100.00	0.0
PA	2,251	0	2,251	99.99	0.0
RI	1	92	93	0.54	99.5
SC	2,289	0	2,289	100.00	0.0
SD	2	0	2	100.00	0.0
TN	3,129	0	3,129	100.00	0.0
TX	3,388	651	4,039	83.88	16.1
UT	20	1	22	93.28	6.7
VA	1,722	1,229	2,951	58.36	41.6
VT	147	0	147	100.00	0.0
WA	160	0	160	100.00	0.0
WI	2,415	0	2,415	100.00	0.0
WV	1,243	0	1,243	100.00	0.0
WY	78	0	78	100.00	0.0
Puerto Rico	1	802	802	0.12	99.9
U.S. Virgin Island	0	45	45	0.14	99.9
U.S. Total	49,985	20,358	70,343	71.06	28.9

TABLE A-2 Example of Results Sheet

AL | All Type Cooling Fresh Water

State	Energy Source (primary)	Generation Technology	Generation (MWh/year)		Total Water Withdrawal (billiongal/year)		Total Water Consumption (billiongal/year)		Water Consumption Distribution (%)		Change in Water Withdrawal (%)	Change in Water Consumption (%)
			Current (2005)	Future Prediction	Current	Future Prediction	Current	Future Prediction	Current	Future Prediction		
AL	Anthracite/Bituminous Co	Steam Turbine	58,634,092	70,474,275	1,664.9	2,062.1	21.6	26.7	29.61%	29.61%	24.00%	24.00%
	Sub-bituminous Coal	Steam Turbine	21,294,385	26,405,013	620.0	768.8	8.1	10.0	11.10%	11.10%	24.00%	24.00%
	Coal-based Synfuel	Steam Turbine	0	0	0.0	0.0	0.0	0.0	0.00%	0.00%	0.00%	0.00%
	Total Coal		78,128,457	96,879,287	2,274.9	2,820.9	29.6	36.7	40.71%	40.71%	24.00%	24.00%
	Distillate Fuel Oil	Combined Cycle Steam Part	1	1	0.0	0.0	0.0	0.0	0.00%	0.00%	24.00%	24.00%
		Combined Cycle Combustion Turbine	7,902	9,798	0.2	0.2	0.0	0.0	0.00%	0.00%	24.00%	24.00%
		Gas Turbine	50,360	62,446	0.0	0.0	0.0	0.0	0.00%	0.00%	0.00%	0.00%
		Internal Combustion Engine	443	549	0.0	0.0	0.0	0.0	0.00%	0.00%	24.00%	24.00%
		Steam Turbine	200,173	248,214	4.4	5.5	0.1	0.1	0.09%	0.09%	24.00%	24.00%
	Oil-Other and Waste Oil	Steam Turbine	42,692	52,938	0.9	1.2	0.0	0.0	0.02%	0.02%	24.00%	24.00%
	Petroleum Coke	Steam Turbine	31,540	39,110	0.7	0.9	0.0	0.0	0.01%	0.01%	24.00%	24.00%
	Total Petroleum		**333,110**	**413,057**	**6.3**	**7.8**	**0.1**	**0.1**	**0.12%**	**0.12%**	**24.00%**	**24.00%**
	Natural Gas	NGCC	12,925,030	16,027,024	6.0	8.2	0.3	0.3	0.37%	0.37%	24.00%	24.00%
		Gas Turbine	419,623	520,360	0.0	0.0	0.0	0.0	0.00%	0.00%	0.00%	0.00%
		Steam Turbine	524,609	650,515	11.6	14.4	0.2	0.2	0.22%	0.22%	24.00%	24.00%
	Blast Furnace Gas	Steam Turbine	65,859	81,665	1.5	1.8	0.0	0.0	0.02%	0.02%	24.00%	24.00%
	Other Gas	Steam Turbine	41,005	50,846	0.9	1.1	0.0	0.0	0.01%	0.01%	24.00%	24.00%
	Total NG and Other Gases		13,976,515	17,330,650	19.0	23.6	0.5	0.6	0.62%	0.62%	24.00%	24.00%
	Nuclear	Steam Turbine	31,694,223	39,300,837	647.1	802.4	20.0	24.9	27.59%	27.59%	24.00%	24.00%
	Water	Hydraulic Turbine	10,144,951	12,579,260	0.0	0.0	20.3	25.1	27.88%	27.88%	0.00%	24.00%
	Black Liquor	Steam Turbine	2,478,536	3,073,386	1.7	2.1	1.5	1.9	2.06%	2.06%	24.00%	24.00%
	Landfill Gas	Steam Turbine	3,581	4,441	0.1	0.1	0.0	0.0	0.00%	0.00%	24.00%	24.00%
	Sludge Waste	Steam Turbine	12,633	15,913	0.0	0.0	0.0	0.0	0.01%	0.01%	24.00%	24.00%
	Wood/Wood Waste Solid	Steam Turbine	1,151,849	1,428,293	0.8	1.0	0.7	0.9	0.97%	0.97%	24.00%	24.00%
	Total Renewables		13,791,385	17,101,315	2.6	3.3	22.5	27.9	30.94%	30.94%	24.00%	24.00%
	Tires	Steam Turbine	12,701	15,749	0.0	0.0	0.0	0.0	0.01%	0.01%	24.00%	24.00%
	Other	Steam Turbine	12,392	15,366	0.0	0.0	0.0	0.0	0.00%	0.00%	24.00%	24.00%
	Total Others		**25,093**	**31,115**	**0.0**	**0.0**	**0.0**	**0.0**	**0.01%**	**0.01%**	**24.00%**	**24.00%**
	Grand Total		137,948,581	171,056,240	2,950.0	3,658.0	72.7	90.1	100.00%	100.00%	24.00%	24.00%

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