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Water: A critical resource in the thermoelectric power industry

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Abstract

Water availability represents a growing concern for meeting future power generation needs. In the United States, projected population growth rates, energy consumption patterns, and demand from competing water use sectors will increase pressure on power generators to reduce water use. Water availability and use also exhibit strong regional variations, complicating the nature of public policy and technological response.

The US Department of Energy's (DOE) National Energy Technology Laboratory (NETL) is engaged in a research and development (R&D) program to reduce freshwater withdrawal (total quantity of water utilized) and consumption (portion of withdrawal not returned to the source) from existing and future thermoelectric power generating facilities. The Innovations for Existing Plants (IEP) Program is currently developing technologies in 5 categories of water management projects to reduce water use while minimizing the impacts of plant operations on water quality.

This paper outlines the freshwater withdrawal and consumption rates for various thermoelectric power generating types and then estimates the potential benefits of IEP program technologies at both the national and regional levels in the year 2030. NETL is working to protect and conserve water resources while leveraging domestic fossil fuel resources, such as coal, to increase national energy security.

Keywords: Water resource availability; Thermoelectric power; Water consumption; Water withdrawal

1. Water a scarce resource?

Limited access to affordable energy and water hinders economic development around the world. By 2025, more than 60% of the world's population will live in countries with significant imbalances between water requirements and supplies, largely in Asia, Africa, and Latin America. More than 1 billion people currently lack access to safe drinking water, and 2.4 billion people lack access to improved sanitation [1].

Despite the almost universal access to safe drinking water and sanitation in the United States, Americans are not immune from water supply concerns. Competition for domestic water resources is increasing, costs are rising, and local, state, and regional officials are being forced to take a more active role in water resource management.

Elevated public concern, coupled with heightened public policy interest in water supply and availability, may have serious repercussions on the energy industry. The beginnings of this energy–water flashpoint are already upon us. In March 2006, an Idaho state House committee unanimously approved a 2-year moratorium on construction of coal-fired power plants in the state based on environmental and water supply concerns [2]. In an article discussing a proposed 1200 MW plant in Nevada, opposition to the plant stated, "There's no way Washoe County has the luxury anymore to have a fossil-fuel plant site in the county with the water issues we now have. It's too important for the county's economic health to allow water to be blown up in the air in a cooling tower [3]."

Because freshwater supplies are limited, choices will have to be made regarding the most valuable use of this limited

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resource. In water-stressed areas of the United States, power plants will increasingly compete with other water users. Agriculture and public supply will be the most likely competitors due to their large water withdrawals. As with all resources, tradeoffs will occur, and concerns will increasingly be raised over which use is more important: water for drinking and personal use, growing food, or energy production.

2. Water use for thermoelectric power generation

"Thermoelectric Power Generation" is a broad category of power plants consisting of coal, nuclear, oil, natural gas, and the steam portion of gas-fired combined cycles. Thermoelectric generation represents the largest segment of US electricity production, with coal-based power plants alone generating about half of the nation's electric supply. According to the US Geological Survey's (USGS) water use survey data [4], thermoelectric generation accounted for 39% (136 billion gallons per day [BGD]) of all freshwater withdrawals in the nation in 2000, second only to irrigation, see Fig. 1. Each kilowatt-hour (kWh) of thermoelectric generation requires the withdrawal of approximately 25 gallons of water (weighted-average for all thermoelectric power generation), which is primarily used for cooling purposes. However, power plants also use water for operation of flue gas desulfurization (FGD) devices, ash handling, wastewater treatment, and wash water.

When discussing water and thermoelectric generation, it is important to distinguish between water withdrawal and water consumption. Water *withdrawal* represents the total water taken from a source, while water *consumption* represents the amount of water withdrawal that is not returned to the source. Freshwater consumption for the year 1995 (the most recent year for which these data are available) is presented in Fig. 2 [5]. Freshwater consumption for thermoelectric uses appears low (only 3%) when compared with other use categories (irrigation was responsible for 81% of water consumed). However, even at 3% consumption, thermoelectric power plants consumed more than 3 BGD.

Large quantities of cooling water are required for thermoelectric power plants to support the generation of electricity. There are basically 2 types of cooling water

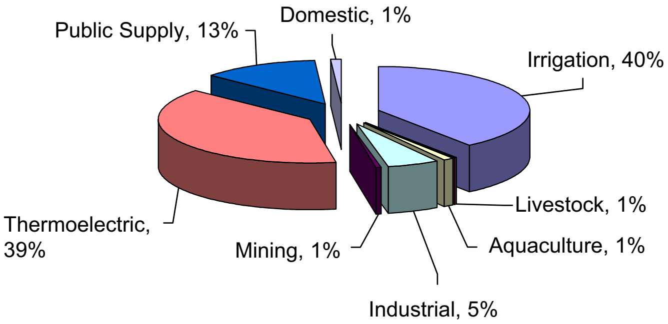

Fig. 1. US freshwater withdrawal (2000).

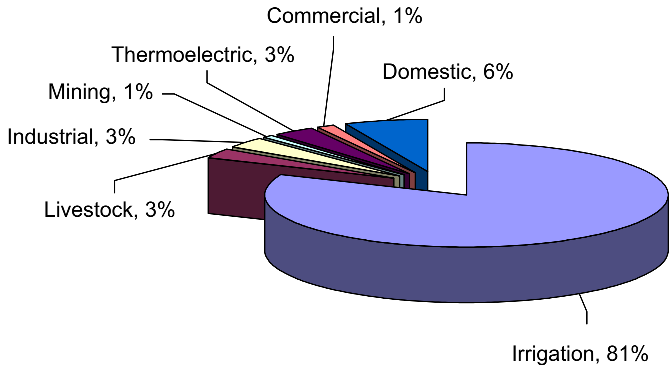

Fig. 2. US freshwater consumption (1995).

system designs: once-through (open loop) and recirculating (closed loop). In once-through systems, the cooling water is withdrawn from a local water body such as a lake, river, or ocean and the warm cooling water is subsequently discharged back to the same water body. As a result, plants equipped with once-through cooling water systems have relatively high water withdrawal, but low water consumption. There are 3 common types of recirculating cooling water systems: wet cooling towers (wet recirculating), cooling ponds (wet recirculating), and air cooled (dry recirculating).

The most common type of recirculating system uses wet cooling towers to dissipate the heat from the cooling water to the atmosphere. Another type of wet recirculating system uses cooling ponds or lakes to accomplish evaporation as opposed to a mechanical device.

Air-cooled systems, also referred to as dry recirculating cooling systems, use either direct or indirect air-cooled steam condensers. In a direct air-cooled steam condenser, the turbine exhaust steam flows through air condenser tubes that are cooled directly by conductive heat transfer using a high flow rate of ambient air that is blown by fans across the outside surface of the tubes. Therefore, cooling water is not used in the direct air-cooled system. In an indirect air-cooled steam condenser system, a conventional water-cooled surface condenser is used to condense the steam, but an air-cooled closed heat exchanger is used to conductively transfer the heat from the water to the ambient air. As a result, there is no evaporative loss of cooling water with an indirect-air dry recirculating cooling system and both water withdrawal and consumption are minimal.

In the United States, existing thermoelectric power plants use each of these types of systems, with estimates indicating that 42.7% of generating capacity is once-through, 41.9% wet cooling towers, 14.5% cooling ponds, and 0.9% dry recirculating [6].

3. Plant design impacts on water use

The amount of water withdrawal and consumption depends on the type of technology used at a given plant.

NETL analyzed various thermoelectric power plant configurations with respect to freshwater use and defined a series of "model plant" profiles to characterize the water use patterns across the thermoelectric power generation industry. Model plant profiles were developed using a hierarchical approach of generation type, cooling water type, cooling water system type, boiler type (coal plants only), and FGD type (coal plants only). Water withdrawal and consumption factors were developed for each model plant profile using the data sources described in Table 1. The resulting national average factors for each model plant profile are listed in Table 2. A complete description of the approach used to develop the factors can be found in a report published on the DOE/NETL website [7].

The water withdrawal and consumption factors shown in Table 2 illustrate the effect of power plant configuration on water resource requirements. For example, coal-fired thermoelectric power plants equipped with once-through or cooling pond systems withdraw large amounts of water, but less than 5% is lost (consumed). Wet cooling tower systems, on the other hand, withdraw 30–50 times less water, but more than 75% of the water is lost during plant operations. Plants equipped with recirculating cooling water systems consume almost 5 times as much water as consumed in once-through systems on a gallon per kilo-watt hour (gal/kWh) basis. The quantity of water consumed by freshwater recirculating systems is of particular concern when considering Clean Water Act 316(b) regulations that favor the use of freshwater recirculating cooling systems when evaluating new thermoelectric power plant options.

Table 1
Data sources used to develop current water withdrawal and consumption factors

Resource	Type of data
AEO 2006	• Projections of thermoelectric capacity and generation by NERC region • Plant capacity, generation, and capacity factor breakdown by 4 categories: existing unscrubbed, existing scrubbed, new PC (scrubbed), and IGCC
NETL 2005 coal power plant database—including data from 2003 EIA-767	• Plant generation • Average water withdrawal and consumption • Cooling water source • Type of cooling water system • Type of boiler • Type of FGD system
EIA-860	• Plant location by NERC region • Plant summer capacity
CMU—integrated environmental control model (IECM)	• Water use factors for wet FGD and dry FGD
Parsons-power plant water consumption study, August 2005	• Water use factors for boiler make-up • Water use factors for IGCC plants
NETL IEP descriptions for water-related projects	Reductions in water withdrawal and consumption factors

4. Future US thermoelectric power generation water use projections

Growing concerns about freshwater availability must be reconciled with growing demand for power in the United States. Thermoelectric generating capacity is expected to increase by nearly 22% between 2005 and 2030, based on the Energy Information Administration's (EIA) *Annual Energy Outlook (AEO) 2006* [8].

Future freshwater withdrawal and consumption requirements for the US thermoelectric generation sector were estimated for 5 cases, using AEO 2006 regional projections for capacity additions and retirements:

Case 1: *Status Quo*—Additions and retirements are proportional to current water source and type of cooling system.
Case 2: *Regulatory-driven*—All additions use freshwater and wet recirculating cooling, while retirements are proportional to current water source and cooling system.
Case 3: *Regulatory-light*—90% of additions use freshwater and wet recirculating cooling, and 10% of additions use saline water and once-through cooling, while retirements are proportional to current water source and cooling system.
Case 4: *Dry Recirculating Cooling*—25% of additions use dry recirculating cooling and 75% of additions use freshwater and wet recirculating cooling. Retirements are proportional to current water source and cooling system.
Case 5: *Conversion*—Additions use freshwater and wet recirculating cooling, while retirements are proportional to current water source and cooling system. Five percent of existing freshwater once-through cooling capacity is retrofitted with wet recirculating cooling every 5 years starting in 2010.

Summary results for the 5 cases, on a national basis, are presented in Table 3. The year 2005 was used as a baseline against which to measure projected future withdrawal and consumption for each case. Using this baseline, Table 3 shows the percent change from the 2005 baseline to each of the future years. The negative values for withdrawal indicate decreased withdrawal, while the positive consumption values indicate increasing consumption over time. For all cases, withdrawal declined and consumption increased. These results are consistent with current and anticipated regulations and industry practice, which favor the use of

Table 2
National average water withdrawal and consumption factors for model thermoelectric power plants, year 2005

Generation type	Cooling water system type	Boiler type	Type of FGD	Withdrawal factor (gal/kWh)	Consumption factor (gal/kWh)
Coal	Once-through	Subcritical	Wet	27.113	0.138
			Dry	27.088	0.113
			None	27.046	0.071
		Supercritical	Wet	22.611	0.124
			Dry	22.590	0.103
			None	22.551	0.064
	Wet cooling tower	Subcritical	Wet	0.531	0.462
			Dry	0.506	0.437
			None	0.463	0.394
		Supercritical	Wet	0.669	0.518
			Dry	0.648	0.496
			None	0.609	0.458
	Cooling pond	Subcritical	Wet	17.927	0.804
			Dry	17.902	0.779
			None	17.859	0.737
		Supercritical	Wet	15.057	0.064
			Dry	15.035	0.042
			None	14.996	0.004
Nuclear	Once-through	NA	NA	31.497	0.137
	Wet cooling tower	NA	NA	1.101	0.624
Oil & NG	Once-through	NA	NA	22.74	0.09
	Wet cooling tower	NA	NA	0.25	0.16
	Cooling pond	NA	NA	7.89	0.11
NGCC	Once-through	NA	NA	9.01	0.002
	Wet cooling tower	NA	NA	0.15	0.13
	Cooling pond	NA	NA	5.95	0.24
	Air cooled	NA	NA	0.004	0.004
IGCC	Wet cooling tower	NA	NA	0.226	0.173

NA not applicable.

Table 3
Thermoelectric water impacts, national results

Future power generation cases		2005 (BGD)	Percent change from 2005 baseline				
			2010	2015	2020	2025	2030
Case 1	Withdrawal	149.2	2.3	−2.4	−1.1	−0.3	−0.5
	Consumption	6.2	6.5	9.7	17.7	22.6	27.4
Case 2	Withdrawal	149.2	0.1	−5.5	−7.1	−7.5	−8.6
	Consumption	6.2	8.1	11.3	21.0	27.4	32.3
Case 3	Withdrawal	149.2	0.1	−5.6	−7.2	−7.6	−8.8
	Consumption	6.2	6.5	11.3	19.4	25.8	30.6
Case 4	Withdrawal	149.2	0.1	−5.6	−7.3	−9.8	−9.2
	Consumption	6.2	6.5	9.7	17.7	19.4	21.0
Case 5	Withdrawal	149.2	−7.7	−17.8	−23.5	−26.7	−30.5
	Consumption	6.2	11.3	19.4	32.3	40.3	48.4

freshwater recirculating cooling systems over once-through cooling systems. Case 5 provides the most extreme water consumption impacts. Converting a modest share of existing once-through power plants to recirculating fresh-water plants significantly reduces water withdrawal, but significantly increases water consumption. Case 4 indicates that dry recirculating cooling could significantly reduce water consumption; compared with cases 1–3.

However, regional water impacts can be significantly different than national data averages might suggest. To characterize the significance of the regional impacts on water use, it is necessary to compare regional electricity demand and capacity forecasts with representative water withdrawal and consumption estimates to identify regions where water issues could become acute.

AEO 2006 projections of capacity and generation to 2030 were used to calculate future thermoelectric generation water withdrawal and consumption by region using the 13 North American Electric Reliability Council (NERC) control regions, excluding Alaska and Hawaii. A description of the NERC regional abbreviations is provided in Table 4.

While all 5 cases were evaluated as part of a NETL 2006 Water Analysis Study [7], this paper is focused on the national and regional impacts of case 2, which represents a plausible future cooling system scenario.

The regional analysis revealed some significant differences from the national averages. For example, in case 2, the national percent changes in Table 3 indicate that water withdrawal will fall by 8.6% and that water consumption will rise by 32.3% between 2005 and 2030. However, as shown in Figs. 3 and 4, on a regional basis water withdrawal ranges from a 25% increase in Florida (FRCC Region) to a 30% decline in Texas (ERCOT Region); and while freshwater consumption increases in all regions, the biggest gains come in California (WECC/CA Region), at 352%; Florida (FRCC Region), at 199%; New York (NPCC/NY), at 132%; and the Rocky Mountain/desert southwest region (WECC/RM Region), at 74% [7].

Table 4
Description of NERC regions

Region number	Abbreviation	Region
1	ECAR	East Central Area Reliability Coordination Agreement
2	ERCOT	Electric Reliability Council of Texas
3	MAAC	Mid-Atlantic Area Council
4	MAIN	Mid-America Interconnected Network
5	MAPP	Mid-Continent Area Power Pool
6	NPCC/NY	Northeast Power Coordinating Council/New York
7	NPCC/NE	Northeast Power Coordinating Council/New England
8	FRCC	Florida Reliability Coordinating Council
9	SERC	Southeastern Electric Reliability Council
10	SPP	Southwest Power Pool
11	WECC/NWPP	Western Electricity Coordinating Council/Northwest Power Pool
12	WECC/RM	Western Electricity Coordinating Council/Rocky Mountains, AZ, NM, southern NV
13	WECC/CA	Western Electricity Coordinating Council/California

The regional results reflect recent US population shifts. Regions with strong population growth, such as the Southeast and Southwest, exhibit high growth in water consumption requirements, while regions with minimal to modest population growth, such as the Midwest and mid-Atlantic, exhibit modest growth in water consumption requirements.

Based on AEO 2006 forecasts for thermoelectric power generation, growing concerns over future water availability are warranted to meet the National Energy Policy goals for energy security. As the United States leverages domestic fossil fuel resources, such as coal, to increase national energy security, regional water availability may become a more pressing issue. New water management strategies are needed for existing and future thermoelectric power generation to conserve water resources, meet environmental regulations, and improve our national energy security while meeting future energy demands.

5. NETL research program to reduce water use in thermoelectric power generation

Recognizing the emerging importance of water in the context of energy supply, NETL is developing advanced technologies, which are categorized in Table 5, aimed at reducing freshwater withdrawal and consumption associated with thermoelectric generation. NETL's Innovations

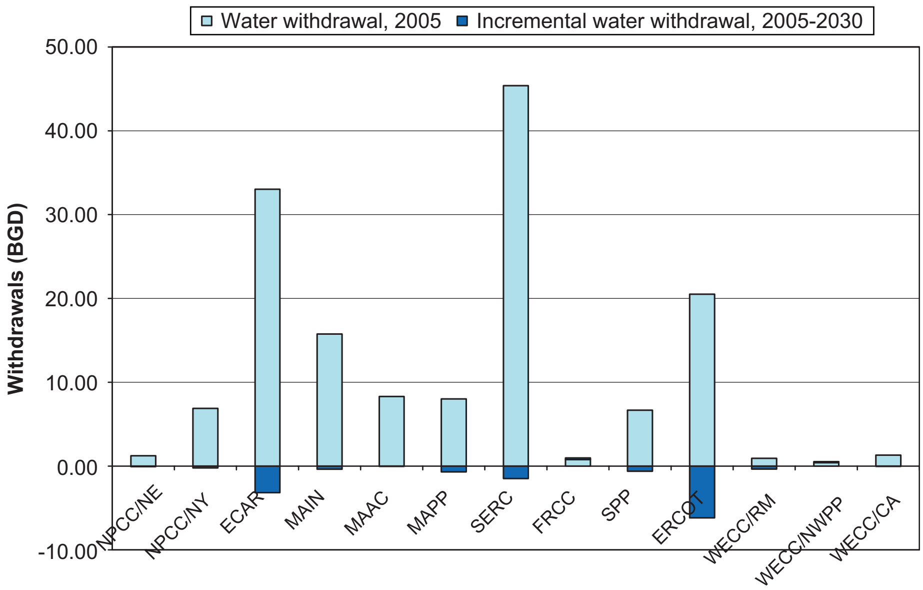

Fig. 3. Average daily regional freshwater withdrawal for thermoelectric power generation, case 2.

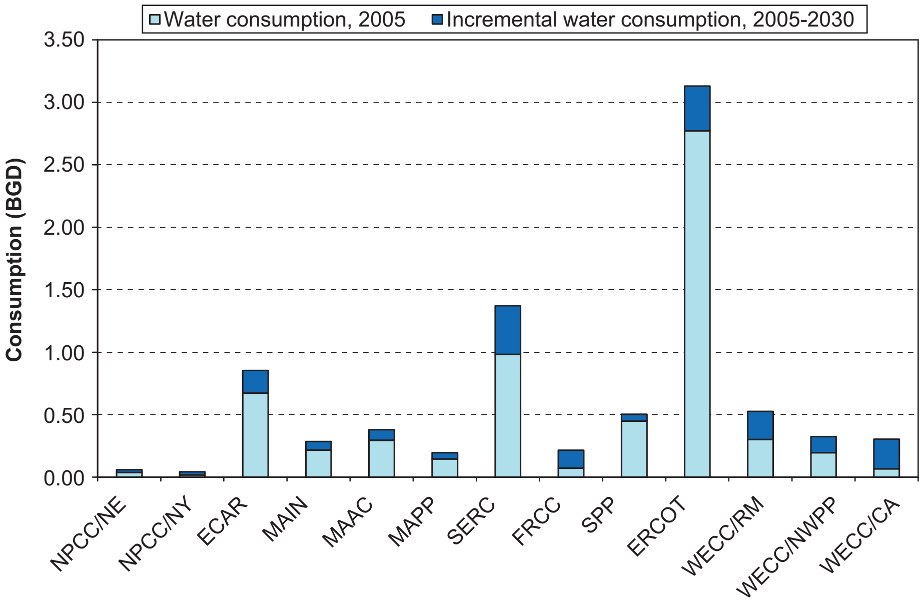

Fig. 4. Average daily regional freshwater consumption for thermoelectric power generation, case 2.

Table 5
IEP energy–water technology categories & current projects

Category	Description
A	Provide alternate source of cooling water make-up • Use of produced water in recirculated cooling systems at power generation facilities and development of an impaired water cooling system • Development and demonstration of a modeling framework for Assessing the Efficacy of using mine water for thermoelectric power generation • Reuse of treated internal or external wastewaters in the cooling systems of coal-based thermoelectric power plants
B	Increase cycles of concentration for wet recirculating systems, thereby decreasing wet cooling tower blowdown requirements • A synergistic combination of advanced separation and chemical scale inhibitor technologies for efficient use of impaired water as cooling water in coal-based power plants • Application of pulsed electrical fields for advanced cooling in coal-fired power plants
C	Advanced cooling technology • Use of Air2Air^{TM} technology to recover fresh-water from the normal evaporative cooling loss at coal-based thermoelectric power plants
D	Reclaim water from combustion flue gas for use as cooling water make-up • Water extraction from coal-fired power plant flue gas • Recovery of water from boiler flue gas • Reduction of water use in wet FGD system
E	Reduce cooling tower evaporative losses via coal drying • Use of coal drying to reduce water consumed in pulverized coal power plants

Additional details are accessible at: www.netl.doe.gov search term "Energy-Water Interface".

for Existing Plants (IEP) Program has established 2 major objectives:

- Short-term—have technologies ready for commercial demonstration by 2015 that, when used alone or in combination, can reduce freshwater withdrawal and consumption by 50% or greater for thermoelectric power plants equipped with wet recirculating cooling technology at a levelized cost of less than \$2.40 per thousand gallons freshwater conserved.
- Long-term—have technologies ready for commercial demonstration by 2020 that, when used in combination, can reduce freshwater withdrawal and consumption by 70% or greater at a levelized cost of less than \$1.60 per thousand gallons freshwater conserved.

NETL's IEP Program is a comprehensive R&D effort directed at the development of advanced technologies that can enhance the environmental performance of the existing fleet of fossil-fueled thermoelectric power plants. The program's primary focus is on coal-fired power generation. NETL conducted 2 competitive research solicitations, in 2003 and 2005, making 12 awards for water-related projects [9].

6. Water conservation strategies for existing and future thermoelectric power generating plants

NETL's IEP Program has been investing in water conservation and management strategies to develop practical solutions to conserve water resources, minimize impacts on water quality, and provide environmentally sound solutions for increasing national energy security through domestic resources. The IEP Program's energy-water technology initiatives are divided into 5 project categories, as described in Table 5.

To evaluate the potential benefits of IEP technologies, assumptions had to be made regarding the amount of freshwater that each technology type would conserve in terms of reduced withdrawal and/or consumption. In cases where a project has not progressed to the point of presenting results, the analysis assumed that the outcomes projected by the technology developer would be achievable.

Table 6 summarizes the percent reductions in water withdrawal and consumption for each IEP technology category and plausible combinations thereof. Applicability of a given technology category is determined by the type of power generation and plant configuration, as described in the sections below. In calculating the water savings from technology combinations, care was taken to prevent double-counting of technology benefits by ensuring the values were properly combined. In some cases, the impacts are additive; in others, the impacts have a more complicated relationship.

Table 6
Potential water withdrawal and consumption reductions by IEP technology category combinations

Category combination	Freshwater withdrawal reduction %	Freshwater consumption reduction %
A	All generation types: 27.0%	All generation types: 27.0%
B	All generation types: 11.1%	All generation types: 0.0%
C	All generation types: 20.0%	All generation types: 20.0%
D	Coal: 3.8% Fossil/non-coal: 5.9% NGCC: 8.8% IGCC: 8.7%	Coal: 3.8% Fossil/non-coal: 5.9% NGCC: 8.8% IGCC: 8.7%
E	Coal: 5.6%	Coal: 5.6%
AB	All generation types: 38.1%	All generation types: 30.4%
AC	All generation types: 47.0%	All generation types: 47.0%
BC	All generation types: 28.9%	All generation types: 20.0%
ABC	All generation types: 55.9%	All generation types: 50.4%
ABDE	Coal: 46.9% Fossil/non-coal: 48.9% NGCC: 51.9% IGCC: 51.8%	Coal: 40.3% Fossil/non-coal: 42.6% NGCC: 45.9% IGCC: 45.8%
ACDE	Coal: 55.3% Fossil/non-coal: 57.3% NGCC: 60.3% IGCC: 60.2%	Coal: 55.3% Fossil/Non-Coal: 57.3% NGCC: 60.3% IGCC: 60.2%
BCDE	Coal: 36.7% Fossil/non-coal: 38.7% NGCC: 41.7% IGCC: 41.6%	Coal: 28.8% Fossil/Non-Coal: 31.1% NGCC: 34.4% IGCC: 34.3%
ABCDE	Coal: 63.7% Fossil/non-coal: 65.7% NGCC: 68.7% IGCC: 68.6%	Coal: 59.1% Fossil/non-coal: 61.4% NGCC: 64.7% IGCC: 64.6%

Note: (1) The "Fossil/non-coal" generation type is inclusive of natural gas, oil, and nuclear power generation; the fossil/non-coal benefit estimates are considered equally applicable to all three generation types.
(2) The combination of technology scenarios was limited in the study to reduce the number of scenarios evaluated. Combinations not presented in the table are technical feasible.

6.1. *Category A—provide alternate source of cooling water make-up*

Category A is primarily applicable to thermoelectric plants equipped with recirculating cooling systems. The quantities of water available from alternate sources would be too small to warrant recovery in plants equipped with once-through cooling systems. The IEP category A projects are projected to reduce freshwater withdrawal rates, on average, by 3.2 million gallons per day (MGD) per recirculating location. This translates into a 27% reduction in freshwater withdrawal. In terms of consumption, use of the alternate water source is assumed to be evenly split between the evaporative stream and the blowdown stream. Therefore, the percent consumption reduction is equal to the percent withdrawal reduction.

6.2. *Category B—increase cycles of concentration for wet recirculating systems*

Category B applies to all thermoelectric plants equipped with wet recirculating systems. These IEP projects are projected to double the cycles of concentration (COC) feasible at each plant. This translates into a water withdrawal reduction of 11.1% based on minimal drift and 100 nominal units of evaporation. Increasing the cycles of concentration reduces the amount of makeup water required due to the reduction in blowdown frequency, but has no impact on the amount of water evaporated. Therefore, there is no reduction in water consumption.

6.3. *Category C—advanced cooling technology*

Category C applies to all thermoelectric plants equipped with wet recirculating systems. IEP technologies under development are expected to achieve an average 20% water recovery rate from the evaporative water stream of a recirculating cooling water system. Assuming recovered water is used to replace a portion of the makeup water, this translates into freshwater withdrawal and consumption reductions of 20%.

6.4. *Category D—reclaim water from combustion flue gas for use as cooling water make-up*

Category D applies to all fossil steam thermoelectric power plants (coal and non-coal). The projects in category D discuss a projected 50% water recovery from the flue gas stream. It is assumed that this water is used to replace a portion of the cooling tower makeup, making it functionally equivalent to category A. The percent withdrawal reduction, however, is heavily dependent on plant type; combined-cycle plants, for example, typically have more moisture in the flue gas than coal-fired plants. The percentage reduction in freshwater withdrawal and consumption used in the analysis ranges from 3.8% for coal-fired power plants to 8.8% for natural gas combined-cycle power plants.

6.5. Category E—reduce cooling tower evaporation losses via coal drying

Category E applies only to coal plants, and more specifically, only to plants burning low-rank coals with high moisture contents. The technology developed in category E reduces evaporative losses from the cooling tower by recovering heat from the circulating water leaving the condenser and using that heat to dry coal. Results from the category E project indicate a maximum evaporative loss reduction of 380 gpm for a 550 MW power plant when recovering heat solely from the recirculating cooling water. Reducing the evaporative, or consumption, losses by 380 gpm is equivalent to a 5.6% reduction in freshwater withdrawal and consumption.

7. Preserving water resources

NETL's IEP Program has established a goal of having technologies ready for commercial demonstration by 2015 that reduce water use by 50% or greater at thermoelectric power plants equipped with wet recirculating cooling technology at a levelized cost of less than $2.40 per thousand gallons freshwater conserved. The long-term program goal is to reduce water use by 70% or greater with a levelized cost of less than $1.60 per thousand gallons of freshwater conserved. Although these technologies may be ready for deployment by 2015, it would likely require from 5 to 15 years for the technologies to be fully implemented across the industry. Therefore, each of the 13 technology scenarios were analyzed for 3 levels of technology market penetration—10%, 30%, and 50%. These percentages were applied to the model plants in Table 2 for which the technology category is applicable. Both national and regional water withdrawal and consumption estimates were calculated for each of the 13 technology scenarios at the 3 market penetration levels for the year 2030. The following formula indicates how water withdrawal and consumption were calculated when incorporating the IEP technologies:

$$\text{Water Withdrawal, Consumption(gal/h)} = (\text{RC})(\%\text{RC})(\text{CF}_{\text{w,c}})[1 - (\%\text{TCR})(\%\text{MP})],$$

where RC is the total regional capacity, kW; %RC the proportion of capacity assigned to model plant, %/100; $\text{CF}_{\text{w,c}}$ the capacity factor-weighted water withdrawal (w) or consumption (c) scaling factor for model plant, gal/h/kW; %TCR the technology category reduction if applicable to model plant, %/100; %MP the technology category market penetration, %/100.

The 13 technology scenarios were analyzed to estimate the potential range of benefits obtainable from the IEP Program technologies at the varying levels of market penetration for each of the 5 cases. Both national and regional benefit estimates were calculated. As discussed previously, only case 2 results are presented here. The national water withdrawal and consumption benefits for each technology scenario compared with the baseline national levels are shown in Figs. 5 and 6. Results are presented for the years 2030 at 10%, 30%, and 50% market penetration levels. The bars labeled "Base" in the figures refer to the national water withdrawal and consumption quantities without any IEP technologies applied. As demonstrated in the figures, the single

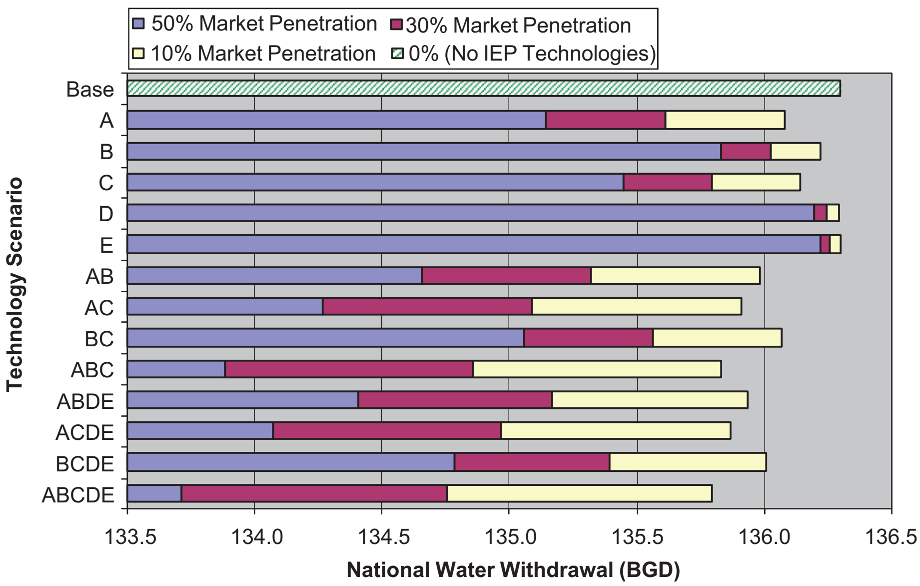

Fig. 5. National water withdrawal with IEP program technologies (case 2, year 2030).

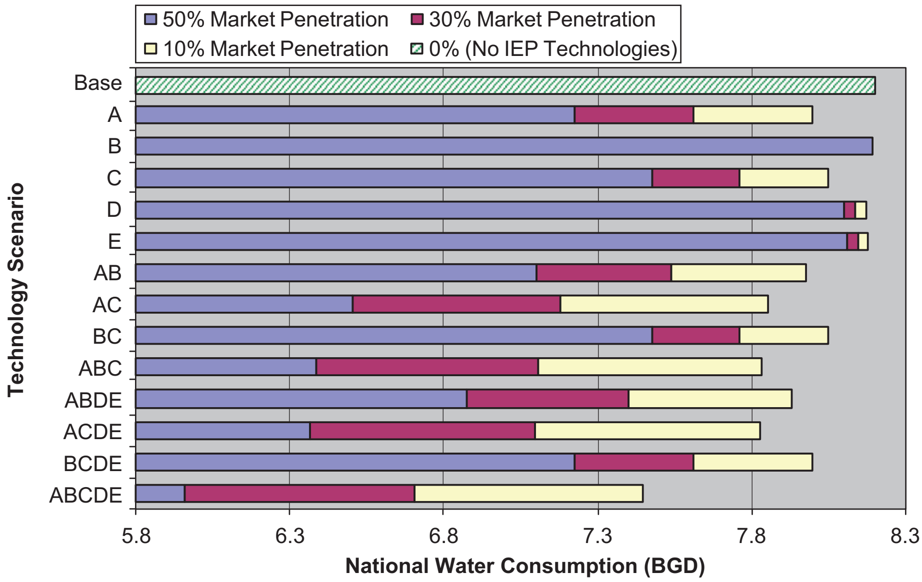

Fig. 6. National water consumption with IEP program technologies (case 2, year 2030).

Table 7
Percent reduction in water withdrawal with IEP program technologies by region for 50% market penetration (case 2, year 2030)

	A	B	C	D	E	AB	AC	BC	ABC	ABDE	ACDE	BCDE	ABCDE
ECAR	0.5	0.2	0.3	0.1	0.1	0.7	0.8	0.5	1.0	0.8	0.9	0.7	1.1
ERCOT	3.0	1.2	2.2	0.1	0.0	4.2	5.2	3.2	6.1	4.3	5.2	3.4	6.2
MAAC	0.8	0.3	0.6	0.1	0.1	1.1	1.3	0.8	1.6	1.3	1.5	1.1	1.7
MAIN	0.3	0.1	0.2	0.0	0.0	0.4	0.5	0.3	0.6	0.5	0.6	0.4	0.7
MAPP	0.4	0.2	0.3	0.0	0.1	0.5	0.7	0.4	0.8	0.6	0.8	0.5	0.9
NPCC/NY	0.1	0.0	0.1	0.0	0.0	0.1	0.2	0.1	0.2	0.2	0.2	0.2	0.2
NPCC/NE	0.8	0.3	0.6	0.2	0.0	1.1	1.3	0.8	1.6	1.6	1.6	1.5	1.8
FRCC	4.3	1.8	3.2	0.9	0.6	6.0	7.5	4.6	8.9	8.0	8.9	6.9	10.0
SERC	0.5	0.2	0.4	0.1	0.0	0.7	0.9	0.5	1.0	0.8	1.0	0.7	1.1
SPP	0.6	0.3	0.5	0.1	0.1	0.9	1.1	0.7	1.3	1.2	1.3	1.0	1.5
WECC/NWPP	8.1	3.3	6.0	1.1	1.4	**11.4**	**14.0**	8.6	**16.7**	**14.0**	**16.3**	**11.2**	**18.8**
WECC/RM	11.5	4.7	8.5	1.6	2.0	**16.2**	**19.9**	**12.3**	**23.7**	**19.7**	**23.1**	**15.8**	**26.6**
WECC/CA	4.0	1.6	3.0	0.6	0.8	5.6	7.0	4.3	8.3	7.1	8.2	5.6	9.4

technology categories require higher levels of market penetration to reduce water withdrawal and consumption then the technology combinations. Greater improvements in the reduction of water consumption are achievable with the IEP technology scenarios than for water withdrawal on the national level.

Because the individual technology categories are not necessarily applicable to all thermoelectric power plants, and because of differences in the breakdown of power plant types by region, water withdrawal and consumption impacts vary across the regions. Tables 7 and 8 show the percentage change in withdrawal and consumption from the baseline level at a 50% market penetration level by region for each of the 13 technology scenarios in the year 2030. Regional technology scenario combinations with the potential to reduce water withdrawal and consumption by 10% or greater are highlighted within the tables.

For all 5 technology categories and the combinations thereof, the WECC/RM (Rocky Mountain, Arizona, New Mexico, and southern Nevada) region shows the greatest percentage decrease in freshwater withdrawal. WECC/NWPP (Northwestern states of Washington, Oregon, Utah, Idaho and parts of Nevada, Montana, and Wyoming) shows the second greatest decrease in withdrawals for all technologies and combinations. FRCC (Florida), WECC/CA (California), and ERCOT (majority of Texas) also show relatively high withdrawal savings compared with the other 8 regions. With respect to consumption, the regional differences aren't as evident; consumption declines substantially for most regions. For both withdrawal and consumption, the regional differences can be traced to differences in the amount of new thermoelectric capacity being added, the type of thermoelectric capacity, and the current withdrawal and consumption quantities.

For the individual technology categories, category A will have the greatest impact on freshwater withdrawal and consumption at thermoelectric power plants, because the

Table 8
Percent reduction in water consumption with IEP program technologies by region for 50% market penetration (case 2, year 2030)

	A	B	C	D	E	AB	AC	BC	ABC	ABDE	ACDE	BCDE	ABCDE
ECAR	**11.7**	0.0	8.7	1.9	1.8	**13.2**	**20.4**	8.7	**21.9**	**17.8**	**23.4**	**13.7**	**27.1**
ERCOT	**13.2**	0.0	9.8	0.3	0.1	**14.9**	**23.0**	9.8	**24.7**	**15.6**	**23.3**	**10.7**	**25.5**
MAAC	**11.8**	0.0	8.7	1.6	1.1	**13.3**	**20.5**	8.7	**22.0**	**17.1**	**22.6**	**13.2**	**30.9**
MAIN	9.9	0.0	7.4	0.9	0.7	**11.2**	**17.3**	7.4	**18.5**	**13.5**	**18.5**	**10.1**	**20.2**
MAPP	**10.8**	0.0	8.0	1.5	1.8	**12.2**	**18.9**	8.0	**20.2**	**15.7**	**21.7**	**11.3**	**28.1**
NPCC/NY	**11.8**	0.0	8.7	3.8	0.8	**13.3**	**20.6**	8.7	**22.0**	**21.4**	**23.5**	**19.6**	**47.3**
NPCC/NE	**12.3**	0.0	9.1	3.8	0.7	**13.8**	**21.4**	9.1	**23.0**	**22.4**	**24.2**	**21.0**	**44.6**
FRCC	**13.4**	0.0	9.9	2.8	2.0	**15.0**	**23.2**	9.9	**24.9**	**21.6**	**27.0**	**17.4**	**38.9**
SERC	**10.1**	0.0	7.5	1.5	1.2	**11.4**	**17.6**	7.5	**18.8**	**14.6**	**19.8**	**10.9**	**31.4**
SPP	6.5	0.0	4.8	1.2	1.0	7.3	**11.2**	4.8	**12.1**	**10.3**	**13.0**	8.3	**16.3**
WECC/NWPP	**13.0**	0.0	9.7	1.8	2.3	**14.7**	**22.7**	9.7	**24.3**	**19.4**	**26.2**	**14.2**	**28.3**
WECC/RM	**12.3**	0.0	9.1	1.7	2.1	**13.9**	**21.5**	9.1	**23.1**	**18.2**	**24.7**	**13.3**	**26.7**
WECC/CA	**13.3**	0.0	9.8	2.2	2.5	**14.9**	**23.0**	9.8	**24.7**	**20.3**	**27.0**	**15.1**	**32.1**

use of alternate sources of cooling water is applicable across all thermoelectric generation types. The savings per plant are also greater than that from the other 4 technology categories (27% for both withdrawal and consumption). Category C shows the second greatest impact on withdrawal and consumption savings. Like category A, category C is also applicable to all forms of thermoelectric generation and has a relatively high water savings percentage (20%) for both withdrawal and consumption.

Combining technologies results in greater savings in freshwater withdrawal and consumption than achieved by the technologies individually. In general, withdrawal and consumption savings increase with the number of categories combined (i.e., combination ABC results in greater savings for withdrawal and consumption than combinations AB, AC, or BC).

IEP technology benefits from categories ABCDE achieved the highest level of water withdrawal and consumption reduction. For case 2, implementing categories ABCDE at 50% penetration could nationally result in a 30% reduction in freshwater consumption in 2030. Regionally, this value would vary from 16.3% in SPP (Kansas, Oklahoma, Louisiana, western Missouri, and northern part of Texas) to 47.3% in NPCC/NY (New York).

8. Conclusion

Water availability is a regional and national concern for meeting future power generation needs. Based on EIA projections of thermoelectric generation in 2030, NETL estimates that daily freshwater withdrawals could range from 103.7 BGD to 148.4 BGD compared with an estimated 149.2 BGD baseline for 2005, and that daily freshwater consumption could increase to 7.8 BGD or 8.2 BGD from a 2005 baseline of 6.2 BGD [7]. Within the United States, the concerns over water availability for energy production and other uses is more prevalent in some regions than others. Recent public concerns over water availability have already begun to impact the thermoelectric power industry in areas such as Idaho, Arizona, South Dakota, Nevada, and tribal areas such as the Navajo Nation. The growing concerns over water availability, coupled with projected population growth rates and energy consumption patterns, are poised to magnify the importance of water resources in the near future.

Environmental regulations will likely increase water consumption rates for future additions of thermoelectric power generation in the United States. As a result, the number of viable locations for siting a thermoelectric power facility will become even more challenging and potentially create unwanted environmental, cost, or energy security trade-offs.

DOE/NETL is engaged in a R&D program to reduce freshwater withdrawal and consumption from existing and future thermoelectric power generating facilities. The IEP Program is currently developing an array of water management technologies ready for commercial demonstration by 2015 that could be used to reduce freshwater withdrawal and consumption by 50% or greater at thermoelectric power plants equipped with wet recirculating cooling technology at a levelized cost of less than $2.40 per thousand gallons freshwater conserved. The IEP Program also has a long-term goal of having technologies ready for commercial demonstration by 2020 that, when used in combination, can reduce freshwater withdrawal and consumption by 70% or greater at a levelized cost of less than $1.60 per thousand gallons freshwater conserved.

Based on this analysis, advanced technologies that enable alternate sources of cooling water make-up to be used and that reduce evaporation and/or drift loss from existing wet cooling towers resulted in the greatest savings in freshwater withdrawal and consumption. Emphasis on R&D into these types of technologies, and others, could propel the thermoelectric generation power sector toward improved water resource management practices that effectively balance environmental concerns, including water resource conservation, with the need for national energy security through reliance on domestic power resources.

While the potential benefits of the IEP Program look promising to reduce freshwater consumption, additional R&D is necessary to ensure continual improvement of water resource management strategies for thermoelectric power generation. Technology combinations demonstrated the potential for improvement beyond the current program goal and the significant potential for further reduction in freshwater use through both innovative technologies and sound water resource management strategies.

Water is considered a scarce resource in the thermoelectric power industry. It is essential to improving plant efficiency which reduces the quantity of fossil fuel energy resources consumed per unit of energy generated. It is essential to the economic viability of power production that helps provide affordable and reliable energy to industrial, commercial, and residential customers across the United States. In water-stressed areas of the United States, power plants will increasingly compete with other water users. As with all resources, trade-offs will occur, and concerns will increasingly be raised over which use is more important: water for drinking and personal use, recreational purposes, growing food, or energy production. NETL is working towards reducing the burden of these trade-offs by protecting and conserving our scarce water resources while continuing to support National Energy Policy goals for improved energy security.

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