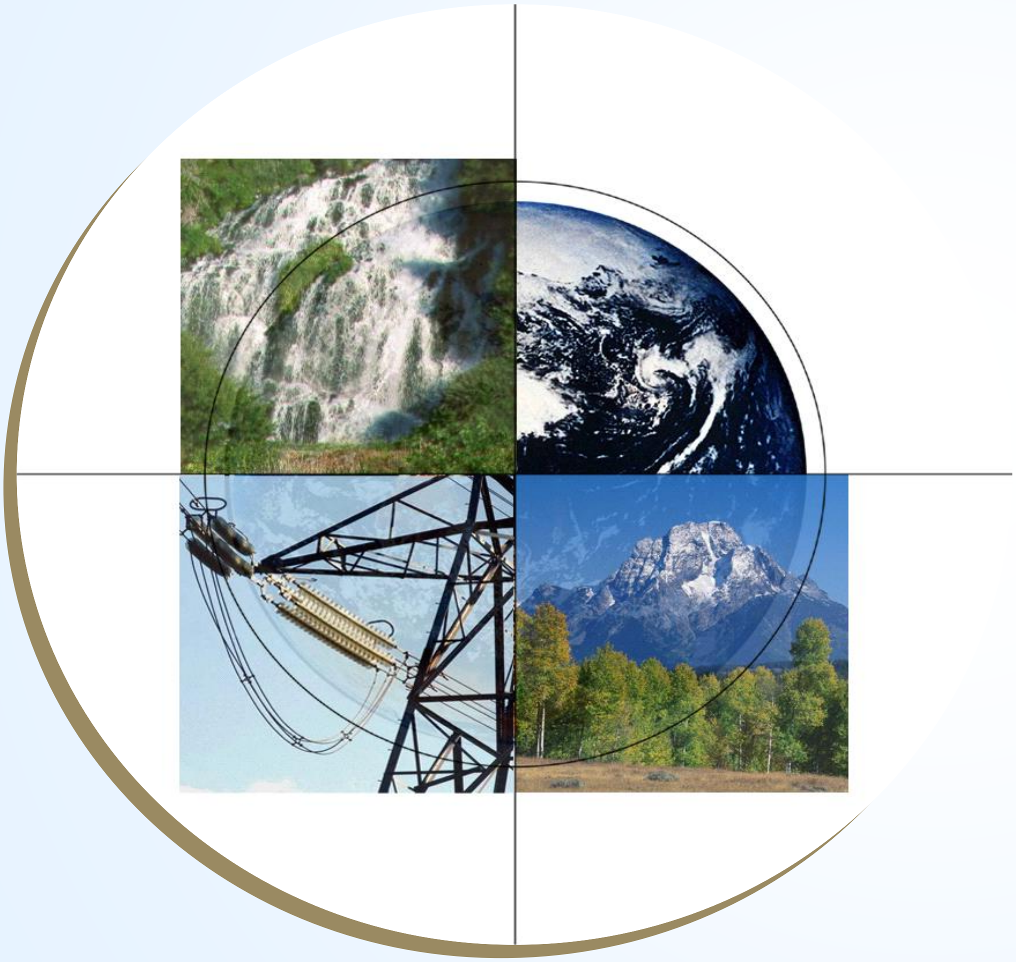
EXISTING PLANTS PROGRAM:

ENERGY – WATER R&D

Technology Roadmap & Program Plan



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U.S. Department of Energy
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National Energy Technology Laboratory

NETL

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I. Overview

The production of energy requires a reliable, abundant, and predictable source of freshwater - a resource that is limited in many parts of the United States and throughout the world.

Energy production and water usage are inextricably linked[1]. Each requires the other, as illustrated in Figure 1. As energy and water see increasing demand and growing limitations on supply, they must be managed together to maintain reliable energy and water supplies that will enable full use of the Nation's energy reserves.

Thermoelectric power plants (coal, oil, natural gas, and nuclear fueled power generators) require significant quantities of water for generating electrical energy. For example, a 500-megawatt (MW) coal-fired power plant uses more than 12 million gallons of water per hour[2]. The largest demand for this water is process cooling. The two commonly used metrics to measure water use are withdrawal and consumption. The water required for thermoelectric plant operation is withdrawn primarily from large volume sources, such as lakes, rivers, oceans, and underground aquifers. Water consumption is used to describe the loss of withdrawn water, typically through evaporation into the air, which is not returned to the source. The United States Geological Survey (USGS) estimated that thermoelectric generation

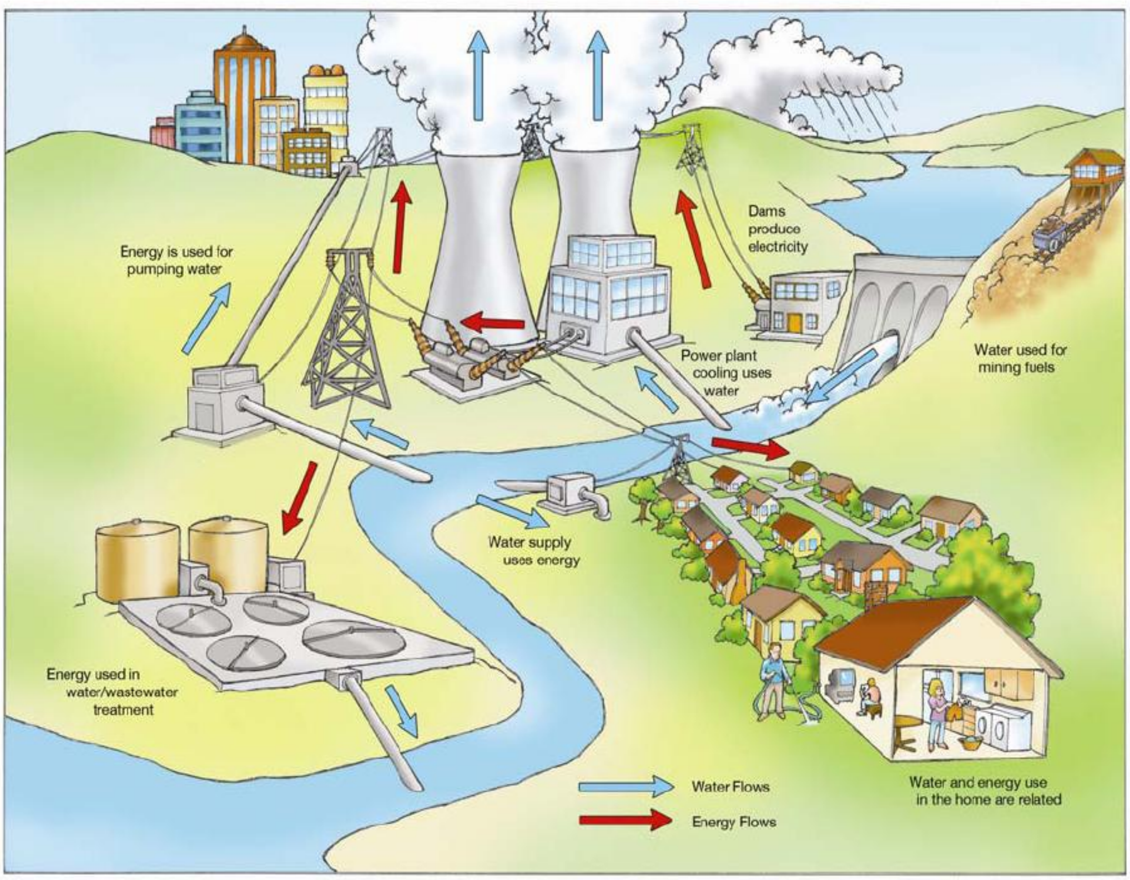


FIGURE 1. EXAMPLES OF INTERRELATIONSHIPS BETWEEN WATER AND ENERGY[1]

accounted for approximately 39 percent of freshwater withdrawals, ranking only slightly behind agricultural irrigation as the largest source of freshwater withdrawals in the United States in 2000[3]. However, thermoelectric water consumption associated accounted for only 2.5 percent of total U.S. freshwater consumption in 1995 (see Figure 2). A recent U.S. Department of Energy/National Energy Technology Laboratory (DOE/NETL) study estimated that in 2005 total U.S. freshwater withdrawals for thermoelectric power generation amounted to

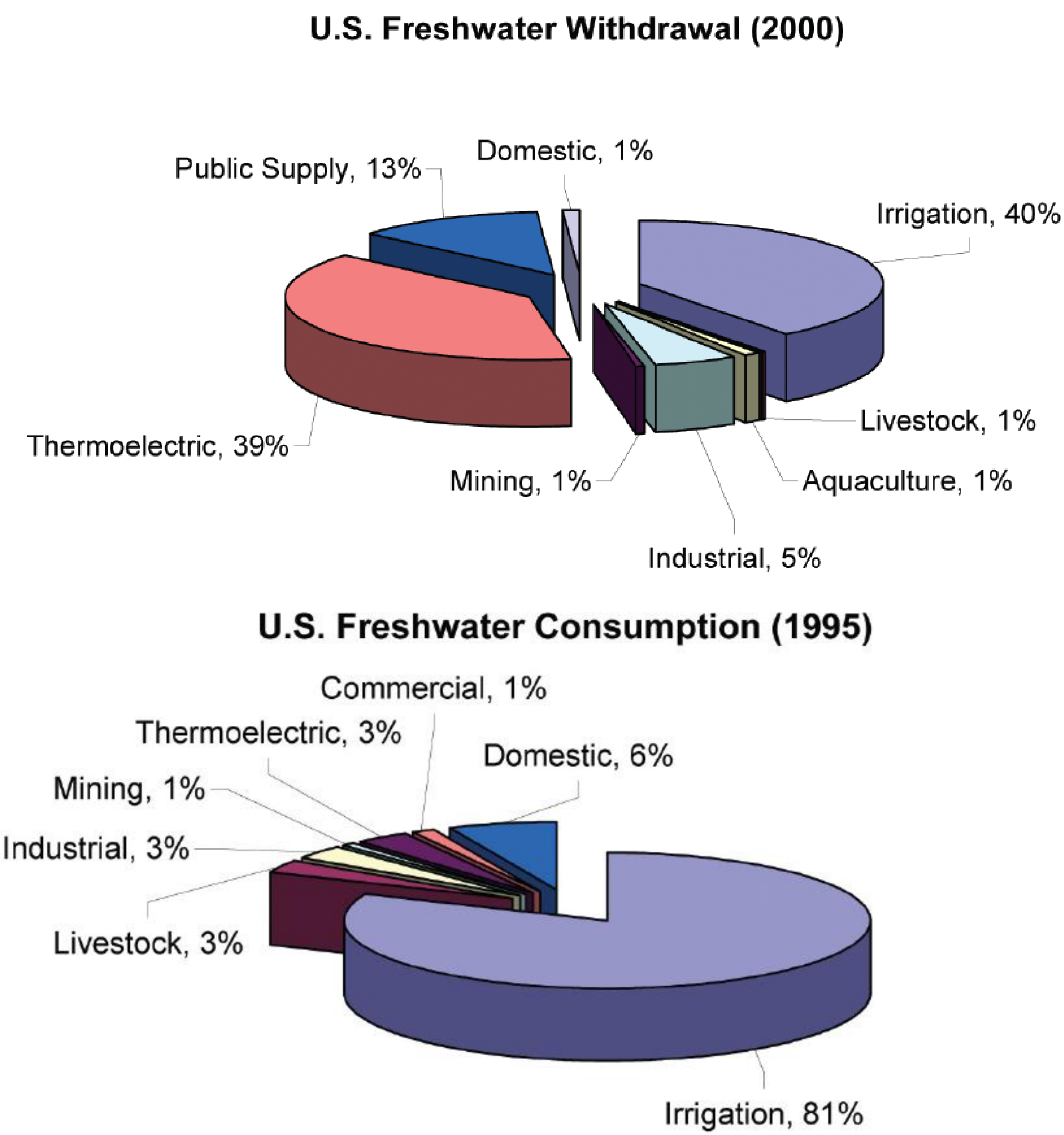


FIGURE 2. U.S. FRESHWATER CONSUMPTION VERSUS WITHDRAWAL[3]

approximately 146 billion gallon per day (bgd), while freshwater consumption was 3.7 bgd.

A potentially influential factor in future water use in energy generation may be carbon capture and sequestration (CCS). Carbon capture technologies that are commercially available today typically consume large quantities of water, and could increase water consumption by 50 to 90 percent depending on the power generation platform. Carbon sequestration activity has the potential to produce formation water during carbon dioxide (CO_2) injection operations.

The interface of energy and water, or the energy-water nexus, can be defined as the many relationships between energy and water that are necessary to ensure an adequate supply of both resources for every purpose[4]. As noted above, water is needed to make use of energy, and energy is needed to make use of water. Understanding the interlocking nature of energy-water interactions is the key to determining how to make the most efficient uses of these critical resources, both for short-term economic benefit and for longer-term societal and environmental sustainability. The interdependence of these relationships is indicated in Figure 3.

A summary comparison of water and energy issues (see Table 1) shows a striking correspondence between issues on the water side and issues on the energy side. The immediacy of these issues lends particular urgency to the effort to understand and manage the energy-water nexus.

One of the key considerations in evaluation of the energy-water nexus is the increasing demand for both commodities over time. Thermoelectric generating capacity is projected to increase by nearly 18 percent between 2005 and 2030[5]. Depending upon the assumptions invoked, water withdrawal to support electricity generation is expected to stay the same or decline slightly over the same time period. However, water consumption is expected to increase by anywhere from 28 to nearly 50 percent on a national basis.

Under its Existing Plants Program, NETL is pursuing an integrated energy-water research and development (R&D) program that addresses water management issues relative to coal-based power generation. This initiative is intended to clarify the link between energy and water, deepen the understanding of this link and its implications, and integrate current water-related R&D activities into a national energy-water R&D

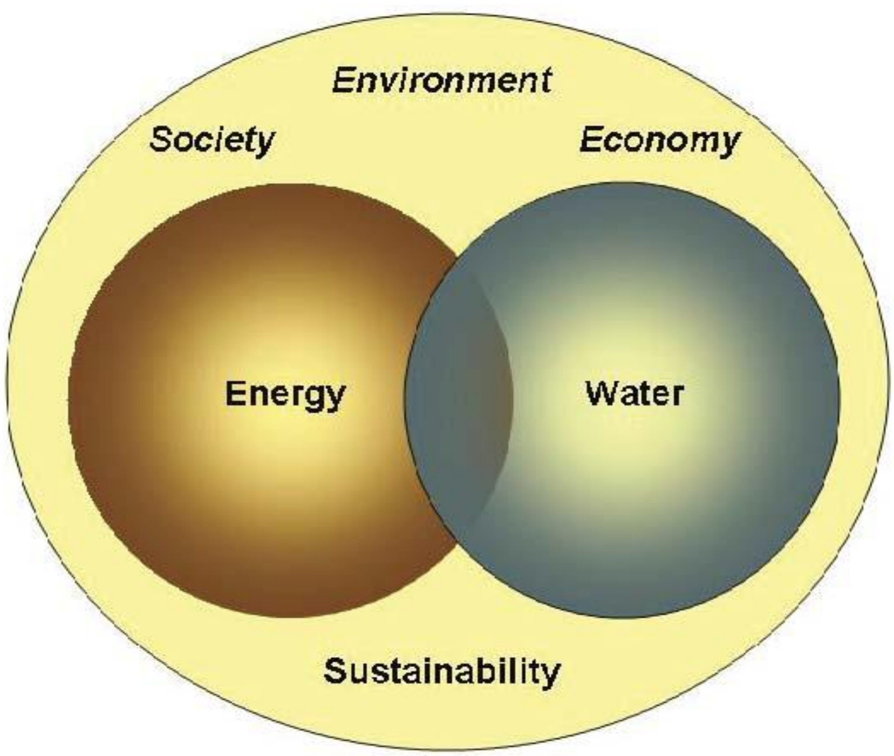


FIGURE 3. THE ENERGY-WATER NEXUS[4]

Table 1. Comparison of Water and Energy Issues

Water Issues	Energy Issues
Rapidly growing demand for clean, freshwater is creating competition for limited water resources that may also limit energy production.	Steadily growing demand for energy requires greater water use and consumption of often scarce freshwater resources.
All regions of the United States are vulnerable to water shortages, particularly during periods of drought.	All regions of the United States are vulnerable to energy (electricity) shortages at times of peak demand.
Regional imbalances in water availability may require more energy to overcome.	Regional imbalances in electricity distribution may require more water in regions where energy is produced.
Water availability is usually dependent on electricity supply.	Electricity availability is usually dependent on water supply.
Freshwater sources are limited and require energy to transport, distribute, and deliver.	Supplies of readily accessible fuels are becoming depleted and require more energy to extract.
The regulatory framework for environmental protection against watershed incursions may require more energy.	The regulatory framework for environmental protection from power plant emissions requires more water, directly and indirectly.
There is a need for greater efficiency in water sourcing, distribution, and use.	There is a need for greater efficiency in energy exploration, production, and use.
To lower intensity of water use, non-consumptive uses of water need to be further explored.	To lower intensity of energy use, renewable and emerging energy resources need to be further explored.
The water infrastructure is aging, and its maintenance or replacement will require energy.	The energy infrastructure is aging, and its maintenance or replacement will require both energy and water.
Population is continuing to grow, increasing water demand.	Population is continuing to grow, increasing energy demand.
Long-term societal and economic sustainability of water resources and watersheds may require curbs on water usage.	Long-term societal and economic sustainability may require curbs on energy usage.

program. The vision and mission of the NETL Energy-Water R&D Program is summarized in Figure 4, along with its relationship to the more broad vision and mission of DOE as a whole and the Fossil Energy (FE) Program[4].

NETL is well-suited to lead such a program due to its involvement and accomplishments in a number of areas involving energy-water interactions. The three principal focus areas for the Existing Plants Energy-Water R&D Program include:

- ***Non-Traditional Sources of Process and Cooling Water***
- ***Innovative Water Reuse and Recovery***
- ***Advanced Cooling Technology***

Non-traditional sources of cooling water typically include waters that have previously been considered unsuitable for cooling water purposes due to some form of organic or inorganic contamination such as the presence of high dissolved solids concentrations. These non-traditional sources can range from mine drainage waters to produced waters from mineral extraction processes to municipal wastewaters.

Innovative water reuse and recovery involves capturing water that historically has been discharged in either aqueous or vapor form and reusing the water in the power plant. Applications here range from ash pond waters to water captured from flue gases.

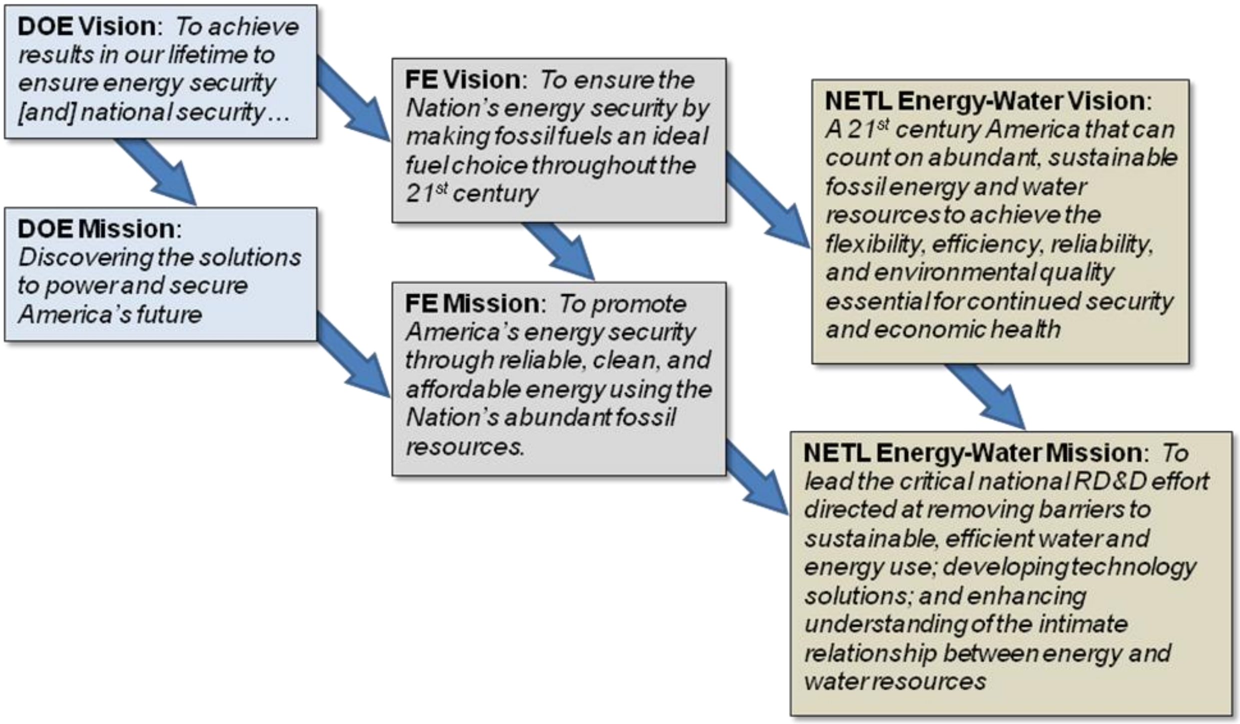


FIGURE 4. DOE/FE/NETL VISION AND MISSION CASCADE[4]

Advanced cooling technology involves innovative ways to cool power plant waters while minimizing water consumption. Systems being evaluated range from advanced mechanical systems (i.e., cooling towers) to constructed wetlands that can help cool power plant waters and provide wildlife habitat.

The Existing Plants Energy-Water R&D Program requires a broad, multidisciplinary scientific approach involving long-term, high-risk investment with little profit incentive over the short term, i.e., the same type of Federal research effort that has been devoted to other traditional energy R&D areas in order to advance knowledge in areas industry is unlikely to support on its own. As in the case of fossil energy research successes, society stands to benefit from investments in new technologies that enhance the understanding and handling of the energy-water relationship.

At its heart, the Existing Plants Energy-Water Program effort stems from the increasing importance of energy and water interactions for the Nation's future. The effort focuses the resources of the Federal government on managing the complex, multidisciplinary effort (in collaboration with industry and academia) necessary for success.

Over time, Federal R&D progress in understanding the interface of energy and water, or energy-water nexus, will affect many areas of national importance, such as national defense, food production, human health, manufacturing, recreation, tourism, and other daily activities. The cumulative effect will be a healthy balance between energy and water resources and needs, and a sustainable and secure future for the United States.

II. Water and Energy Availability

A wide variety of societal issues, policy and regulatory debate, environmental questions, technological challenges, and economic concerns exist at the interface of energy and water. Water is emerging as a significant factor in economic development activities. Planning efforts must consider the availability and quality of water resources in a given locality or region to ensure that supplies are available to accommodate existing and future water consumers. Failure to do so can result in growth limitations, inequitable development, and heated public debate and litigation regarding usage priorities. In order for the energy industry to be environmentally responsible, technologically ready, and economically stable, advanced research to explore and resolve water issues is imperative.

Limited supply of freshwater necessitates making choices regarding withdrawal and consumption. Water availability, withdrawal, and consumption are top priorities on the public agendas of many nations throughout the world. This issue is also taking on greater importance in the U.S. public agenda. Power plants will increasingly compete with other water users in water-stressed areas of the country. Agriculture and public supply will most likely be the greatest competitors due to their large water withdrawal. As with all resources, tradeoffs will occur, and concerns be raised over which uses are more important: water for drinking and personal use, growing food, or energy production.

A. Limited Supply of Water

About 70 percent of the Earth's surface is covered by water. The total worldwide supply of water is about 333 million cubic miles. However, only about three percent of this total is fresh. Of the total freshwater, more than 68 percent is locked up in ice and glaciers, while another 30 percent is in the ground. Fresh surface-water sources, such as rivers and lakes, only constitute about 22,300 cubic miles, which is approximately 1/700th of one percent of total water, as shown in Figure 5. Yet, rivers and lakes are the sources most people use every day for service water (industry, agriculture, residential, etc.) and for drinking[4].

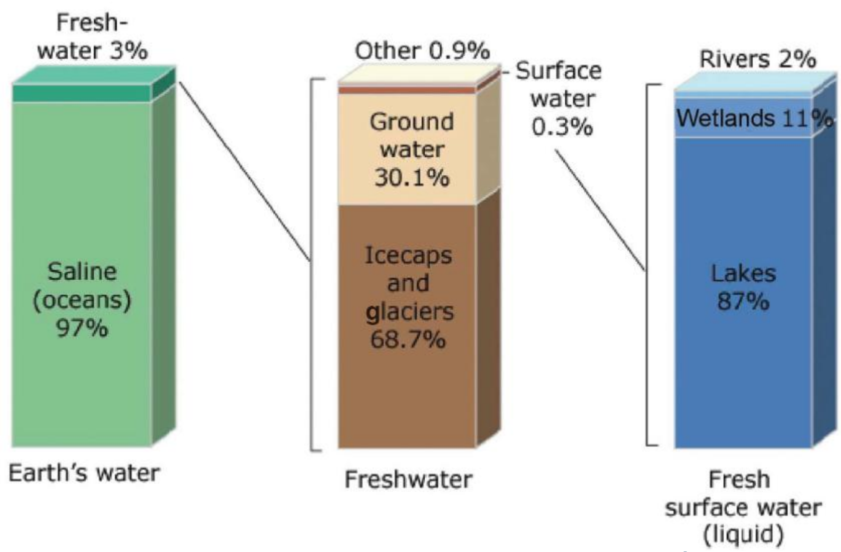


FIGURE 5. EARTH'S WATER DISTRIBUTION[4]

B. All Economic Sectors are Vulnerable to Water Shortages

Water shortages potentially represent the greatest challenge to face all sectors of the U.S. economy in the 21st century. According to a 2003 Congressional Government Accountability Office

(GAO) study[6], 36 states anticipate water shortages in the next 10 years under normal water conditions, and 46 states expect water shortages under drought conditions. National water availability has not been comprehensively assessed since 1978[6]; thus, water availability on a national level is unknown. However, as the GAO report states,

Current trends indicate that demands on the national water supplies are growing while the capacity to store surface water is increasingly limited, and groundwater is being depleted.

Water supply and demand estimates by the Electric Power Research Institute (EPRI) for the years 1995 and 2025 also indicate a high likelihood of local and regional water shortages[7].

Water availability issues are intensified by the fact that population increases are occurring in water-stressed areas. Figure 6 shows the percent change in population by state from 1990 to 2000 and Figure 7 shows mean annual precipitation from 1890 to 2002. Comparing the figures shows that areas where precipitation is low, especially in the Southwest, are also areas of greatest population growth[8].

C. Fast-Growing Demand Intensifies Competition for Water

Freshwater availability is a critical limiting factor in economic development and sustainability, and indirectly impacts all economic segments through limitations on electric-power supply. In its reference case for 2009, DOE's Energy Information Administration (EIA) projects that between 2007 and 2030 the U.S. population will grow by more than 70 million and electricity consumption will grow by nearly 20 percent[5]. Although the impact of this growth will be felt nationally, much of it is expected to occur in the

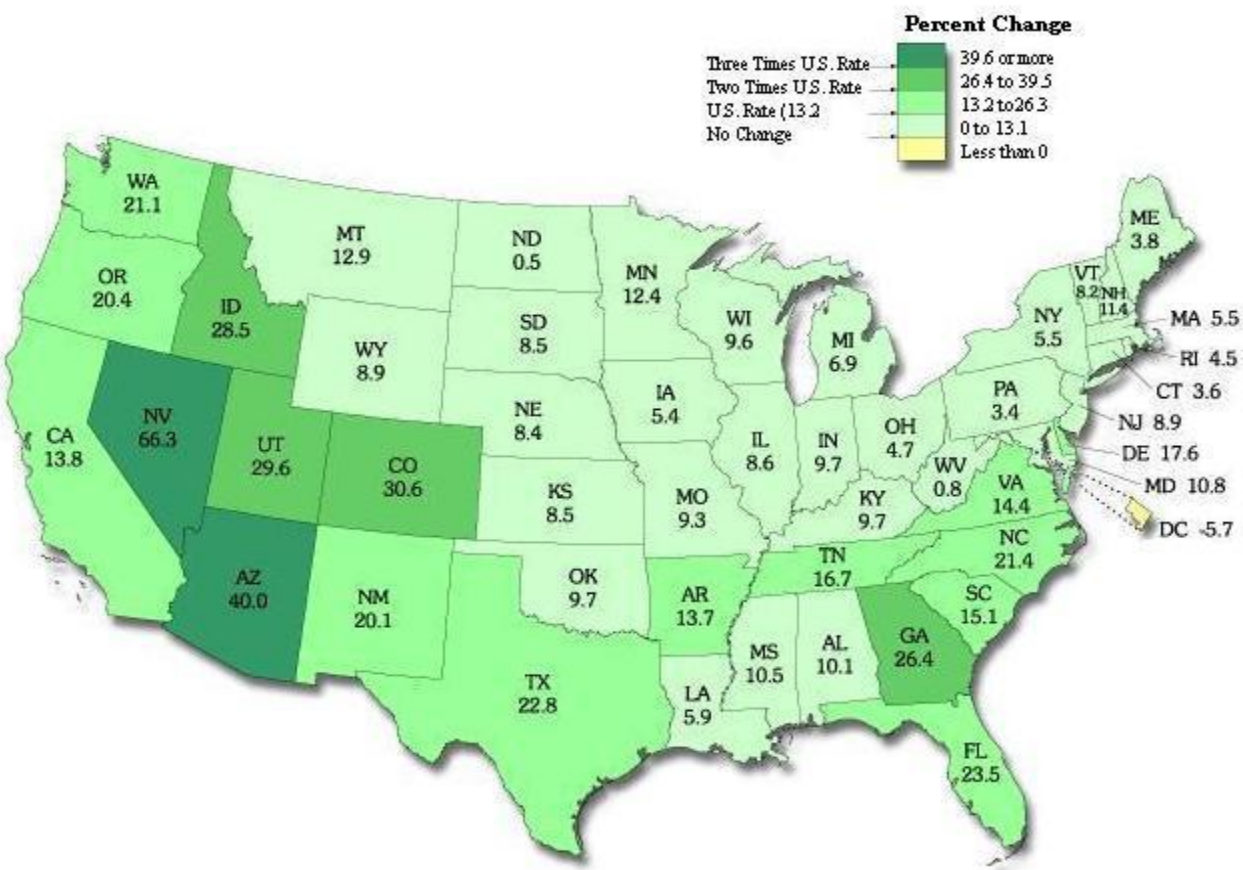


FIGURE 6. PERCENT CHANGE IN POPULATION BY STATE: 1990 -2000[8]

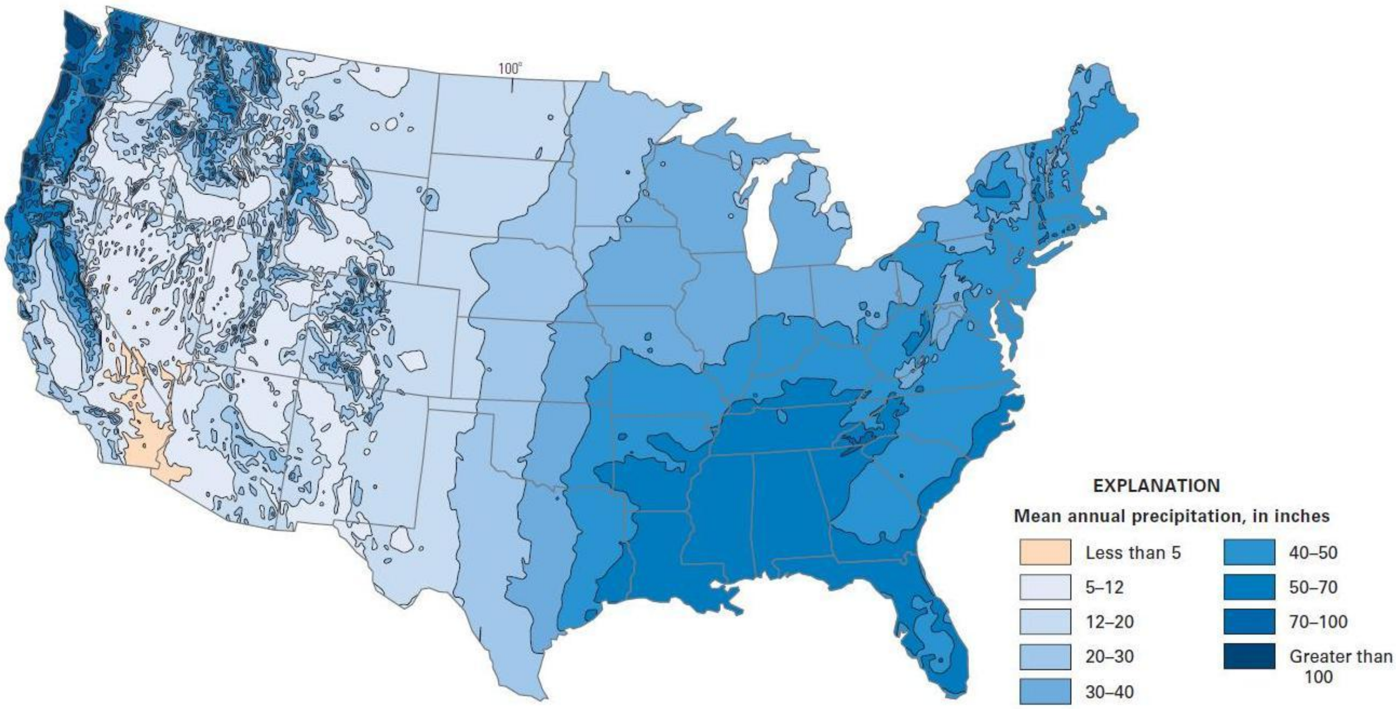


FIGURE 7. MEAN ANNUAL PRECIPITATION, 1890 -2002[8]

Southeastern, Southwestern, and far western regions of the country, where water already is in limited supply.

As the population and economic development of the United States increases, demands for water will grow from all sectors of the economy, including public supply, agriculture, domestic, livestock, industrial, and in-stream use, particularly in regions of the country with limited freshwater supplies. At the same time, the demand for fossil energy will continue to grow, putting additional stress on water resources. This issue will be especially difficult for thermoelectric power generators due to the large amount of cooling water required for power generation.

Concerns over limited water quantities are not restricted to thermoelectric generation. As indicated in Figure 2, 346 bgd of freshwater was withdrawn in the United States in the year 2000[3]. The largest use, agricultural irrigation, accounted for 138 bgd of freshwater withdrawn. The second largest use, thermoelectric generation, withdrew 136 bgd, followed by public supply, industrial uses, aquaculture, domestic use, mining, and livestock. Interestingly, thermoelectric generation withdrew the largest amount of saline water, 60 bgd (96 percent of all saline withdrawn). Withdrawal of saline water (and other non-traditional waters) reduces the strain on freshwater supplies and is one promising area for research[3].

Freshwater consumption for thermoelectric purposes is relatively low at 3 percent when compared to other use categories (irrigation was responsible for 81 percent of water consumed). However, even at 3 percent consumption, more than 3 bgd was consumed[3]. As a result of growing public pressures to withdraw less water, coupled with Clean Water Act requirements, consumption will likely increase significantly due to greater use of closed-loop cooling systems, which consume far more water than once-through cooling systems as a result of evaporation losses.

In addition to the water uses described above, increased value is being placed on in-stream freshwater uses, consisting mainly of habitat/species protection and recreational uses. In-stream uses will require a minimum flow rate or depth to be maintained in water bodies.

D. Impacts on Water Supply Systems

Moving large quantities of water over long distances is highly energy intensive. Significant infusions of energy at many points in the process are required to generate and maintain system water pressure. There are more than 60,000 water systems and 15,000 wastewater systems in the United States[9]. These systems are among the largest energy consumers in the country, using about 75 billion kWh/yr, or 3 percent of annual U.S. electricity consumption[9]. In addition, there is demand that includes energy for what is termed end use, namely, the energy required at the consumer level to further treat, circulate, heat, or cool the water.

Energy requirements and efficiency losses (and potential gains) exist at every stage of the water supply chain, from source and conveyance, water treatment, local water distribution, and end uses, to wastewater collection and treatment. Research opportunities exist for strategies and technologies to maximize efficiency and minimize energy loss at every stage during the process. Considering that water resources research funding has remained generally constant (in real dollars) since 1973, while per capita water research spending has decreased almost 30 percent between 1973 and 2001, a need for increased research in water source availability and competing demands for water is evident[4]. While it is recognized as an important research need, it is not currently part of the NETL Energy-Water R&D Program.

E. Managing Energy-Related Water Demand

The production of energy from fossil fuels (fuel and electricity) is dependent on the availability of adequate and sustainable supplies of water as shown in Figure 1.

Impacts in Mining, Processing, and Transportation of Fossil Fuels

Water is required in the mining, processing, and transportation of fossil fuels. The mining industry withdrew approximately 2 bgd of freshwater for all mineral extraction purposes (including oil and natural gas recovery) in the year 2000[10]. Surface and underground coal mining can result in acidic, metal-laden water that must be treated before it can be discharged to nearby rivers and streams (or be reclaimed by creating wetlands and lakes). About 10 percent of total U.S. coal shipments were delivered by barge in 2003. Consequently, low river flows can create shortfalls in coal inventories at power plants[7].

Natural gas and oil production can displace large quantities of groundwater. Approximately 10 barrels (420 gallons) of "produced water" are pumped to the surface for each barrel of oil[11]. The development of coal bed methane (CBM) resources can also generate a substantial volume of produced water that may require treatment and disposal[11]. Carbon sequestration is another technology area that could potentially displace significant quantities of produced water from subterranean formations[10]. Water management issues can and do materially impact domestic natural gas and oil development projects at a time when commodity prices are extremely high and additional sources of supply are sorely needed[11].

Impacts on Power Generation

Thermoelectric power plants require large amounts of water for efficient electricity production. On average, each kWh of thermoelectric generation requires approximately 25 gallons of water, primarily used for cooling purposes to condense steam. Power plants also use water for operation of pollution control devices such as flue gas desulfurization (FGD) technology as well as for ash handling, wastewater treatment, and wash

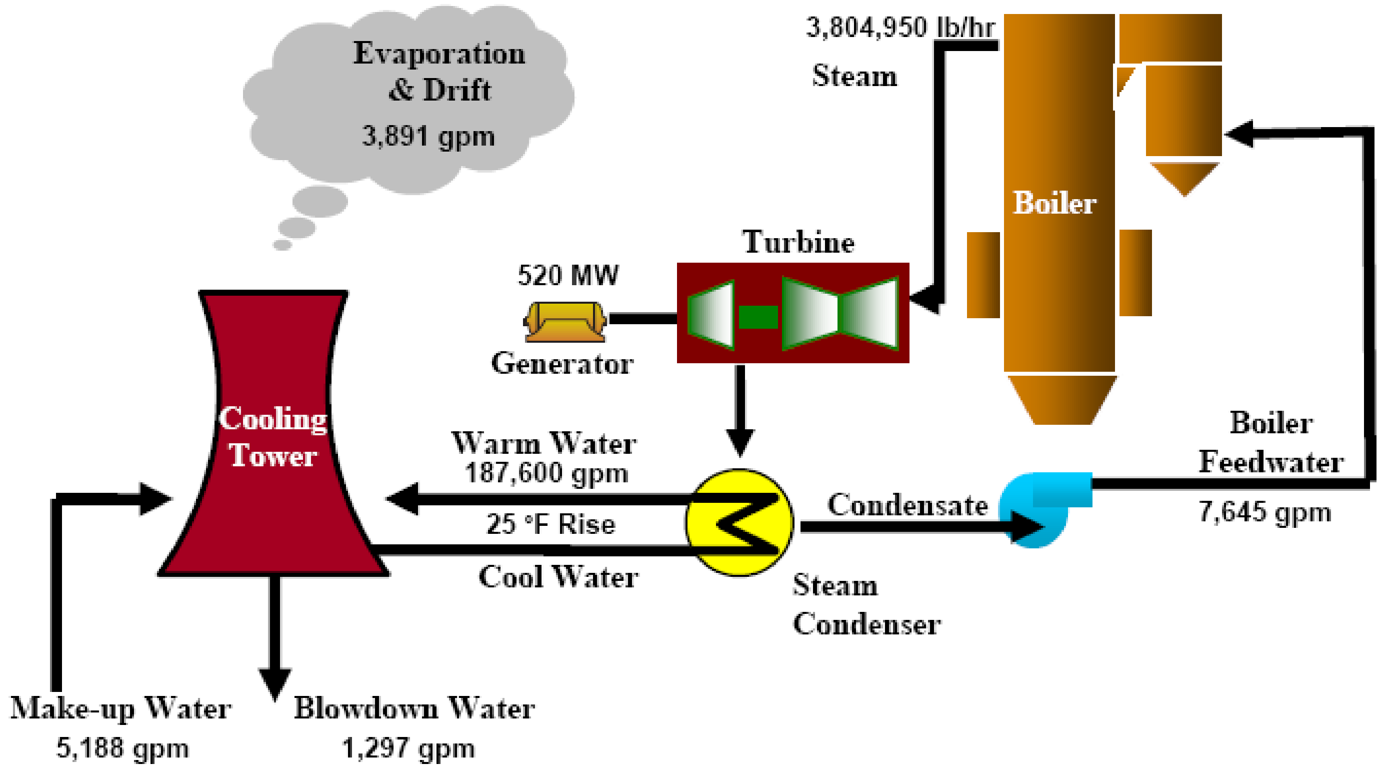


FIGURE 8. WET RECIRCULATING WATER COOLING SYSTEM FOR A 520 MW COAL-FIRED BOILER[12]

water. A recent study analyzing water withdrawal and water consumption for various coal-fired technologies found that cooling water use accounted for at least 80 to 90 percent of total plant water usage[12].

Cooling-related water withdrawal and consumption levels at a particular power plant are a function of the configuration of the plant, its choice of cooling technology, ambient conditions, and the acceptable temperature rise in the cooling water. These factors dictate the amount of water required to provide the heat transfer that will condense the steam exiting the steam turbine. Power plants can use either a closed-loop or open-loop cooling system. Closed-loop, recirculating systems (cooling towers and cooling ponds: see Figure 8) significantly reduce the amount of water withdrawn, but result in much higher consumption levels than open-loop, once-through systems, which have huge water withdrawal requirements but minimal consumption levels[12].

In the United States, existing thermoelectric power plants use both types of systems; approximately 58 percent of generating capacity is open-loop, 41 percent closed-loop, and 1 percent dry cooling[12]**.** Because water availability has not historically been a critical siting issue in the power sector, the choice of cooling technology depended more on ready access to water and on cost and performance characteristics. However, the use of closed-loop systems is likely to become much more pronounced in the future due to Clean Water Act provisions and public pressure. Although open-loop systems can still be legally permitted, the complexity of the permitting, analysis, and reporting requirements will likely discourage their use[12].

National and Regional Impacts

According to EIA estimates, while most areas of the United States currently have adequate power generation capacity, all electricity demand regions are expected to need about 23 percent additional, currently unplanned, capacity by 2030. More than 75 percent of the new capacity estimate is provided via thermoelectric generation, with coal-fired plants making up most of the additions[5].

The most significant increases in new thermoelectric capacity are expected in the Southeast and the West – with expected increases of 61 percent and 66 percent over current capacity, respectively, with most of that being coal-fired. The Midwest and South are expected to add some new natural-gas-fired plants to either maintain a diverse capacity mix or to provide reserve capacity. These increases in projected capacity will occur in regions of the United States that are challenged in terms of both current and future freshwater availability. Nuclear and renewable energy sources will supplement fossil fuel facilities[12].

NETL has conducted a water needs analysis to evaluate withdrawal and consumption rates moving forward in time to 2030. A total of five cases were evaluated in which different assumptions were made regarding replacement of cooling technologies over time. For all cases, retirements are assumed to be proportional to current water sources and cooling system types. The factor that varies among cases is the mix of cooling system types for additional generating capacity. For Cases 1-3, freshwater wet recirculating systems will be used (1) in the same proportion in new systems as they are in current systems, (2) in100 percent of new systems, or (3) in 90 percent of new systems (with the remaining 10 percent saltwater recirculating systems). Case 4 assumes 25 percent dry cooling and 75 percent freshwater wet recirculating systems for new capacity. Finally, for Case 5, all additional capacity uses freshwater wet recirculating cooling and current flow-through systems are converted to wet recirculating systems at the rate of 5 percent every five years[12].

On a national basis, consumption is expected to increase for all five cases, with withdrawal declining or remaining roughly the same. These results are consistent with current and anticipated regulations and industry practice, which favor the use of freshwater recirculating cooling systems that have lower withdrawal requirements but higher consumption than once-through cooling systems. If the results from 2005 are used as a baseline, percent changes in withdrawal and consumption can be calculated, as indicated in Table 2. The negative values indicate decreased

Table 2. National Percent Change in Thermoelectric Water Consumption and Withdrawal[12]

		Percent Change From 2005 Baseline				
		2010	**2015**	**2020**	**2025**	**2030**
Case 1	Withdrawal	1.2	-2.1	2.3	4.9	5.0
	Consumption	4.5	7.5	14.8	21.6	28.4
Case 2	Withdrawal	-0.1	-4.7	-4.3	-4.1	-5.0
	Consumption	5.4	10.1	20.8	30.5	40.0
Case 3	Withdrawal	-0.1	-4.7	-4.3	-4.2	-5.1
	Consumption	5.1	9.4	19.2	27.8	36.5
Case 4	Withdrawal	-0.2	-4.9	-4.6	-4.7	-5.6
	Consumption	4.5	8.4	16.5	23.5	30.7
Case 5	Withdrawal	-4.2	-12.9	-16.0	-19.2	-23.2
	Consumption	7.1	13.8	26.4	37.8	48.9

withdrawal over time, while the positive consumption values represent increased consumption[12].

Regional analyses were also conducted to evaluate future withdrawal and consumption in specific parts of the country. The regional analyses reveal some significant differences from the national averages. Using Case 2, which represents a plausible future cooling system scenario, as an example, the national level results indicate that water withdrawal will fall by five percent and consumption will rise by 40 percent over the 2005 to 2030 time period. However, on a regional basis, changes in withdrawal range from a 50 percent increase in Florida to a 24 percent decline in Texas. Freshwater consumption increases in all regions except California, with the largest increases coming in Florida (336 percent), New York (207 percent), and New England (93 percent)[12].

Impacts of Carbon Capture

As noted in Section 1, carbon dioxide capture processes could have significant water requirements when fitted onto new and existing fossil energy power plants. The current "state-of-the-art" technology for post-combustion CO_2 capture from existing coal-based power plants is wet-scrubbing with aqueous amine-based solvents. The additional water required for a power plant with this type of CO_2 capture technology is largely due to the additional cooling water[13]. Cooling water is used to lower the temperature of the amine liquid to enhance CO_2 absorption. Following capture, multi-stage CO_2 compression is used to compress the CO2 to supercritical conditions in preparation for pipeline transport. Intercoolers are used between compression stages to cool the CO_2 fluid, thus minimizing compression work. Additional cooling water within the CO_2 capture system is also used for water wash cooling, absorber intercooling, reflux condenser cooling, reclaimer cooling, and lean solvent cooling. All of these processes increase the heat load on the plant cooling water system, which increases the evaporative losses from the cooling tower and therefore increases water withdrawal requirements.

For integrated gasification combined cycle (IGCC) systems, the current state-of-the-art CO_2 capture technologies (i.e., the glycol-based Selexol™ process and the methanol-based Rectisol® process) employ physical solvents that preferentially absorb CO_2 from the fuel gas mixture. The advantage of physical solvents is that less energy is required in the solvent regeneration step. The increased water use for an IGCC plant is largely due to the steam used in the water gas shift (WGS) reaction. The WGS reactors are located before the Selexol unit and convert the carbon monoxide (CO) to CO_2. Water is required for this reaction to occur: $CO + H_2O \leftrightarrow CO_2 + H_2$. Additional water use is required to cool the syngas before entering the Selexol absorption reactor. Similar to post-combustion capture, additional cooling water is also required for CO_2 compression[13].

Table 3 presents an estimate of water consumption for various types of thermoelectric power plants equipped with wet recirculating cooling systems and both with and without CO_2 capture. As indicated, addition of carbon capture increases water consumption by 50 to 90 percent for fossil fuel electric generating facilities[13].

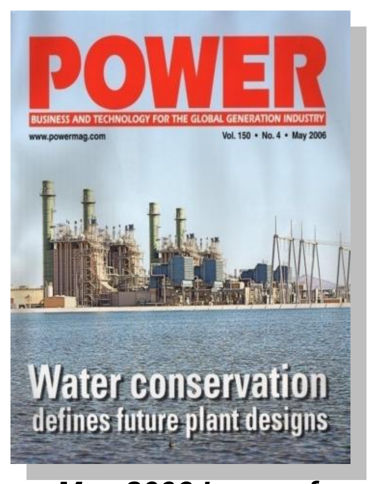
F. Summary

Water supply concerns expressed by state regulators, local decision-makers, and the general public are already impacting numerous power projects across the United States, as indicated by Figure 9. These concerns point toward a future of increased conflicts and competition for water that the power industry will need to operate their thermoelectric generation facilities. These conflicts will be national in scope, but regionally driven. It is likely that power plants in the West will be confronted with issues related to water rights, especially regarding who owns the water and the impacts of chronic and sporadic drought. In the East, current and future environmental requirements could be the most significant impediment to securing sufficient water, although local drought conditions could also impact water availability.

Table 3. Water Consumption for Thermoelectric Power Plants with and without Carbon Capture[13]

	Without CO_2 Capture	With CO_2 Capture	% Change With CO_2 Capture
Water Consumption Factors (gallons per MWh net Power)			
Nuclear	720	--	
Subcritical PC	520	990	+90%
Supercritical PC	450	840	+90%
IGCC, slurry-fed	310	450	+50%
NGCC	190	340	+80%

- **U.S. Supreme Court to Hear Case on Power Plant Cooling Methods**
  - *McClatchy-Tribune Regional News, April 2008*
- **Drought Could Force Nuke-Plant Shutdowns**
  - *The Associated Press, January 2008*
- **Sinking Water and Rising Tensions**
  - *EnergyBiz Insider, December 2007*
- **Stricter Standards Apply to Coal Plant, Judge Rules; Activists Want Cooling Towers for Oak Creek**
  - *Milwaukee Journal Sentinel, November 2007*
- **Journal-Constitution Opposes Coal-Based Plant, Citing Water Shortage**
  - *The Atlanta Journal-Constitution, October 2007*



May 2006 Issue of Power Magazine

FIGURE 9. HEADLINES REGARDING WATER-RELATED IMPACTS ON POWER PLANT SITING AND OPERATION[4]

III. Technology Pathways: The Energy-Water Program Roadmap

The Energy-Water Program roadmap presents a consensus on the critical technology pathways that must be researched to meet the goals of the Program. It defines what the science and technology challenges are, including the drivers, R&D pathways, R&D goals, and desired outcomes. These pathways will be pursued in concert with other elements of the Existing Plants Program, collaborative R&D partners, the regulatory community, and others. Section IV, Program Strategy and Implementation, defines how the Energy-Water Program is implementing the research.

The NETL Energy-Water Program was established in the late 1990s. Coordination and collaboration needs to play a vital role in addressing the complex interactions among energy, water, and the environment in the United States. DOE/NETL actively collaborates with other parties from industry, academia, state, and other Federal departments and national laboratories in analyzing and attempting to mitigate the impact of energy production on water supply. In particular, DOE/NETL has collaborated with Argonne National Laboratory, Sandia National Laboratory (SNL), Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), and the Energy and Environment Research Center (EERC) to study the impacts of power technologies upon water systems.

In 2002, in an effort to further national energy-water research, NETL joined with LANL and SNL in sponsoring a series of workshops held to solicit stakeholder input on relevant R&D issues concerning energy and water. These workshops, which involved wide representation from government, industry, interested organizations, and academia, provided input and perspectives on emerging regional and national energy and water needs and challenges, as well as energy and water science and technology research directions.

As a result of these workshops and continuing dialogue with industry and other key stakeholders, NETL joined with LANL and SNL as part of a three-laboratory energy-water cooperative Research Development and Design (RD&D) initiative. This three-lab effort evolved into a multi-laboratory Energy-Water Nexus Team consisting of 12 national laboratories and EPRI. As an adjunct to the Energy-Water Nexus activities, SNL was directed by Congress to develop a Report to Congress and a technology roadmap covering the broad issues, needs, and challenges associated with the linkages between energy and water. NETL directly supported SNL in the preparation of both documents. The Report to Congress was submitted in December 2006. A copy of the Report to Congress and additional information on the Energy-Water Nexus Team can be found at: http://www.sandia.gov/energy-water/. A draft of the energy-water technology roadmap is currently under review by DOE.

In addition to its efforts with the Energy-Water Nexus Team, NETL has been conducting research to reduce the amount of freshwater needed by thermoelectric power plants and to minimize potential water quality impacts. The program sponsors research encompassing laboratory- and bench-scale activities through pilot-scale projects and is built upon partnership and collaboration with industry, academia, and other government and non-governmental organizations. As noted in Section 1, the program is built around three specific pathways, or areas of research:

- ***Non-Traditional Sources of Process and Cooling Water***
- ***Innovative Water Reuse and Recovery***
- ***Advanced Cooling Technology***

The goal statement for the Energy-Water Program is outlined in the box below:

Guided by these over-arching goals, the Energy-Water Program Roadmap is presented in Table 4, which shows each of the research pathways and their drivers, goals, and outcomes. The Energy-Water Roadmap is not static; it will change as new information becomes available from progress in current research and new R&D opportunities.

Energy-Water Program Goal Statement

The short-term goal is to have technologies ready for commercial demonstration by 2015 that, when used alone or in combination, can reduce freshwater withdrawal and consumption by 50 percent or greater for thermoelectric power plants equipped with wet recirculating cooling technology at a levelized cost that is at least 25 percent less compared to state-of-the-art dry cooling technology. The long-term goal is to have technologies ready for commercial demonstration by 2020 that, when used in combination, can reduce freshwater withdrawal and consumption by 70 percent or greater at a levelized cost that is at least 50 percent less compared to state-of-the-art dry cooling technology."

Table 4. The Energy-Water Program Roadmap				
DRIVERS	R&D PATHWAYS		GOALS	OUTCOMES
• Energy production and water usage are inextricably linked • Freshwater availability is a critical limiting factor in economic development and sustainability • Projected increases between 2005 and 2030; Thermoelectric generating capacity - 18 percent, Water Consumption - 28 to 50 percent	**Non-Traditional Sources of Process and Cooling Water**	• Impaired Waters ○ Mine Pool Water ○ Produced Water ○ Municipal Wastewater ○ Cooling Tower Blowdown ○ FGD Blowdown ○ Acid Mine Drainage ○ Reverse Osmosis Reject Water ○ Ash Pond Effluent ○ High-silica Groundwater • Treatment	• Develop Cost-Effective Approaches to Using Lower-quality, Non-traditional Sources of Water to Supplement or Replace Freshwater for Cooling or Other Power Plant Needs	• Reduced impact of power plants on water usage • Minimization of the role of water availability in decision-making regarding future economic and social development • A healthy balance between energy and water resources and needs, and a sustainable and secure future for the United States as a whole
	Innovative Water Reuse and Recovery	• Water Recovery from Boiler Flue Gas ○ Condensing Heat Exchangers ○ Liquid Dessicant ○ Transport Membrane Condenser • Using Waste Heat for ○ Coal Drying ○ Freshwater Production From Saltwater ○ Driving an Ammonia Cycle for Power Production • Reduction of Water Use in FGD • Wetlands	• Reuse of Cooling Water • Beneficial Use of Waste Heat • Water Recovery From Coal • Water Recovery From Flue Gas	
	Advanced Cooling Technology	• Evaluation of Condensing Technology • Enhancements to Dry Cooling • Scale Prevention • Novel Filtration • Evaporative Cooling Impaired Water • Zebra Mussel Control • High Thermal Conductivity Foam for Air Cooled Steam Condensers	• Improve Performance • Reduce Costs ○ Wet Cooling ○ Dry Cooling ○ Hybrid Cooling	

IV. Energy Water Program Plan: Program Strategy and Implementation

Given the technical challenges outlined in the Energy-Water Roadmap (*what* needs to be accomplished) this section delineates *how* the Energy-Water Program R&D portfolio will be implemented. The program strategy has several key elements that guide implementation.

- Work collaboratively with regulators, technology developers, utilities, academia and the public.
- Seek market-based technology solutions that maximize public benefits in a cost-effective manner.
- Respond to differences in regional requirements related to water use and availability.
- Build the program's research portfolio on projects that are competitively selected and peer-reviewed for performance results.
- Serve a facilitating role in providing the data and analysis to resolve scientific and technology issues that hinder effective regulatory and policy pathways.
- Work with stakeholders to elucidate perspectives and opportunities for improved acceptability.
- Continuing public outreach activities that provide information and educational materials about technology options.

The Energy-Water Program seeks market-based technology solutions to water management issues and has two major products:

- Knowledge: High-quality scientific data and analysis for use in policy and regulatory determinations
- Technology: Advanced water management systems for coal-fired power plants.

As we move forward, some pathways may not be viable due to environmental, economic, technical, or other reasons. New concepts may open novel pathways that, through the process of roadmap development, can be identified and explored.

The availability of high-quality information and knowledge is key to the development of cost-effective water management and the formulation of balanced regulatory policy. Knowledge that is accepted by all stakeholders has multiple benefits. It can clarify the specific contributions of power plants to water use and consumption, thus providing a scientific basis for water management decisions. The result is improved policy and regulatory approaches that can yield the greatest public benefits at the least cost to the power sector and society at large.

To achieve the transfer of technology and knowledge products, the Energy-Water Program works closely with power producers, the Environmental Protection Agency (EPA), state and local agencies, and other stakeholders.

Program R&D performers include universities, nonprofit organizations, and industry, as well as NETL in-house research. Specific projects for the program have been funded through four competitive solicitations, with one project funded in 2002, five additional projects awarded in August 2003, seven in November 2005 and 10 in July 2008. Other projects have been funded through the Small Business Innovative Research and the University Coal Research Programs. The project titles and brief summaries are presented in tables for each research program area.

Roadmapping is an iterative process that incorporates new information as it becomes available. In order to guide technology development along market-based options, the roadmapping effort relies on widespread collaboration to develop a scientific and technical consensus.

A. Non-Traditional Sources of Process and Cooling Water

In the past, process and cooling water for thermoelectric power plants has typically been withdrawn from surface water sources (e.g., rivers and lakes) or from groundwater supplies. These are the same sources that have traditionally supplied drinking water and irrigation water. As the competition for water increases, it is necessary to investigate the use of other water sources for thermoelectric process and cooling water. Water quality requirements for cooling systems can be less restrictive than many other applications such as drinking water supplies or agricultural applications, so opportunities exist for the utilization of lower-quality, non-traditional water sources. Examples include surface and underground mine pool water, geological carbon sequestration and CBM produced waters, and industrial and/ or municipal wastewater. These impaired waters potentially could be used to offset freshwater withdrawals for thermoelectric power stations including advanced power systems. Specific areas of investigation include: (1) evaluating the use of non-traditional water (e.g., coal mine water and produced water from oil and gas extraction) for cooling with respect to amount available, quality of the water, and the types of water treatment needed for use in a power plant; (2) developing advanced water treatment technology to allow for the use of impaired water and to increase cycles-of-concentration in the operation of cooling systems; and (3) developing advanced assessment tools and carrying out supporting assessment and systems analyses for utilizing impaired waters for power plant applications.

Major Objectives

- Develop cost-effective approaches to using lower-quality , non-traditional sources of water to supplement or replace freshwater for cooling or other power plant needs

The argument most often employed against using non-traditional sources for cooling and process waters is that the waters are too high in total dissolved solids (TDS), which can lead to a variety of problems in power plant operations. In wet recirculating cooling systems, the warm cooling water is typically pumped from the condenser to a cooling tower where the heat is dissipated directly to ambient air. The cooling water is then recycled back to the condenser. Evaporative losses result in the need for a portion of the cooling water to be discharged from the system to prevent excessive buildup of minerals and sediment in the water that could adversely affect performance. This discharged water is known as blowdown. The quantity of blowdown required for a particular cooling water system is determined by the “cycles of concentration” (COC), which is defined as the ratio of dissolved solids in the circulating water to that in the makeup water. As the COC increases, the quantity of blowdown and makeup water decreases.

Table 5 presents the projects being undertaken to address the Non-traditional Water Sources Roadmap.

Table 5. Non-Traditional Sources of Cooling and Process Water Projects

PROJECT TITLE	PROJECT GOALS/OBJECTIVES	APPROACH/RESULTS	RESEARCH PARTNERS
Strategies for Cooling Electric Generating Facilities Utilizing Mine Water	Evaluation of the technical and economic feasibility of using water from abandoned underground coal mines in northern WV and southwestern PA.	• Identification of regional resources • 8 specific sites could supply a 600 MW power plant • Cost analysis – mine water viable cooling option depending on site conditions and water treatment needs	West Virginia University's Water Research Institute
Development and Demonstration of a Modeling Framework for Assessing the Efficacy of Using Mine Water for Thermoelectric Power Generation	Determine whether local mine water can be used as cooling water in a proposed 300 MW gob-fired power plant.	• Determine water quantity and quality characteristics of local mine discharges • Design a mine water collection, treatments and delivery system • Develop cost model	West Virginia University's National Mine Reclamation Center
Use of Produced Water in Recirculated Cooling Systems at Power Generation Facilities	Evaluation of the feasibility of using produced waters (oil and gas extraction) to meet up to 10% of the make-up cooling water demand for the 1800 MW San Juan Generating Station.	• Collection and transport of water to the plant – build 11-mile pipeline and use unused gas and oil pipelines to transport water • High efficiency reverse osmosis treatment for TDS reduction	Electric Power Research Institute (EPRI)
Advanced Separation and Chemical Scale Inhibitor Technologies for Use of Impaired Water in Power Plants	Development of advanced scale control technologies paired with filtering mechanisms to treat impaired waters for use in power plants.	• Chemical anti-scale agents • Membrane separation technology • Filtering – electrodialysis, electrodeionization, nanofiltration	Nalco Company, Argonne National Laboratory
An Innovative System for the Efficient and Effective Treatment of Non-Traditional Waters for Reuse in Thermoelectric Power Generation	Evaluation of specifically designed pilot-scale constructed wetland systems for treatment of targeted constituents in non-traditional waters for reuse in thermoelectric power plants.	• Ash basin water, cooling water blowdown, flue gas desulfurization (FGD) water and produced water • Pilot-scale testing shows promising removal results	Clemson University
Reuse of Treated Wastewaters in the Cooling Systems of Coal-Based Power Plants	Assess the potential of three types of impaired waters for cooling water makeup in coal-base plants: secondary treated municipal wastewater, passively treated coal mine drainage, and ash pond effluent.	• Assessment of availability and proximity of impaired waters to 12 proposed power plant sites • Assessment of regulations and permitting issues • Construction/Testing pilot scale cooling towers	University of Pittsburgh, Carnegie Mellon University
Use of Treated Municipal Wastewater as Power Plant Cooling System Makeup Water: Tertiary Treatment Versus Expanded Chemical Regimen for Recirculating Water Quality Management	Determine optimal treatment approaches for use of wastewater treatment-plant effluent as cooling water.	• Costs/benefits of tertiary treatment of municipal wastewater • Testing of corrosion, scaling, and biofouling control methods	Carnegie Mellon University

Table 5. Non-Traditional Sources of Cooling and Process Water Projects			
PROJECT TITLE	PROJECT GOALS/OBJECTIVES	APPROACH/RESULTS	RESEARCH PARTNERS
Internet-Based GIS Catalog of Non-Traditional Sources for Cooling Water for use at America's Coal-Fired Power Plants	Create an internet-based GIS catalog of non-traditional sources of cooling water for coal-fired power plants to reduce withdrawal and consumption of high quality freshwater.	• Beneficial use of oil and gas produced water, abandoned coal mine water, industrial wastewater, and low-quality groundwater.	Arthur Langhus Layne
Reuse of Produced Water from CO_2 Enhanced Oil Recovery, Coal-Bed Methane, and Mine Pool Water by Coal-based Power Plants.	Evaluate the feasibility of reusing three types of non-traditional water sources for cooling or process water for coal-based power plants.	• Evaluate produced water quantity and quality • Investigate suitable treatment methods • Conduct a detailed economic and benefits analysis	University of Illinois
Technology to Facilitate the Use of Impaired Waters in Cooling Towers	Development of a new silica-removal technology that can be used in combination with other separation technologies to make non-traditional waters available for use in cooling towers	• Material selection and synthesis • Material recycle and bench top demonstrations • Scale-up	GE Global Research

The makeup water quality requirements for the cooling water system depend upon the water quality requirements of the circulating water and the COC at which the system is operated. For example, if the maximum acceptable level of chlorides in the circulating water system is 750 milligrams per liter (mg/L) and the system is operated at three COC, then the makeup water would need to be limited to 250 mg/L (750 divided by three).

Without proper control, the physical and chemical characteristics of the makeup and circulating water can lead to scale formation, corrosion, or microbiological fouling that adversely affect cooling water system performance.

Scale Formation

As water evaporates from the circulating water system, dissolved solids from the makeup water can accumulate to saturation levels and begin to precipitate out of solution as solid scale-forming deposits. Scale formation is a function of the chemical composition of the makeup water, circulating water temperature and pH, and COC. There are several chemical species that contribute to TDS in freshwater makeup to the cooling system that if allowed to reach saturation levels can form scale deposits including calcium carbonate, calcium sulfate, calcium phosphate, and magnesium silicate. Recent studies of various non-traditional waters have identified calcium carbonate, silica, barium sulfate, and calcium sulfate to be chemical constituents that could potentially limit COC based on the effective treatment limits of commercially available scale control technologies.

Corrosion

Corrosion in the cooling water system occurs primarily due to electrolytic action. Therefore, an increase in TDS tends to also increase conductivity and thus the potential for corrosion. Excessive chloride and sulfate ion concentrations are of particular concern. However, acceptable water quality characteristics to minimize corrosion are dependent on the construction materials used throughout the cooling water system. The most serious concern with corrosion occurs with the tubing and tubesheet of the steam condenser. These components are typically constructed of copper alloys, stainless steel, or titanium. The copper alloys are the most susceptible to corrosion, but the stainless steels are also at risk. For example, ammonia can cause corrosion to copper and copper alloys. Pitting corrosion of stainless steels can also be caused by manganese oxide in the circulating water. Chemical treatment using various corrosion inhibitors can be used to prevent corrosion.

Microbiological Fouling

Microbiological growth within the circulating water system results in deposits of slime and algae on heat transfer surfaces known as biofilm. The biofilm deposits can both restrict heat transfer and promote corrosion. Certain chemical species in the makeup water, such as nitrogen, phosphate, and organic compounds, can promote microbiological growth within the circulating water system. Microbiological fouling can be controlled by chlorine, bromine, sodium hypochlorite, chlorine dioxide, hydrogen peroxide, ozone, or various proprietary chemical treatments.

Proper water quality requirements must be maintained in order to prevent scale formation, corrosion, or microbiological fouling that could adversely affect cooling water system performance. Although corrosion and microbiological fouling might be more severe when using non-traditional water for makeup, it is likely that scale formation will be the greatest concern.

Implementation Highlights

♦ Successes to Date

– Eight mine water sources in western Pennsylvania and northern West Virginia with sufficient capacity to support a 600 MW power plant were identified. Cost analysis concluded that depending on site conditions, utilization of mine pool water for power plant cooling could be cost effective.

– Developed pilot-scale cooling towers that can be used to evaluate the impact of multiple impaired waters in side-by side tests (see right).

– Reclaimed water (treated municipal wastewater) represents a valuable resource that can be used for cooling in electric power plants. Eighty-one percent of power plants proposed for construction by the Energy Information Administration (EIA) would have sufficient cooling water supply from one to two publicly owned treatment works (POTW) within a 10-mile radius, while 97 percent of the proposed power plants would be able to meet their cooling water needs with one to two POTWs within 25 miles of these plants.

♦ Moving Forward

– Several studies are underway evaluating methods for treating non-traditional waters so that they can be used in power plant settings. These treatments include chemical additions, advanced filtering mechanisms (electrodialysis, electrodeionization, nanofiltration), membrane separation, silica-removal technologies, and treatment in constructed wetlands. Non-traditional waters currently being evaluated for use include secondary and tertiary treated municipal wastewater, mine pool waters, passively treated coal mine drainage, ash pond effluent, and produced waters from coal bed methane capture, CO_2 enhanced oil recovery, and carbon sequestration in saline aquifers. In addition, an internet-based, GIS catalog of non-traditional waters for cooling waters is being developed.

B. Innovative Water Reuse and Recovery

Major Objectives

Develop methods that allow for:

- Reuse of Cooling Water
- Beneficial Use of Waste Heat
- Water Recovery from Coal
- Water Recovery from Flue Gas

When coal is burned in a boiler, a significant amount of water is discharged in the flue gas. This water can come from several sources, with some water associated with the coal. Sub-bituminous coals have higher water contents than bituminous coals. When the coal is combusted, the associated water is driven off and escapes as water vapor in the flue gas. Another source of water in flue gas is oxidation of hydrogen in the coal. Again, during combustion, any hydrogen in the coal is converted to water and escapes as water vapor in the flue gas. Finally, any moisture in the air that is used for combustion leaves in the flue gas.

There are three basic ways to remove the water from the flue gas:

- Condense it out by cooling
- Use a desiccant
- Filter it out using a membrane

If this water is recovered, it can be used for cooling water make-up or other processes, thus reducing freshwater withdrawals.

Another area of active research in water recovery involves the use of waste heat to dry coal. Hot cooling water leaving the condenser is used to warm air that then is used to drive water from coal. Lowering the temperature of the return cooling water reduces evaporative loss in the cooling tower, thus reducing overall water consumption. In addition, drying the coal prior to combustion can improve power plant efficiency, and in return reduce overall air emissions per unit of electricity produced.

Specific projects that are components of the Innovative Water Reuse and Recovery Program are summarized in Table 6.

Implementation Highlights

♦ Successes to Date

– A process that produces freshwater was demonstrated for power plants that use saltwater for cooling. Saline water cools and condenses the steam and the warmed water from the condenser passes through a diffusion tower to produce humidified air from which freshwater is condensed. The process is cost-competitive with reverse osmosis.

– Process heat from condenser return cooling water was extracted upstream of the cooling tower to warm ambient air that was used to dry coal. Lowering the temperature of the return cooling water reduced evaporative loss in the cooling tower, reducing water consumption, and led to improved plant efficiency.

– A technology was developed to extract water vapor form flue gas using a liquid desiccant. The flue gas is cooled and then sent through either a spray tower or packed bed configuration where the desiccant, calcium chloride, absorbs water fro the flue gas. The wet desiccant is then heated to remove the water as vapor, which is then condensed.

♦ Moving Forward

– Some of the earlier studies cited above are being scaled to full size. For example, results from the coal drying study are being scaled and applied to a 546 MW lignite-fired power production facility in North Dakota. The desiccant study is also being scaled to a full-sized facility. New work involves recovery of water from boiler flue gas using condensing heat exchangers (see above) and transport membrane condensers. In addition, a project is being initiated evaluating the use of constructed wetlands for treatment of aqueous power plant wastes so that the water can be reused in the plant.

Table 6. Innovative Water Reuse and Recovery Projects

Project Title	Project Goals/Objectives	Approach/Results	Research Partners
Use of Coal Drying to Reduce Water Consumed in Pulverized Coal Power Plants	Evaluate the performance and economic feasibility of using low-grade power plant waste heat to partially dry low rank coals.	• Process heat from condenser return cooling water extracted upstream of the cooling tower to warm air that was then used to dry the coal. • Reduced evaporative loss • Increased combustion efficiency	Lehigh University
Full-Scale Coal Drying System at Green River Energy 546 MW lignite-fired Coal Creek Power Station	Scale-up of results from preceding project.	• Pilot-scale facility followed by full scale • Process should yield enough water to completely compensate for make-up	Lehigh University, Green River Energy, and Vattenfall of Sweden
An Innovative Freshwater Production Process for Fossil Fuel Fired Power Plants Using Energy Stored in Main Condenser Cooling Water	Investigation of a desalination technique using waste heat from the condenser that would allow power plants that use saline water for cooling to become net producers of freshwater.	• Saline water cools and condenses low pressure steam • Warmed water from the condenser passes through a diffusion tower to produce moist air which is condensed	University of Florida
Water Conserving Steam Ammonia Power Cycle	Investigation of the use of waste heat to operate an ammonia Rankine Cycle to generate additional power for Kotzebue, Alaska.	• Waste jacket heat from a diesel generator to produce 150 KW of electricity • As much heat as possible added to city water supply – reduces oil consumption for domestic water heating	Energy Concepts Company
Recovery of Water from Boiler Flue Gas Using Condensing Heat Exchangers – Phase I and II	Combination of laboratory, pilot scale, and slip stream experiments and computer simulations to investigate use of condensing heat exchangers to recover water from boiler flue gas.	• Design compact fin tube heat exchanger based on computational fluid mechanics analysis • Removal of acid vapors and condensation of water vapor in separate stages of heat exchanger system	Lehigh University
Water Extraction form Coal-Fired Power Plant Flue Gas	Development of a technology to extract water vapor from coal-fired power plant flue gases using a liquid desiccant.	• Spray tower or packed bed where calcium chloride desiccant absorbs water from the flue gas • Wet desiccant heated to remove adsorbed water	The University of Nor the Dakota's Energy and Environmental Research Center (UND EERC)
Transport Membrane Condenser for Water and Energy Recovery from Power Plant Flue gases	Development and testing of a membrane-based technology to recover water and energy from power plant flue gases.	• Stage 1 – recovery of high-quality water and energy that can be used to replace plant boiler make-up • Stage 2 – recovery of higher-volume/lower-quality water for cooling tower make-up	Gas Technology Institute
Wetland Water Cooling Partnership: The Use of Restored Wetlands to Enhance Thermoelectric Power Plant cooling and mitigate the demand on Surface Water Use	Investigation of the use of wetlands as a treatment method for power plant water reuse and as tertiary treatment of wastewater treatment plant effluent prior to use in a power plant.	• Literature review – wetlands for water cooling and heat management • Conceptual design, technical evaluation, and modeling of specific cooling strategies • Scale model/field testing	Applied Ecological Services

C. Advanced Cooling Technology

The Advanced Cooling Technology component of the Energy-Water R&D Program is focused on research to develop technologies that improve performance and reduce costs associated with wet cooling, dry cooling, and hybrid cooling technologies. In addition, the research area covers innovative methods to control bio fouling of cooling water intake structures as well as advances in intake structure systems.

It is technically possible to cool power plants with minimal water use. However, at this time these types of cooling methods are not as economically feasible as traditional cooling systems. Additional R&D is necessary to develop cooling systems that use as little water as possible, but at a reasonable cost.

Water intake structures are also an area of concern, especially considering the Clean Water Act 316(b) regulation, which requires that the location, design, construction, and capacity of cooling water intake structures reflect the best technology available for minimizing adverse environmental impact. With plant intake structures, the particular concern is impingement and entrainment of aquatic organisms.

Specific projects that are components of the Advanced Cooling Technology program are summarized in Table 7.

Major Objectives

Develop Technologies that Reduce Costs and Improve Performance of:

- Wet Cooling
- Dry Cooling
- Hybrid Cooling
- Intake Bio-fouling Inhibitors

Implementation Highlights

- Successes to Date
  - Air2Air^{R} condensing technology has been demonstrated in a cooling tower application, as shown at right. The left-most cooling tower shown has been fitted with Air2Air^{R} condensing technology, which has resulted in a significant reduction in the release of water vapor. This system has the potential to condense as much as 20 percent of the cooling water that would normally be evaporated. Scaled nationally, potential water savings could be over 1.5 billion gallons/day.
  - Pilot-scale testing of a wet cooling system capable of using low-quality water was conducted. The unit was successful in increasing the cycles of concentration, and no scaling was observed.
  - A particular strain of naturally occurring bacteria (*Pseudonomas fluorescens)* has been shown to be selectively lethal to zebra mussels, but benign to non-target organisms. Significant effort has been expended to reduce the cost associated with this control method, resulting in an 88 percent reduction in cost.

- Moving Forward
  - Several studies are underway evaluating methods for reducing costs for Advanced Cooling Technologies. For example, changes in geometry for the Air2Air^{R} system have the potential to make it more efficient in capturing water. Pulse spark discharges and continuous filtration are being evaluated to determining their impact on scale formation.

Table 7. Advanced Cooling Technology Projects			
PROJECT TITLE	PROJECT GOALS/OBJECTIVES	APPROACH/RESULTS	RESEARCH PARTNERS
Use of Air2Air^R Technology to Recover Fresh-Water at Thermoelectric Power Plants	Evaluation of the performance of Air2Air^R condensing technology in a cooling tower application on a test cell at the San Juan Generating Station (SJGS) in New Mexico.	• Air-to-air heat exchanger above a wet cooling tower takes warm, humid air from the cooling tower and contacts it with cooler, dry outside air to condense and recover a portion of the evaporated water	SPX Cooling Technologies
Improved Performance of an Air Cooled Condenser (ACC) Using SPX Wind Guide Technology at Coal-Fired Thermoelectric Power Plants	Improved efficiency of power-plant air cooled condensers through the development of wind guide technology	• Wind guide vanes and screens associated with fans on force draft ACCs reduce crosswind effects - directing air toward the fan • Degradation of fan performance reduces plant efficiency	SPX Cooling Technologies
Application of Pulsed Electrical Fields for Advanced Cooling in Coal-Fired Power Plants	Investigation of decreasing blowdown by precipitating and then filtering dissolved solids	• Precipitate scaling ions using electrical pulses • Filter precipitated solids with a self-cleaning membrane • Offers ability to operate at higher cycles of concentration	Drexel University
Testing of the Wet Surface Air Cooler	Pilot-scale testing of a wet cooling system capable of using low quality water	• Spray cooling configuration allows operation in a saturated mineral regime • Three separate tube bundles • Each bundle constructed of a different metal to evaluate corrosion potential	EPRI/Niagara Blower
Environmentally-Safe Control of Zebra Mussel Fouling	Evaluation of the use of naturally-occurring bacteria to control zebra mussel populations	• *Pseudomonas fluorescens* selectively lethal to zebra mussels but benign to non-target organisms • Cost competitive	New York State Education Department
Enhanced Performance Carbon Foam Heat Exchanger for Power Plant Cooling	Evaluation of heat transfer enhancement through use of high thermal conductivity foam	• Higher heat transfer rate would allow for smaller heat exchanger • Foam formed into fins to enhance heat transfer rate • Not cost-effective	Ceramic Composites, Inc./ SPX Cooling Technologies

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