NATIONAL ENERGY TECHNOLOGY LABORATORY

Department of Energy/National Energy Technology Laboratory's Water-Energy Interface Research Program: December 2010 Update

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U.S. DEPARTMENT OF ENERGY

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NETL Contact:

Jared Ciferno
Technology Manager
Existing Plants, Emissions and Capture Program

National Energy Technology Laboratory
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LIST OF ABBREVIATIONS AND ACRONYMS

Acronym/Abbreviation	**Definition**
ACC	Air Cooled Condenser
AEO 2009	EIA's Annual Energy Outlook 2009
AES	Applied Ecological Services
AMD	Acid Mine Drainage
AML	Abandoned Mine Land
ANL	Argonne National Laboratory
As	Arsenic
bbl	Barrels
BGD	Billion Gallons Per Day
Btu	British thermal units
$CaCO_3$	Calcium Carbonate
CBM	Coalbed Methane
CCPI	Clean Coal Power Initiative
CCS	Carbon Capture and Sequestration
CMU	Carnegie Mellon University
CO_2	Carbon Dioxide
COC	Cycles of Concentration
CWA	Clean Water Act
DOE	U.S. Department of Energy
DOI	U.S. Department of Interior
ED	Electrodialysis
EDR	Electrodialysis Reversal
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EPEC	Existing Plants Emissions and Capture
EPRI	Electric Power Research Institute
ESP	Electrostatic Precipitator
FE	Office of Fossil Energy
FGD	Flue Gas Desulfurization
GHG	Greenhouse Gas
GIS	Geographic Information System
gpm	Gallons Per Minute
GRE	Green River Energy
GTI	Gas Technology Institute
Hg	Mercury
IAES	Institute for Advanced Energy Solutions
IGCC	Integrated Gasification Combined Cycle
IPR	Integrated Pollutant Removal
ITS	Ice Thermal Storage
Kw	Kilowatts
kWh	Kilowatt-Hour
LANL	Los Alamos National Laboratory

LFCM	Ligand-Functionalized Core Material
LLNL	Lawrence Livermore National Laboratory
mg/L	Milligrams Per Liter
MGD	Million Gallons Per Day
MW	Megawatt
NETL	National Energy Technology Laboratory
NF	Nanofiltration
NO_X	Nitrogen Oxides
NPDES	National Pollutant Discharge Elimination System
O&M	Operation and Maintenance
ORD	Office of Research and Development
PM	Particulate Matter
PMA	Polymaleic Acid
POTW	Publicly Owned Treatment Works
ppm	Parts Per Million
PRB	Powder River Basin
psi	Pounds Per Square Inch
R&D	Research and Development
RD&D	Research Development and Design
RO	Reverse Osmosis
SCR	Selective Catalytic Reduction System
SDWA	Safe Drinking Water Act
Se	Selenium
SJGS	San Juan Generating Station
SNL	Sandia National Laboratories
SO_2	Sulfur Dioxide
SO_3	Sulfur Trioxide
TDS	Total Dissolved Solids
TKPP	Pyrophosphate
TMC	Transport Membrane Condenser
TMDL	Total Maximum Daily Load
TTA	Tolyltriazole
TVA	Tennessee Valley Authority
UND EERC	University of North Dakota Energy and Environmental Research Center
USGS	United States Geological Survey
WQS	Water Quality Standards
WSAC	Wet Surface Air Cooler

Prepared by:

Jared P. Ciferno
U.S Department of Energy/National Energy Technology Laboratory

Ronald K. Munson
Leonardo Technologies, Incorporated

James T. Murphy
Leonardo Technologies, Incorporated

INTRODUCTION

Coal-fired power plants use significant quantities of both coal and water for electricity generation. For example, a 500-MW power plant burns approximately 250 tons per hour of coal while using more than 12 million gallons per hour of water for cooling and other process requirements.[a,1]

As U.S. population and associated economic development continue to expand, the demand for electricity increases. Thermoelectric generating capacity is expected to increase by nearly 15 percent between 2008 and 2035, according to projections from the Energy Information Administration's (EIA) *Annual Energy Outlook 2010* (AEO 2010).[2] 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.[3] Withdrawal is expected to remain the same or decrease because plants likely to be retired between 2005 and 2030 are older facilities that are more likely to employ high-withdrawal, once-through cooling. New facilities that will be built over that time period are likely to employ lower-withdrawal but high-consumption wet recirculating cooling systems. These projections are based on a business-as-usual approach, and do not reflect responses to potential energy/climate legislation being proposed by Congress.

A potentially influential factor in future water use in energy generation is carbon capture and sequestration (CCS). In fact, if coal is to remain an important component of energy production in the United States under any future climate/energy legislation, CCS will be essential. Carbon capture technologies that are commercially available (on a small scale) today typically consume large quantities of water, and could increase water consumption by 50 to more than 90 percent depending on the power generation platform.[3] The additional water required for a power plant with carbon dioxide (CO_2) capture technology is largely due to the additional cooling water requirements used during capture and compression, thereby increasing the evaporative losses from the cooling tower.[4]

Given the factors noted above, coal-fired power plants may increasingly compete for freshwater with other sectors such as domestic, commercial, agricultural, industrial, and in-stream use – particularly in regions of the country with limited freshwater supplies.[5] In addition, current and future water-related environmental regulations and requirements will challenge the operation of existing power plants and the permitting of new thermoelectric generation projects.

In response to these challenges to national energy sustainability and security, the Department of Energy/Office of Fossil Energy's National Energy Technology Laboratory (DOE/NETL) has initiated an integrated research and development (R&D) effort under its Existing Plants Emissions and Capture (EPEC) Program directed at technologies and

[a] Actual cooling water flow rate requirements for a particular plant will vary depending on type of cooling water system and design parameters.

concepts to reduce the amount of freshwater used by power plants and to minimize any potential impacts of plant operations on water quality.[6] The vision and mission for this effort is presented in the box below:

NETL Water-Energy Program Vision and Mission
Vision: A 21st century America that can count on abundant, sustainable fossil energy and water resources to achieve the flexibility, efficiency, reliability, and environmental quality essential for continued security and economic health.
Mission: To lead the critical national RD&D effort directed at removing barriers to sustainable, efficient water and energy use; develop technology solutions; and enhance understanding of the intimate relationship between energy and water resources.

This report is an update to a report produced in April 2006.[1] It provides background information on the relationship between water and thermoelectric power generation and describes the R&D activities currently being sponsored by DOE/NETL's EPEC Program to address current and future water-energy issues.

BACKGROUND

Water Use for Thermoelectric Power Generation

Thermoelectric generation represents the largest segment of U.S. electricity production, with coal-based power plants alone generating about half of the Nation's electric supply. According to water use survey data from the U.S. Geological Survey (USGS), thermoelectric generation accounted for 41 percent of all freshwater withdrawals in the Nation in 2005, slightly ahead of irrigation (see Figure 1).[7] Each kilowatt-hour (kWh) of thermoelectric generation requires the withdrawal of approximately 25 gallons of water, primarily used for cooling purposes.[b] 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 and 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 this data is available) is also presented in Figure 1.[8] Freshwater consumption for thermoelectric uses appears low (only three percent) when compared to other use categories (irrigation was responsible for 81 percent of water consumed). However, even at three percent consumption, more than 3 billion gallons per day (BGD) were consumed.

[b] This number is a weighted average that captures total thermoelectric water withdrawals and generation for both once-through and recirculating cooling systems.

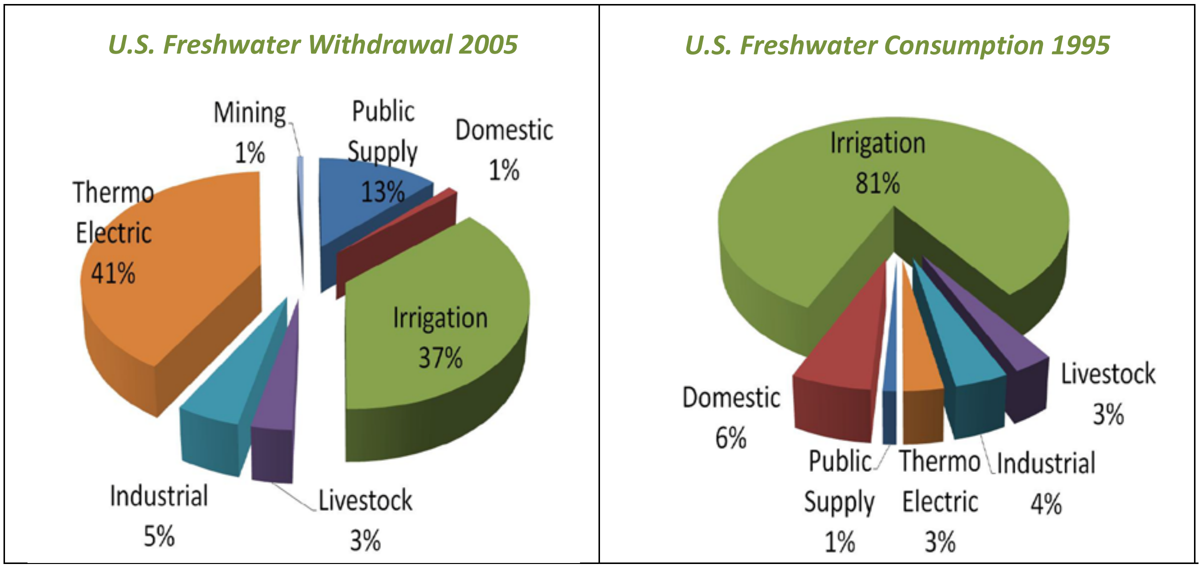


Figure 1: U.S. Freshwater Withdrawal Versus Consumption

Large quantities of cooling water are required for thermoelectric power plants to support the generation of electricity. Thermoelectric generation relies on a fuel source (fossil or nuclear) to heat water to steam that is used to drive a turbine-generator. Steam exhausted from the turbine is condensed and recycled to the steam generator or boiler. The steam condensation typically occurs in a shell-and-tube heat exchanger known as a condenser. The steam is condensed on the shell side by the flow of cooling water through tube bundles located within the condenser. Cooling water mass flow rates of greater than 25 times the steam mass flow rate are necessary depending on the allowable temperature rise of the cooling water, which is typically 15ºF to 25ºF.

There are three general types of cooling system designs used for thermoelectric power plants: once-through, wet recirculating, and dry. In once-through systems, the cooling water is withdrawn from a local body of water such as a lake, river, or ocean and the warm cooling water is subsequently discharged back to the same water body after passing through the surface condenser. As a result, plants equipped with once-through cooling water systems have relatively high water withdrawal, but low water consumption.

There are two primary technologies used to support wet recirculating cooling systems – wet cooling towers and cooling ponds. The most common type of recirculating system uses wet cooling towers to dissipate the heat from the cooling water to the atmosphere. In wet recirculating systems, warm cooling water is pumped from the steam condenser to a cooling tower. The heat from the warm water is transferred to ambient air flowing through the cooling tower. In the process, a portion of the warm water evaporates from the cooling tower and forms a water vapor plume. The cooled water is then recycled back to the condenser. Because of evaporative losses, a portion of the cooling water needs to be discharged from the system – known as blowdown − to prevent the buildup of minerals and sediment in the water that could adversely affect performance. The quantity of blowdown required for a particular cooling water system is determined by a parameter known as "cycles of concentration", which is defined as the ratio of dissolved solids in the circulating water to that in the makeup water. As the cycles of concentration increases, the quantity of blowdown and makeup water decreases. For a wet recirculating system, only makeup water needs to be withdrawn from the local water body to replace water lost through evaporation and blowdown. As a result, plants equipped with wet recirculating systems have relatively low water withdrawal, but high water consumption, compared to once-through systems. Typical wet recirculating cooling water system flow rates for a 500-MW coal-fired plant are shown in Figure 2.[9]

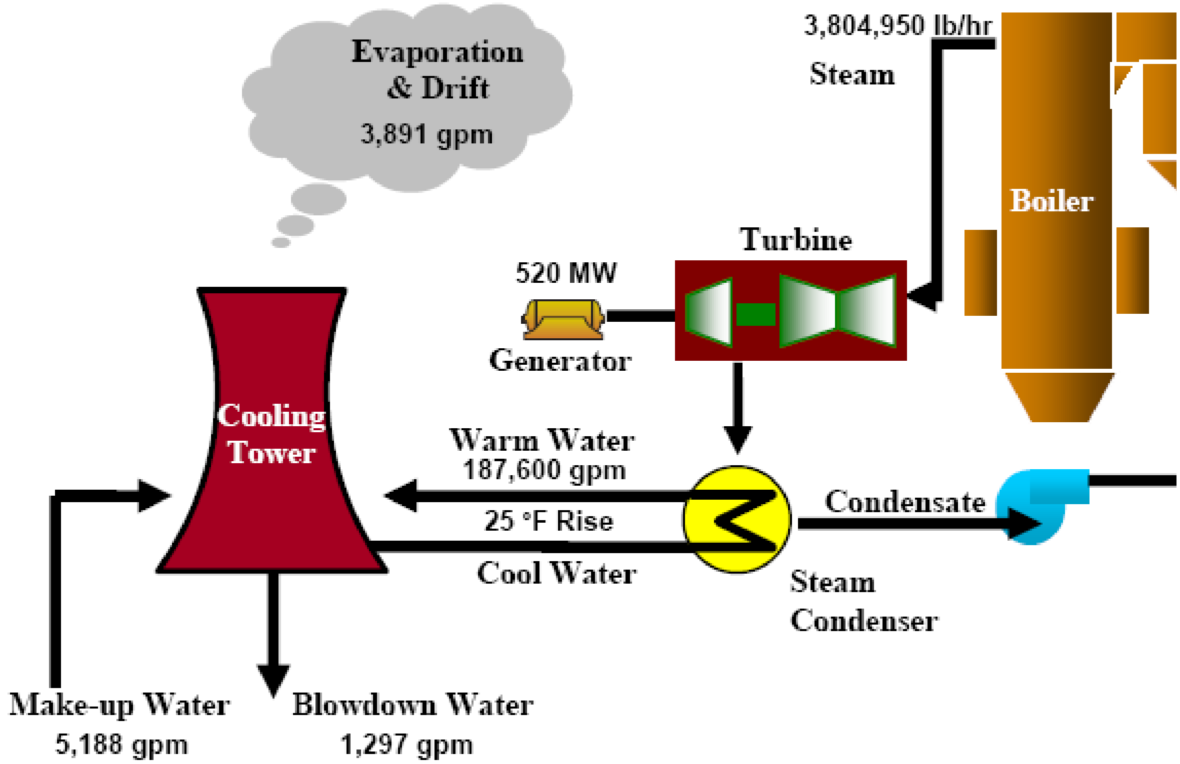


Figure 2: Process Flow Schematic for a Wet Recirculating Cooling Water System

Wet cooling towers are available in two basic designs – mechanical draft and natural draft. Mechanical draft towers utilize a fan to move ambient air through the tower, while natural draft towers rely on the difference in air density between the warm air in the tower and the cooler ambient air outside the tower to draw the air up through the tower. In both designs, the warm cooling water is discharged into the tower for direct contact with the ambient air. A cooling pond serves the same purpose as a wet cooling tower, but relies on natural conduction/convection heat transfer from the water to the atmosphere as well as evaporation to cool the recirculating water.

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. Dry recirculating cooling systems are not as prevalent as the wet recirculating cooling systems due to relatively higher capital and operating costs and lower performance. For example, the U.S. Environmental Protection Agency (EPA) estimated capital costs for a dry cooling tower to be 6.5 percent of total plant capital costs (versus two percent for a wet cooling tower).[10]

Approximately 88 percent of freshwater withdrawal by thermoelectric generators in 2000 was used at plants with once-through cooling systems. Table 1 presents an estimate of average water withdrawal and consumption for once-through and recirculating systems based on year 2000 data from the Energy Information Administration's (EIA) Form 767 report.[11] Once-through systems have high water withdrawal requirements, but since nearly all of the water is returned to the source body, consumptive losses are low on a percentage basis. Recirculating wet systems have lower water withdrawal requirements, but consumptive losses through direct evaporation can be relatively high on a percentage basis. In 2001, approximately 31 percent of thermoelectric generating units were equipped with wet cooling towers, representing approximately 38 percent of installed generating capacity.

Table 1: Average Cooling System Water Withdrawal and Consumption

Type of Cooling Water System	Average gal/kWh	
	Water Withdrawal	Water Consumption
Once-through	37.7	0.1
Recirculating wet	1.2	1.1

Impact of Water Availability on Thermoelectric Power Generation

Freshwater availability is a critical limiting factor in economic development and sustainability and directly impacts electric-power supply. A 2003 study conducted by the Congressional General Accounting Office indicated that 36 states anticipate water shortages in the next 10 years (2003 to 2013) under normal water conditions, and 46 states expect water shortages under drought conditions.[12] 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 in the United States.[13] The area that is expected to face the most serious water constraints is the arid southwestern United States.

The demand for water for thermoelectric generation will increasingly compete with demands from other sectors of the economy such as agriculture, domestic, commercial, industrial, mining, and in-stream use. EPRI projects the potential for future constraints on thermoelectric power in 2025 for Arizona, Utah, Texas, Louisiana, Georgia, Alabama, Florida, and all of the Pacific Coast states.[13] Competition over water in the western United States, including water needed for power plants, led to a 2003 Department of Interior (DOI) initiative to predict, prevent, and alleviate water-supply conflicts.[14] Other areas of the United States are also susceptible to freshwater shortages as a result of drought conditions, growing populations, and increasing demand.

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 in the box below. 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.

- **Planned Power Plant Would Take Billions of Gallons**
  - *Mankato Free Press, July 2008*
- **New power-plant drain on rivers sparks debate**
  - *San Antonio Express News, June 2009*
- **Water Shortage Works Against Kansas Coal-Fueled Power Plants**
  - *KC Tribune, May 2010*
- **Water Issues Behind Legal Challenges to Georgia Coal Plants**
  - *Environment News Service, May 2010*
- **New Weapon in Coal Plant Fight: Water**
  - *Houston Chronicle, October 2010*

Key environmental regulations that can potentially impact power plants are summarized below.

Environmental Regulations Affecting Thermoelectric Power Generation Water Use

The U.S. EPA has been charged with maintaining and improving the Nation's water resources for uses, including, but not limited to, agricultural, industrial, nutritional, ecological, and recreational. To accomplish this goal, EPA has issued several regulations under the CWA and the Safe Drinking Water Act (SDWA) that directly impact the discharge of pollutants from power plants to receiving waters, as well as the intake of water for cooling and other power plant needs. The following is a summary of regulations that affect power plant water use.

The Clean Water Act

The CWA provides for the regulation of discharges to the Nation's surface waters and calls for a Federal-state partnership in which the Federal government sets the standards for pollution discharge and states are responsible for the implementation and enforcement. Initial emphasis was placed on “point source” pollutant discharge, but 1987 amendments authorized measures to address “non-point source” discharges, including stormwater runoff from industrial facilities. Permits are issued under the National Pollutant Discharge Elimination System (NPDES), which designates the highest level of water pollution or lowest acceptable standards for water discharges. With EPA approval, the states may implement standards *more* stringent than Federal water quality standards, but they may not be *less* stringent. Certain sections of the CWA are particularly applicable to water issues related to power generation and are described below in more detail.

- *CWA §303 Water Quality Standards and Implementation Plans* – Section 303 of the CWA, the Total Maximum Daily Load (TMDL) program, requires states to develop lists of impaired waters – water bodies that do not meet water quality standards (WQS) that the states have set, even after the installation of the minimum required levels of pollution control technology. States must then establish priority rankings for waters that do not meet the WQS and develop TMDLs for these water bodies. A TMDL specifies the maximum amount of a pollutant that an impaired water body can receive and still meet WQS. While states are responsible for establishing the TMDL, the CWA requires EPA to approve or disapprove the impaired water lists and TMDLs established by the states. After establishing a TMDL, states have 10 years to develop implementation plans for improving the quality of the affected waters.
- *CWA §304 Effluent Guidelines* – Section 304 of the CWA authorizes EPA to establish effluent guidelines for point sources. EPA has recently completed a multi-year study of the Steam Electric Power Generating industry and, based on the results, has determined that revising the current effluent guidelines for the industry is warranted. EPA’s decision to revise the current effluent guidelines is largely driven by the high level of toxic-weighted pollutant discharges from coal fired power plants and the expectation that these discharges will increase significantly in the next few years as new air pollution controls are installed. Over the course of the study EPA has identified technologies that are available to significantly reduce these pollutant loads.
- *CWA §316(a) Water Thermal Discharge* – Section 316(a) requires the regulation of water thermal discharge from cooling water systems in order to protect shellfish, fish, and other aquatic wildlife.
- *CWA §316(b) Cooling Water Intake Structures* – Section 316(b) is arguably the most urgent water-related issue facing thermoelectric power generation in the near-term. This section requires that the location, design, construction, and capacity of cooling water intake structures reflect the best technology available for minimizing adverse environmental impact, such as impingement or entrainment of aquatic organisms due to the operation of cooling water intake

structures. Regulations to implement Section 316(b) are being issued in three phases that cover different facility categories. The Phase I rule was issued in December 2001 and effectively requires most new thermoelectric power generation plants to install closed-cycle cooling systems due to standards for water intake capacity and velocity. The Phase II rule, issued in July 2004, applies to existing thermoelectric power generation plants that withdraw more than 50 million gallons per day (MGD) of water and use at least 25 percent of the water withdrawn for cooling purposes only. Although the Phase II rule requires significant percentage reductions in both impingement and entrainment losses from uncontrolled levels, it also provides flexible compliance alternatives so that conversions of open-cycle to closed-cycle cooling water systems are not mandated. However, in response to a legal challenge, the Phase II rule was suspended in 2007. An updated Phase II rule is still pending. Regulations for Phase III were finalized in 2006 and apply to other industrial sources and new offshore and coastal oil and gas extraction facilities.

The Safe Drinking Water Act

The SDWA serves to protect humans from contaminants in the Nation's public drinking water supply. Amended in 1986 and 1997, the law requires many actions to protect drinking water and its sources. The SDWA requires EPA to set national drinking water standards and create a joint Federal-state system to ensure compliance. While the provisions of the SDWA apply directly to public water systems in each state, the Act is relevant to thermoelectric power generation because waste streams may contain detectable levels of elements or compounds that have established drinking water standards. Under the SDWA, regulations that would require additional limits on mercury (Hg), arsenic (As), and other trace metals could also affect how power plants dispose of coal by-products.

EXISTING PLANTS EMISSIONS AND CAPTURE PROGRAM

The interface of energy and water, or the water-energy 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.[15] 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 water-energy interactions is the key to determining how to make the most efficient use 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.

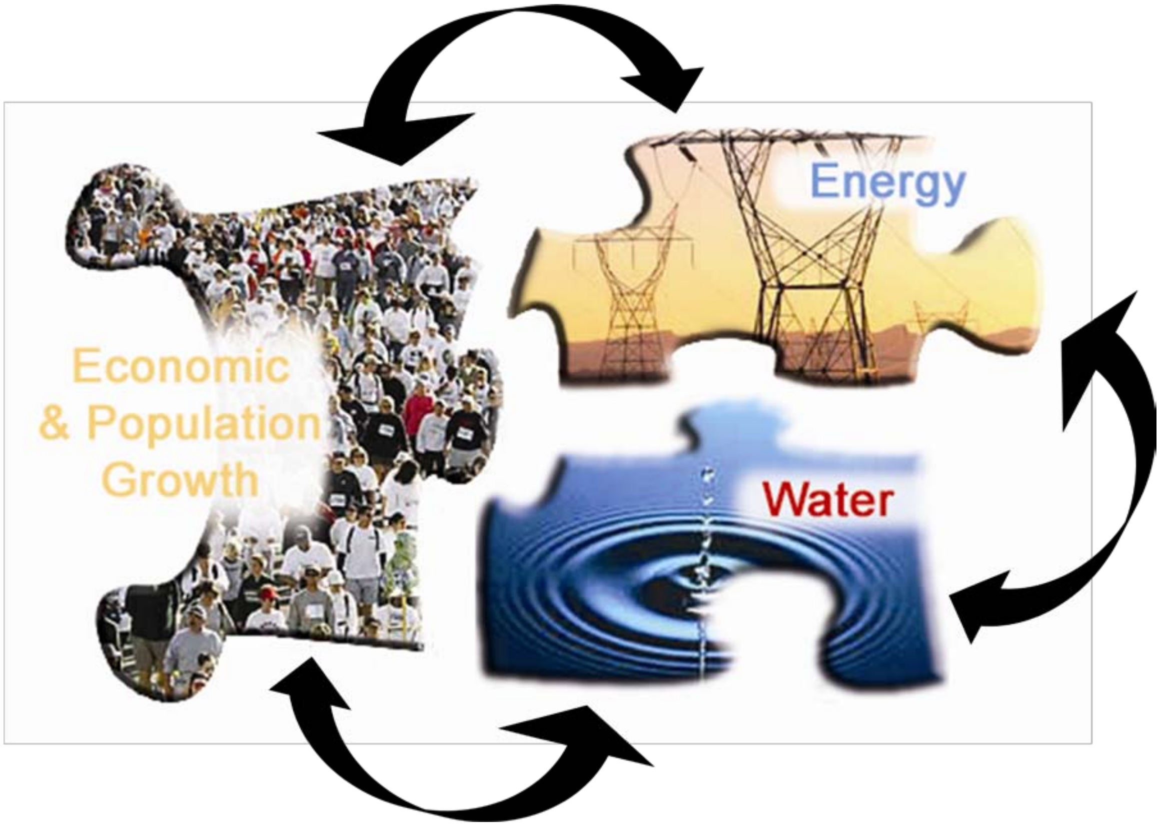


Figure 3: The Water-Energy Nexus

A summary comparison of water and energy issues (see Table 2) 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 water-energy nexus.

Table 2: 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 water use curbs.	Long-term societal and economic sustainability may require curbs on energy usage.

Under its Existing Plants Program, the National Energy Technology Laboratory (NETL) is pursuing an integrated water-energy 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 water-energy R&D program. The vision and mission of the NETL Water-Energy R&D Program is summarized in Figure 4, along with its relationship to the more broad vision and mission of the U.S. Department of Energy (DOE) as a whole and the Fossil Energy (FE) Program.

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

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

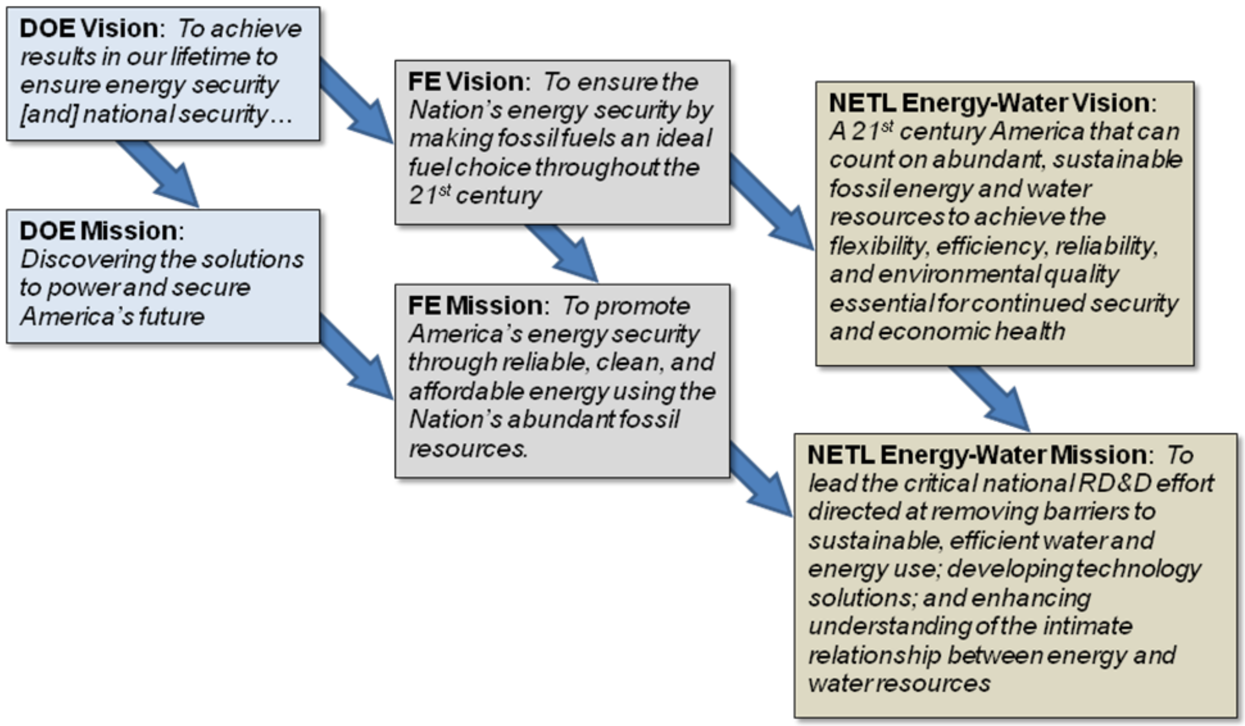


Figure 4: DOE/FE/NETL Vision and Mission Cascade

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.

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 Water-Energy 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 water-energy relationship.

At its heart, the Existing Plants Water-Energy R&D 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 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.

The NETL Water-Energy 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 (ANL), Sandia National Laboratory (SNL), Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), and the University of North Dakota's Energy and Environment Research Center (UND EERC) to study the impacts of power technologies upon water systems.

In 2002, in an effort to further national water-energy 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 water-energy cooperative research development and design (RD&D) initiative. This three-lab effort evolved into a multi-laboratory Water-Energy Nexus Team consisting of 12 national laboratories and EPRI. As an adjunct to the Water-Energy 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.

In addition to its efforts with the Water-Energy 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. Several key elements guide program 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 Water-Energy 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.

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 Water-Energy Program works closely with power producers, the 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 following is a brief summary of R&D projects in the three research focus areas.

Non-Traditional Sources of Process and Cooling Water

Research and analyses are being conducted to evaluate and develop cost-effective approaches to using non-traditional sources of water to supplement or replace freshwater for cooling and other power plant needs. Water quality requirements for cooling systems can be less stringent 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. Projects in this focus area are summarized in Table 3 and described in greater detail below.

Table 3: 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 1,800-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

Project Title	Project Goals/Objectives	Approach/Results	Research Partners
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 make-up 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
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

Strategies for Cooling Electric Generating Facilities Utilizing Mine Water: Technical and Economic Feasibility – West Virginia WRI

West Virginia University's Water Research Institute conducted a study to evaluate the technical and economic feasibility of using water from abandoned underground coal mines in the northern West Virginia and southwestern Pennsylvania region to supply cooling water to power plants.[16] The amount of mine water available, the quality of the water, and the types of water treatment needed are all factors analyzed during this study. Non-traditional water sources, such as coal mine discharges, not only have the potential to reduce freshwater power plant cooling requirements, but they also can improve the efficiency of the cooling process due to the lower water temperatures associated with deep-mine discharges.

The study included identification of available mine water reserves in the region with sufficient capacity to support power plant cooling water requirements under two scenarios. The first scenario was to provide the make-up water requirements for a 600-MW plant equipped with a closed-loop recirculating cooling water system. The second scenario was to provide the entire cooling water requirement for a 600-MW plant equipped with a closed-loop recirculating cooling water system utilizing a flooded underground mine as a heat sink. If feasible, the second scenario would eliminate the need for a wet cooling tower to dissipate the heat to the atmosphere.

The study identified eight potential sites under the first scenario where underground mine water is available in sufficient quantity to support the 4,400 gallons per minute (gpm) make-up water requirements for a closed-loop, 600-MW plant. Three of these sites were further evaluated for preliminary design and cost analysis of mine pool water collection, treatment, and delivery to a power plant. One site was selected for each of three mine pool water chemistry categories based on “net alkalinity,” as measured in milligrams per liter (mg/L) equivalent concentration of calcium carbonate ($CaCO_3$) − net acidic (<-50 mg/L), neutral (-50 to +50 mg/L), and net alkaline (>+50 mg/L). The net alkalinity of the mine pool water determines the water treatment requirements. The mine pool water treatment process includes pre- and post-aeration, neutralization with hydrated-lime, and clarification. A water treatment option using hydrogen peroxide for neutralization was also evaluated. The cost analysis concluded that, depending on site conditions and water treatment requirements, utilization of mine pool water as a source of cooling water make-up can be cost-competitive with freshwater make-up systems. Table 4 provides a summary of the capital and operating cost estimates for mine pool water collection and treatment systems at the three sites.

Table 4: Cost Estimate for Mine Pool Water Collection and Treatment System

Cost	Flaggy Meadows (net-acidic)	Irwin (near-neutral)	Uniontown (net-alkaline)
Total Capital Cost, $	5,740,000	3,770,000	3,464,000
Operating Cost, $/yr	1,367,000	363,000	433,000
Annualized Cost, $/1000 gallons	0.79	0.26	0.29

Based on fluid and heat flow modeling of the second scenario, it was determined that interconnection of two adjoining mines would be necessary to provide sufficient heat transfer residence time to adequately cool the recirculating water flow. As a result, the study identified only one potential site for a closed-loop recirculating cooling water system utilizing a flooded underground mine as a heat sink. Furthermore, that site would be limited to the cooling water requirements of a 217-MW unit. This project was completed in January 2005.

Use of Produced Water in Recirculated Cooling Systems at Power Generation Facilities – Electric Power Research Institute

EPRI evaluated the feasibility of using produced waters, a by-product of natural gas and oil extraction, to meet up to 10 percent of the approximately 20 MGD of make-up cooling water demand for the mechanical draft cooling towers at Public Service of New Mexico’s 1,800-MW San Juan Generating Station (SJGS) located near Farmington, New Mexico.[17]

Two major issues associated with this use of produced water are: (1) the collection and transportation of the produced water to the plant and (2) the treatment of the produced water to lower the total dissolved solids (TDS) concentration.

Providing cost-effective collection and transportation of produced water from the wellhead or disposal facility to the power plant is a significant issue. There are more than 18,000 oil and gas wells in the San Juan Basin in New Mexico, where SJGS is located, that generate more than 2 MGD of produced water. Most of the produced water in the region is collected in tanks at the wellhead and transported by truck to local saltwater disposal facilities. The SJGS evaluated an approach for transportation of produced water to the plant site (Figure 5). An 11-mile pipeline would be built to gather and convey production near the wells. Additionally, existing unused gas and oil pipelines would be converted to transport produced water from the newly built pipelines to the power plant.

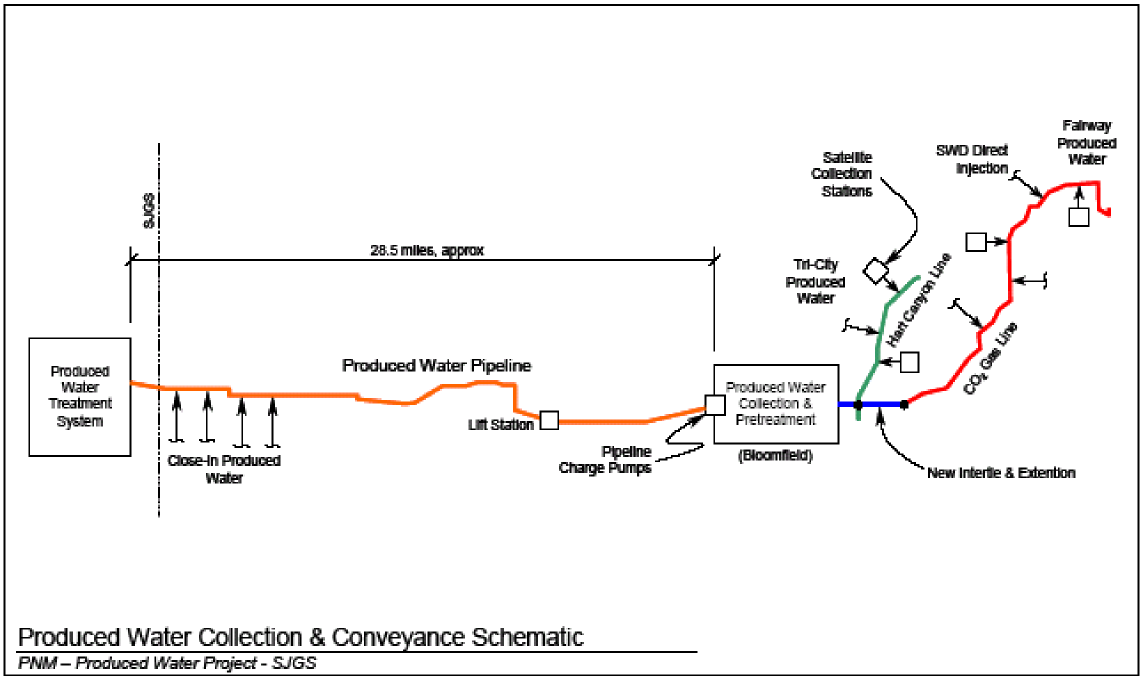


Figure 5: Pipeline System for Transportation of Produced Water to San Juan Generating Station

Cooling water currently used at the SJGS is withdrawn from the San Juan River and contains only 360 mg/L of TDS. Water quality is an issue when using produced water to supplement plant cooling water requirements due to high TDS concentrations. Produced water from CBM and natural gas extraction has a TDS concentration ranging from 5,440 to 60,000 mg/L. For comparison, seawater contains 26,000 mg/L. Produced water must be treated prior to use at the plant in order to reduce TDS to an acceptable level. High-efficiency reverse osmosis (RO) with a brine concentrator distillation unit was found to be the most economical treatment method. This project was completed in 2006.

Development and Demonstration of a Modeling Framework for Assessing the Efficacy of Using Mine Water for Thermoelectric Power Generation – West Virginia University's National Mine Land Reclamation Center

The purpose of this study is to develop and demonstrate a framework for assessing the costs, technical and regulatory aspects, and environmental benefits of using mine water for thermoelectric power generation. The framework provides a systematic process for evaluating the hydrologic, chemical, engineering, and environmental factors to be considered and evaluated in using mine water as an alternative to traditional freshwater supply.[18] A 300-MW power plant (Beech Hollow Power Plant) has been proposed to burn coal refuse from the Champion coal refuse pile – the largest coal waste pile in Western Pennsylvania (Figure 6). The plans called for use of public water at the rate of 2,000 to 3,000 gpm. Numerous surface and underground mines exist within six miles of the proposed power plant. Under this project, the mine discharges in the vicinity of the proposed plant have been located, sampled, and their flow determined under wet and dry weather conditions. This data has been integrated with power plant water requirements and environmental considerations to design a mine water collection, treatment, and delivery system to meet the power plant water needs under all weather conditions.

Figure 6: Beech Hollow Power Plant Site

About half of this water need may be available from a single watershed that includes several creeks that are fed by mine discharges. Use of this water by the power plant would have a major impact on the restoration of the downgradient stream. Additional mine water is available from streams that are severely impacted by AMD. Diversion of water to the power plant in these watersheds will reduce, but not eliminate, the acid load of the receiving streams. This illustrates a potentially important benefit associated with using mine drainage water in a power plant setting. If these impaired waters are diverted for beneficial use, treated, and then returned to surface or ground water, the negative impacts that could occur if the drainage waters flowed directly into surface waters can be avoided.

The wide distribution and generally small size of the mine discharges in the vicinity of the power plant will adversely affect the economics of complete mine water use at this site. However, this distribution presented a robust basis for developing the computer-based design aid that is one of the project deliverables. The design aid consists of an interactive Microsoft Excel spreadsheet with Visual Basic macros. Work on the design aid focused on the design of the water piping system needed to transport the water from the mine discharge to the water treatment plant or power plant. Data analysis included the length of pipe, static and dynamic head, pipe diameter, pipe cost, pump horsepower requirements, operations and maintenance (O&M) cost, and water temperature changes resulting from buried pipe flow. Field and laboratory research has been completed on this project, and a final project report will be completed in 2010.

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 – Nalco Company

The overall objective of this project, conducted by Nalco Company in partnership with ANL, was to develop advanced scale-control technologies to enable coal-based power plants to use impaired water in recirculating cooling systems.[19] The use of impaired water is currently challenged technically and economically due to additional physical and chemical treatment requirements to address scaling, corrosion, and biofouling. Nalco's research focused on methods to economically manage scaling issues (see Figure 7). The overall approach was to use synergistic combinations of physical and chemical technologies with separations to reduce the scaling potential and scale inhibitors extending the safe operating range of the system, to maximize water utilization efficiency and minimize waste discharge.

Figure 7: Example of Pipe Scaling

Research was conducted in three parts with laboratory R&D and small, pilot-scale field demonstration. Initially, researchers worked to establish quantitative technical targets, developed scale inhibitor chemistries for high stress conditions, and determined the feasibility of the membrane separation technologies to minimize scaling. Subsequently, researchers developed additional novel scale inhibitor chemistries, developed selected separation processes, and optimized the compatibility of technology components at the laboratory scale. Finally, integrated technologies were tested using selected pilot-scale model sites to validate the performance.

The technology developed will make the use of impaired waters by coal-fired power plants more feasible. Benefits of the new technologies include reducing the volume of make-up water required for recirculating cooling systems, reducing the volume of water generated from cooling tower blowdown, and lowering the cost of impaired water use to a point that is as cost efficient as using freshwater. This project will be completed in August 2010.

Reuse of Treated Internal or External Wastewaters in the Cooling Systems of Coal-Based Thermoelectric Power Plants – University of Pittsburgh

The overall objective of this study, conducted by the University of Pittsburgh and Carnegie Mellon University (CMU), was to assess the potential of three types of impaired waters for cooling water make-up in coal-based thermoelectric plants.[20] The impaired waters studied include: secondary treated municipal wastewater; passively treated coal mine drainage; and ash pond effluent (Figure 8). Researchers used a combination of pilot- and laboratory-scale studies, engineering and regulatory assessments, and mathematical modeling efforts.

Figure 8: Examples of Impaired Waters

To determine the feasibility of impaired water use, a variety of activities were conducted, including: assessment of the availability and proximity of impaired waters at 12 power plant locations spanning the major geographic regions of the continental 48 states; assessment of regulations and permitting issues relevant to use of impaired waters for cooling operations; determination of general water quality for each of the three types of impaired waters being studied and specific water quality of impaired waters at the selected sites; construction and testing of model cooling towers; field testing of key operational parameters for the cooling system operated with the three different impaired waters; development of a mathematical model for water quality characteristics in cooling systems operated with different impaired waters; and assessment of the treatment needs for the cooling tower discharge streams. Another important project objective was the development and demonstration of small pilot-scale cooling towers for side-by-side evaluation of the use of impaired waters under different operating conditions. The pilot-scale cooling towers are pictured in Figure 9.

Chemical treatment agents were added to the incoming waters of the pilot-scale cooling towers to evaluate their impacts on cooling tower performance. These included scaling inhibitors polymaleic acid (PMA) and 2-phosphonobutane-1,2,4-tricarboxylic acid (PBTC), corrosion inhibitors tolyltriazole (TTA) and pyrophosphate (TKPP), and chlorine compounds (free chlorine and monochloramine) to combat biofouling.

Overall, mild steel, copper, and copper-nickel showed acceptable corrosion rates in the pilot-scale towers with or without corrosion inhibitor addition. The corrosion inhibitors TTA and TKPP did not appear to reduce corrosion rates or increase inhibition effectiveness, and scaling seemed to be primarily responsible for protection of the metal alloys. Higher monochloramine levels to prevent biofouling caused higher corrosion rates initially, but their influence was minimized after the scale layer grew thicker and protected the metal alloys.

Another significant outcome of the project was quantification of the availability of municipal wastewaters for power plant applications. There are several reasons why reclaimed water represents a potentially valuable alternative source of cooling water. Municipal wastewater is available in communities throughout the country, and treatment facilities are designed to handle specific design flows. Thus, the quantity of water leaving the treatment plants is well defined and can be factored into the design and operation of power plant cooling systems. Data analysis has revealed that 81 percent of power plants proposed for construction by the EIA would have sufficient cooling water supply from one to two publicly owned treatment works (POTWs) 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. Thus, municipal wastewater will be the impaired water source most likely to be locally available in sufficient and reliable quantities for power plants. This project was completed in 2009.

Figure 9: Pilot Scale Cooling Towers in Operation at the Franklin Township Municipal Sanitary Authority

Use of Treated Municipal Wastewater as Power Plant Cooling System Makeup Water: Tertiary Treatment versus Expanded Chemical Regimen for Recirculating Water Quality Management – Carnegie Mellon University

This project builds upon a previous CMU/University of Pittsburgh study described above. The project further examines the feasibility of using treated municipal wastewater (see Figure 10) as cooling system make-up water by conducting experimental studies and economic and social analyses.[21] The experimental studies use novel bench-scale recirculating cooling water systems, as well as novel small-scale pilot cooling towers to evaluate the effects of different levels of additional treatment of secondary treated municipal wastewater on the potential for corrosion, scaling, and biofouling in the cooling system. In addition, the chemical treatments needed to control corrosion, scaling, and biofouling for the municipal wastewater treated to different levels are being investigated.

Figure 10: Municipal Wastewater Treatment Facility – Potential Non-Traditional Water Source

The data obtained from the experimental program is being supplemented with information gained from power plants where municipal wastewater is already used as make-up water for cooling. This information is being used as the basis for life cycle cost analyses of tertiary treatment of municipal wastewater prior to use in power plant cooling systems versus the use of less-treated wastewater plus aggressive in-plant chemical measures for controlling cooling water corrosion, scaling, and biofouling.

Knowledge gained about the nature and degree of chemical treatment required for management of cooling water chemistry is being used to estimate capital and operating costs for each make-up water quality studied in the experimental testing. The total capital and operating cost of managing cooling water chemistry for several tertiary treatment scenarios is being estimated, as well as the costs of the associated chemical treatment for cooling water chemistry management if the tertiary treatment were not employed. Findings are being examined to assess the lowest cost treatment scenario among those studied, and also the most important tradeoffs in terms of additional chemical management avoided for tertiary treatment. This project will be completed in 2012.

Study of the Use of Saline Formations for Combined Thermoelectric Power Plant Water Needs and Carbon Sequestration at a Regional-Scale – Sandia National Laboratory

SNL conducted a study to assess the synergistic use of underground saline formations as both a storage site for captured carbon dioxide (CO_2) – carbon sequestration – and as a source of produced water to support the operation of thermoelectric power plants (Figure 11).[22] The saline water provides an opportunity for beneficial use as an alternative to freshwater make-up for the power plant cooling water and FGD systems. However, the produced water is likely to contain chemical contaminants that require treatment before it can be utilized.

According to the study, the composition of the waters extracted from saline formations will change in later years as compressed CO_2 dissolves in the water and reacts chemically with the mineral formations. Carbon dioxide in water produces carbonic acid, a weak acid. When acid exceeds the buffering capacity of the waters, the pH will decrease. The pH of the water in contact with the CO_2 is expected to initially drop from near 8.0 to a range of 3.5 to 5.0, depending on the surrounding minerals. More minerals will dissolve in the acidic environment, but slow processes will eventually precipitate carbonate minerals again.

The goal would be to only extract water that had not been in contact with the injected CO_2, so changes in acidity are not of concern. However, the disposal of saline formation waters could still present permitting challenges for sequestration operations with regard to discharge limits on TDS. Sequestration activities in saline formations will likely be restricted to formations with TDS greater than 10,000 mg/L to protect potential drinking water sources. This project will be completed in 2010.

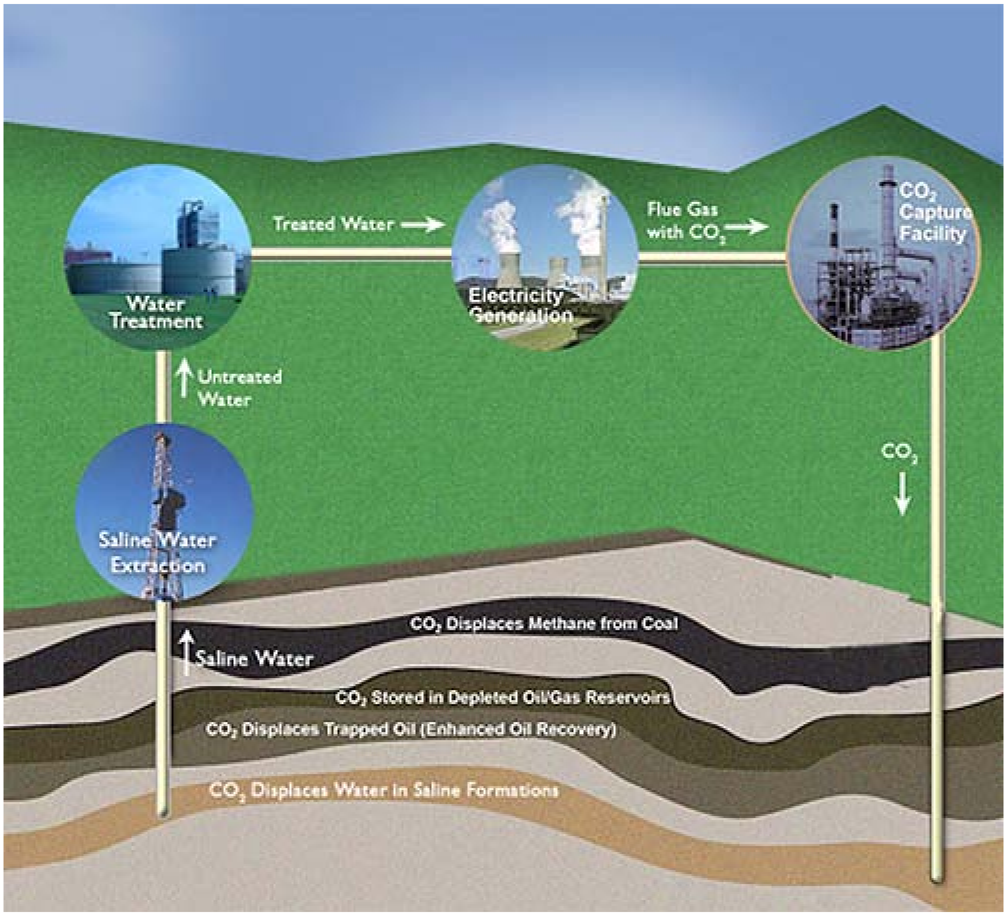


Figure 11: Carbon Sequestration in Saline Formations Could Produce Water That Could be Used in Power Plant Applications Following Treatment

Thermoelectric Power Plant Water Demands Using Alternative Water Supplies: Power Demand Options in Regions of Water Stress and Future Carbon Management – Sandia National Laboratory

SNL conducted a regional modeling assessment of non-traditional water sources for use in thermoelectric power plants.[23] The assessment includes the development of a model to characterize water quantity and quality from several sources of non-traditional water, initially focused within the southeastern United States. The project includes four primary tasks: (1) identify water sources, needs, and treatment options; (2) assess and model non-traditional water quantity and quality; (3) identify and characterize water treatment options including an assessment of cost; and (4) develop a framework of metrics, processes, and modeling aspects that can be applied to other regions of the United States.

Based upon study results from the southeastern United States, work has been done to describe additional produced waters within saline formations in other water-stressed areas of the country. The deep saline formations initially investigated in the Southeast had TDS far greater than the 20,000 mg/L selection criteria initially assumed for feasible treatment. With the criteria stating that the formations are to be located at least 2,500 feet below the surface and the TDS be between 10,000 and 20,000 mg/L, only one of the four sites initially investigated in the Southeast was suitable. The Black Warrior Basin Coal Test Site is located in northern Alabama, but potential sites have also been investigated in Florida, Georgia, and Texas. As part of this study, a tool has been developed to guide other investigations of suitable carbon sequestration sites for produced waters that could be treated for power plant use. This study will be completed August 2010.

Nanofiltration Treatment Options for Thermoelectric Power Plant Water Treatment Demands – Sandia National Laboratory

SNL is conducting a study on the use of nanofiltration (NF) treatment options to enable use of non-traditional water sources as an alternative to freshwater make-up for thermoelectric power plants.[24]

The project includes a technical and economic evaluation of NF for two types of water that contain moderate to high levels of TDS: (1) cooling tower recirculating water and (2) produced waters from oil and gas extraction operations. RO is the most mature and commonly considered option for high TDS water treatment. However, RO is generally considered to be too expensive to make treatment of produced waters for power plant use a feasible application. Therefore, SNL is investigating the use of NF, which could be a more cost-effective treatment option than RO. Similar to RO, NF is a membrane-based process. Although NF is not as effective as RO for the removal of TDS (typical salt rejection is approximately 85 percent, compared to >95 percent for RO), its performance should be sufficient for typical power plant applications. In addition to its lower capital cost, an NF system should have lower operating costs because it requires less pressure to achieve an equivalent flux of product water.

The NF investigation aims to operate on waters with modest TDS (less than 5,000 mg/L) with high recovery (roughly 90 percent) and will estimate the associated costs of operation. NF techniques are more tolerant of fouling than RO and have a high reject rate for divalent cations. The pilot study will be conducted using Dow Filmtec membranes at a ConocoPhillips coalbed methane (CBM) production site in the San Juan Basin of northwest New Mexico.

The NF study is conducting a pilot test at the ConocoPhillips CBM production site followed by pilot testing at an existing cooling tower system located at SNL. Sandia will test and gather operational data for the NF technology at the ConocoPhillips site to compare against the model calculations (reducing TDS from 14,500 to 2,050 mg/L at a feed pressure of 256 pounds per square inch [psi]). Instead of investigating treatment of produced waters, the upcoming pilot work at SNL will focus on nanofiltration as a method to reduce the concentration of dissolved solids in the recirculating stream for the cooling tower. This project will be completed in August 2010.

Internet-Based, GIS Catalog of Non-traditional Sources of Cooling Water for Use at Coal-Fired Power Plants – Arthur Langhus Layne

To reduce high-quality freshwater withdrawal and consumption for power production, project researchers are creating an internet-based, Geographic Information System (GIS) catalog of non-traditional sources of cooling water for coal-fired power plants (see Figure 12).[25] Data is being developed to allow the economically beneficial use of oil and gas produced water, abandoned coal-mine water, industrial waste water, and low-quality groundwater. By pairing non-traditional water sources to power-plant water needs, the research will allow power plants that are affected by water shortages to continue to operate at full capacity without adversely affecting local communities or the environment.

Figure 12: ALL is Developing a GIS Application That Integrates the Locations of Power Plants and Non-Traditional Water Sources

The catalog will identify the location and the water withdrawal and consumption demands for existing and planned coal-fired power plants in the lower 48 states (planned power plants will include those for which a permit application has been submitted), as well as identify the location, volume, and quality of the various alternate water sources near those plants across the Nation. The catalog will be converted to a GIS-based system and will be available over the internet. By clicking a location on a map, a power plant operator will be able to see (either through a pop-up grid or other visual means) the various potential water sources available, the quality of water, the volumes available, and the distance to those waters. Alternate water sources within 15 miles of a given location will be included in the inventory. This will ensure that operators are aware of their options and allow them to quickly assess the costs of accessing these waters to supplement or replace their current supply on a short- or long-term basis. This project will be completed in 2011.

Reuse of Produced Water from CO_2 Enhanced Oil Recovery, Coal-Bed Methane, and Mine Pool Water by Coal-Based Power Plants – University of Illinois/Illinois Geological Survey

In this project, investigators are evaluating the feasibility of reusing three types of non-traditional water sources for cooling or process water for coal-based power plants in the Illinois Basin: (1) produced water from CO_2-enhanced oil recovery (EOR), (2) CBM recovery, and (3) active and abandoned underground coal mines.[26] Tasks include evaluating quantity and quality of the produced water, investigating suitable treatment technologies, and conducting a detailed economic and benefits analysis. The research will provide critical information for the use of these non-traditional water sources for power plant make-up water, which would allow for increased use of non-traditional waters in the Illinois Basin and throughout the United States.

In the majority of oil and gas reservoirs, only 20 to 40 percent of the total amount of the original oil in place can be recovered by standard extraction methods. EOR involves the injection of water and CO_2 into depleted oil fields to extract up to 10 percent of the remaining oil. EOR using CO_2 that has been captured from coal-fired power plants is being viewed as an economically attractive option for maintaining and expanding Illinois' power production capacity in an environmentally acceptable manner. A recent study indicates that 23 to 37 major reservoirs (depending on the assumed oil price and CO_2 cost scenarios) are economically favorable for CO_2-EOR in the Illinois Basin. However, approximately 10 barrels of water are produced for each barrel of crude oil recovered via EOR; this water is treated and re-used for further EOR, but it is eventually released to the environment. Power plant use of the water produced by CO_2-EOR may be an environmentally sustainable alternative for "closing the CO_2-water loop," but the technical and economic viability of this scenario has not been fully explored (see Figure 13).

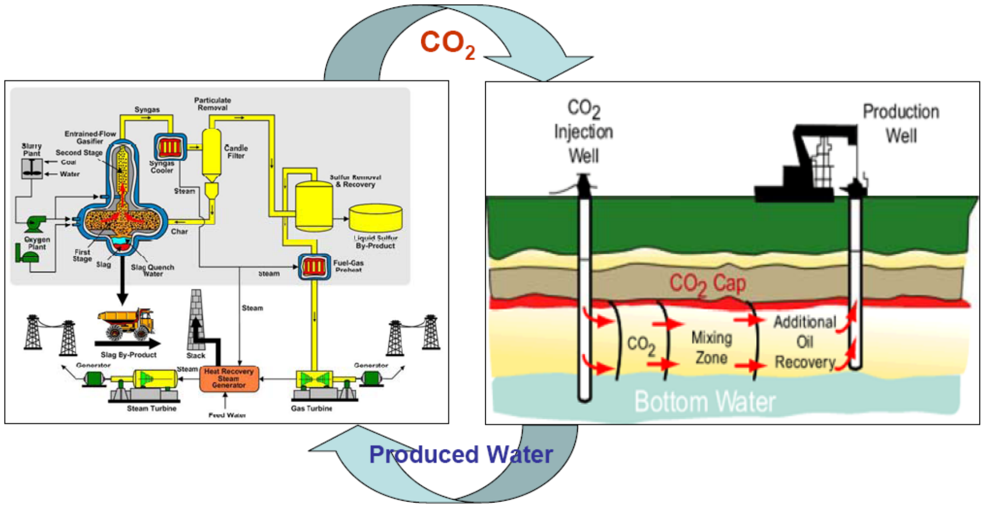


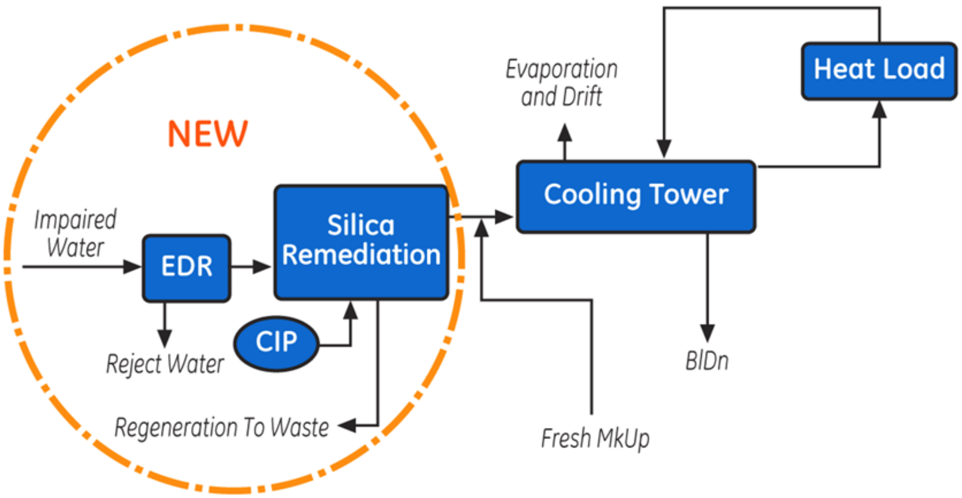
Figure 13: Conceptual illustration of "Closing the CO_2-water loop." Carbon dioxide is produced in the generation of electricity. This CO_2 is then injected into depleted oil and gas reservoirs to enhance oil recovery. Water produced in the process is treated and then returned to the power plant for cooling and other purposes.[27]

CBM operations have been found to produce water volumes ranging from 0.03 (San Juan, New Mexico) to 2.75 (Powder River, Montana) bbl per thousand cubic feet of recovered methane. Currently, CBM is produced from approximately150 boreholes into coal seams in Illinois, but no data are available on water production from CBM in the Illinois Basin. Similarly, potential water storage in the void spaces of abandoned underground coal mines in Illinois is more than 1 trillion gallons, and a mine in White County produces approxomiately 450,000 gallons per day. Although several Eastern power plants already use mine water for cooling purposes, and several studies on power plant use of mine water in the Appalachian region have been performed, no comparable assessment has been made thus far for the Illinois Basin.

It is likely that the coal-based power generation industry will face restrictions for water use because of the limited availability of water resources and the increasing demand for water in the domestic, agricultural, and industrial sectors. Utilization of the non-traditional water sources to be studied in this project represents an innovative solution to supplement/replace freshwater needs of the coal-based power plants. This project will be completed in 2010.

Technology to Facilitate the Use of Impaired Waters in Cooling Towers – GE Global Research

Researchers at GE Global Research are developing a new silica removal technology that can be used in combination with other separation technologies to make non-traditional waters available for use in evaporative cooling towers in thermoelectric power plants.[28] Research includes material selection and synthesis; material recycle and bench-top demonstration; and design engineering, scale-up, and pilot demonstration. Results are expected to allow for the economical use of many impaired waters that are too expensive to treat with current technology. The objective is to develop a new ligand-functionalized core material (LFCM) for the removal of silica from impaired water and couple this technology to electrodialysis reversal (EDR) to allow for the 50 percent reduction of freshwater withdrawal at less than $3.90 kgal of water (Figure 14). Electrodialysis (ED) is a membrane desalination process that uses direct current power to remove salts and other ionized species from water. EDR is a mechanical enhancement of the ED process where the polarity of the applied DC power is periodically reversed. This project will be completed in 2011.



No Change Other Than Use of Impaired Water

State	Fresh MkUp	BlDn	Impaired	EDR BlDn	Regen BlDn	Evaporation	% Savings of Fresh Water
Current	11,194	2,239	0	0	0	8,955	0
New	*5,547*	*2,239*	*6,101*	*-554*	*-?*	*8,955*	*50*

Recirculation Rate = 430,000 gpm Current Cycles = 5

Figure 14: Schematic of the Electrodialysis Reversal Process for use with Impaired Waters

Innovative Water Reuse and Recovery

Projects associated with the Innovative Water Reuse and Recovery focus area are described briefly in Table 5. More detailed descriptions are presented below.

Table 5: 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 Phase II	Combination of laboratory-, pilot-scale, and slipstream 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

PROJECT TITLE	PROJECT GOALS/OBJECTIVES	APPROACH/RESULTS	RESEARCH PARTNERS
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

Use of Coal Drying to Reduce Water Consumed in Pulverized Coal Power Plants – Lehigh University

Lehigh University conducted laboratory-scale testing to evaluate the performance and economic feasibility of using low-grade power plant waste heat to partially dry low-rank coals prior to combustion in the boiler.[29] While bituminous coals have minimal moisture content (less than 10 percent), low-rank coals contain significant amounts of water – subbituminous and lignite coals range from 15 to 30 percent and 25 to 40 percent, respectively. In Lehigh's project, the process heat from condenser return cooling water was extracted upstream of the cooling tower to warm ambient air that was then used to dry the coal. Lowering the temperature of the return cooling water reduced evaporative loss in the tower, thus reducing overall water consumption.

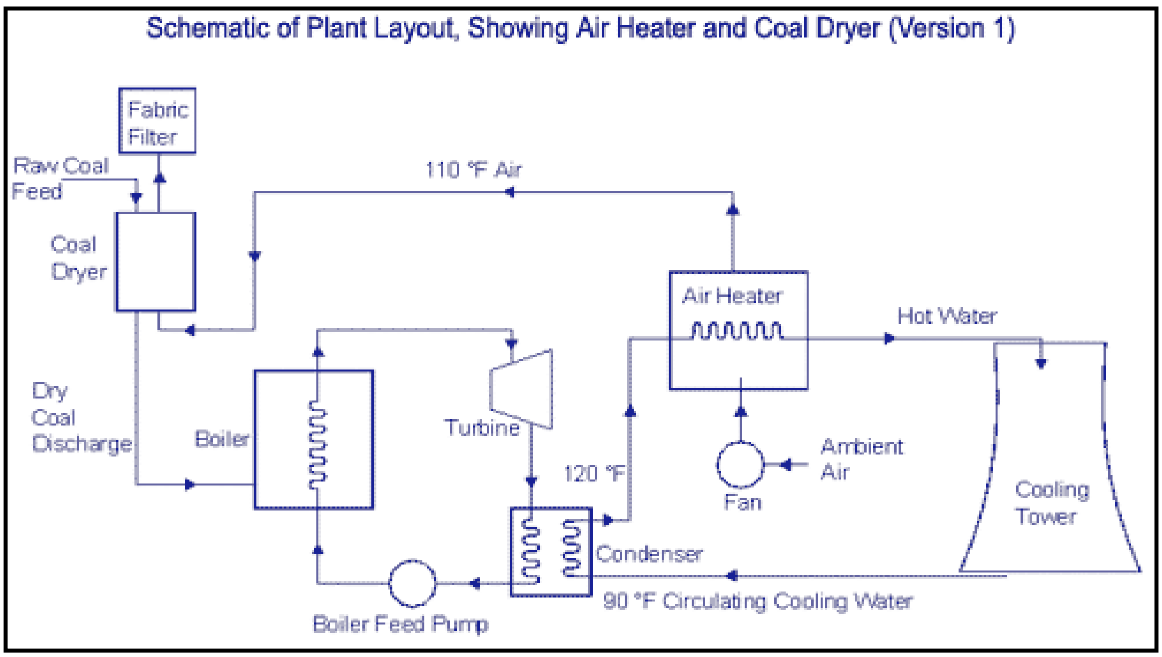


Figure 15: Schematic of Lehigh Coal Drying Process

In addition, drying the coal prior to combustion can improve the plant heat rate, and in return reduce overall air emissions. Figure 15 shows a schematic of the plant layout with the air heater and coal dryer. Variations of this approach, such as using heat from combustion flue gas to supplement the condenser return cooling water to dry the coal, were also being evaluated. Information from this project was used to design a full-scale coal drying system at Great River Energy's 546-MW lignite-fired Coal Creek Power Station located near Underwood, North Dakota, as described below. Lehigh's project was completed in 2006.

Lignite Fuel Enhancement – Great River Energy

The objective of this project, which was funded as part of the Clean Coal Power Initiative (CCPI) program, was to demonstrate a 25 percent reduction in lignite moisture content (e.g., from 40 percent moisture to 30 percent moisture in this application) using plant waste heat; and to optimize and assess plant operation on dried coal to quantify benefits.[30] This technology uses heat that would otherwise be lost out the stack to upgrade low-rank coal feedstock, thereby enhancing plant efficiency and performance. The high moisture content in low-rank coals significantly increases plant heat rates and reduces efficiency by requiring application of heat generated during combustion to vaporize large amounts of water in coal. This heat of vaporization represents a heat loss because it does not contribute to power generation. Moreover, high moisture content coals can contribute to corrosion of ductwork and place an energy penalty on fans that move the vaporized water and pulverizers that process the moisture in the coal. Great River Energy's (GRE) upgrading process improves plant economics, reduces plant heat loss (decreases heat rate), and increases efficiency, thereby reducing water use and emissions of CO_2, Hg, nitrogen oxides (NO_X), sulfur dioxide (SO_2), and particulate matter (PM) per unit of energy produced. This technology has potential application to more than 100 gigawatts of domestic coal-fired capacity that currently uses low-rank coals. Figure 16 provides a schematic diagram of the process.

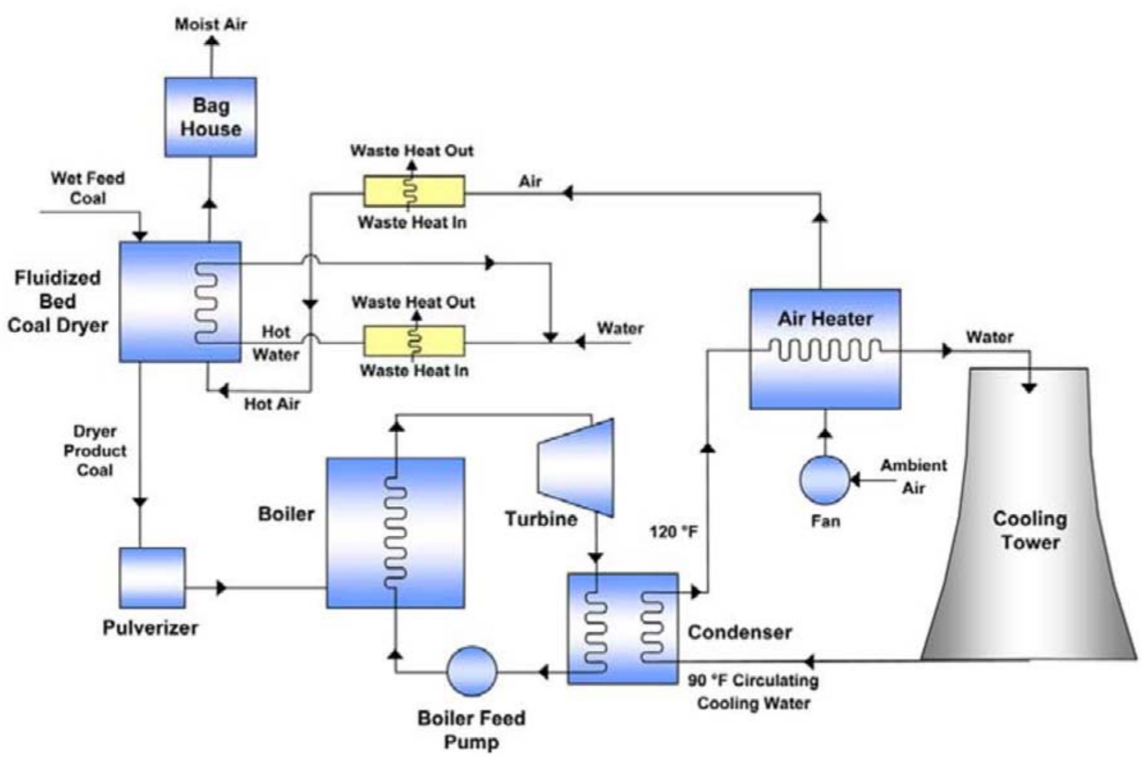


Figure 16: Schematic Diagram of GRE Lignite Fuel Enhancement Process

Following installation and startup, around-the-clock operations of the prototype dryer and data collection were initiated. The moisture of the processed lignite coal was reduced from approximately 38.5 percent to 29.5 percent. The prototype dryer test results indicated emissions reductions for Hg, SO_X, NO_X, and CO_2. Also, reducing moisture in coal increases Hg oxidation and facilitates additional capture in the FGD unit. Following the successful operation of the prototype unit, GRE initiated design activities for full-scale dryers (135 tons/hr) with improved reliability and flexibility with regard to management of the higher density fraction from the first stage, heat input, pressure drop, moisture reduction, and coal throughput. GRE is installing four dryers on Unit 2 as part of the project, and because of the success of the prototype, GRE is installing four more dryers on Unit 1 with its own funds. Thus, the entire Coal Creek Station is being retrofitted with lignite coal dryers. This project is nearing completion in early 2010.

An Innovative Fresh Water Production Process for Fossil Fired Power Plants Using Energy Stored in Main Condenser Cooling Water – University of Florida

The University of Florida investigated an innovative diffusion-driven desalination process to allow power plants that use saline water for cooling to become net producers of freshwater.[31] Hot water from the condenser provides the thermal energy to drive the desalination process. Saline water cools and condenses the low-pressure steam and the warmed water then passes through a diffusion tower to produce humidified air. The humidified air then goes to a direct contact condenser where freshwater is condensed out. This process is more advantageous than conventional desalination technology in that it may be driven by low-temperature waste heat. Cool air, a by-product of this process, can also be used to cool nearby buildings.

A diffusion-driven desalination facility was designed that could produce 1.03 MGD of freshwater from the waste heat of a 100-MW plant. The only energy cost to use this process is the energy used to power the pumps and fans. An economic simulation of the system was performed and showed that production cost is competitive with RO and flash-evaporation technologies. This project was completed in 2006.

Water Extraction from Coal-Fired Power Plant Flue Gas – University of North Dakota Energy & Environmental Research Center (UNDEERC)

The primary purpose of this project was to develop a technology to extract water vapor from coal-fired power plant flue gases in order to reduce makeup water requirements for cooling water systems.[32] Flue gas contains large amounts of water vapor produced from the coal combustion process. Coal contains in-situ water and the combustion of the hydrogen within the coal matrix releases additional water. The amount of water potentially available for recovery from the flue gas is sufficient to substantially reduce the need for freshwater makeup.

This project had two objectives. The first objective was to develop a cost-effective liquid desiccant-based dehumidification technology to recover a large fraction of the water present in the plant flue gas. The second objective was to perform an engineering evaluation to determine how such a technology could be integrated to recover water, improve efficiency, and reduce stack emissions of acid gases and carbon dioxide.

The liquid desiccant-based dehumidification system utilizes low-grade heating and cooling sources available at the power plant. The flue gas is cooled and then subjected to a liquid desiccant absorption process that removes water from the flue gas. By stripping off the absorbed water, the weak desiccant solution is regenerated back to the strong desiccant solution. The water vapor that is produced during the regeneration process is condensed and made available for plant makeup water (see Figure 17).

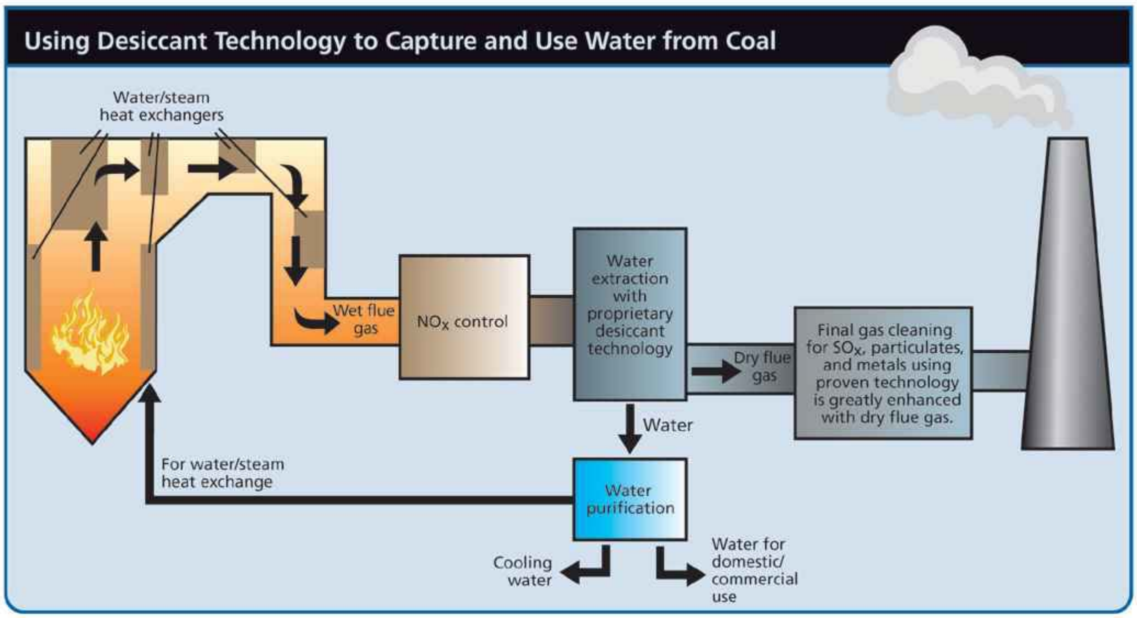


Figure 17: Schematic Diagram of EERC Desiccant Flue Gas Water Capture Technology

The desiccant selection and characterization evaluation was conducted by ranking the merits of potential desiccants based on physical and chemical data along with laboratory testing. One of the desiccants was selected for initial pilot-scale testing. Data from the pilot-scale testing showed that the performance of the system was better than predicted by chemical process models. Based on pH and chemistry, extracted water quality was good and off-gas of undesirable species, such as SO_2 and NOx, from the solution was minimal. Prospects for commercial development of the process are encouraging. This project was finalized in 2006.

Recovery of Water from Boiler Flue Gas – Lehigh University

Conducted by Lehigh University, this project involved a combination of laboratory- and pilot-scale experiments and computer simulations that investigated the use of condensing heat exchangers to recover water from boiler flue gas at coal-fired power plants.[33] Boiler flue gas moisture comes from three sources: fuel moisture, water vapor formed from the oxidation of fuel hydrogen, and water vapor carried into the boiler with the combustion air. The quantity of water vapor in flue gas varies depending on coal rank. Powder River

Basin (PRB) and lignite coal-fired power plants, equipped with a means of extracting all flue gas moisture and using it for cooling tower make-up, would be able to supply from 25 percent (for PRB) to 37 percent (for lignite) of the make-up water using this approach.

Researchers conducted computational fluid mechanics analyses to aid in the design of the three-stage compact fin tube heat exchanger to condense sulfuric acid and water vapor from flue gas (Figure 18). The high-temperature section reduces the flue gas temperature from inlet values in excess of 300°F to an exit temperature of 200°F that condenses the sulfuric acid. The intermediate heat exchanger stage, with inlet and exit flue gas temperatures of approximately 200°F and 110°F, is used to remove additional sensible heat from the flue gas and serve as a buffer stage between the high-temperature and low-temperature sections. In the low-temperature section, temperatures are lowered to below 90°F, and water condensate is extracted. The extent to which removal of acid vapors from flue gas and condensation of water vapor can be achieved in separate stages of the heat exchanger system was determined via laboratory and pilot plant experiments. Additional experiments were conducted to measure the heat transfer effectiveness of the fin-tube bundle designed for condensing water vapor. Analyses of the boiler and turbine cycle were carried out to estimate potential reductions in heat rate due to recovering sensible and latent heat from the flue gas. This project was completed in December 2008.

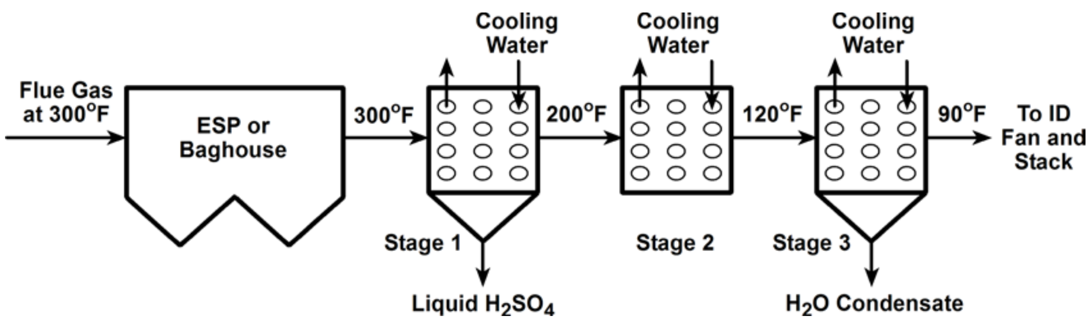


Figure 18: Schematic Diagram of the Three-Stage Compact Fin-Tube Heat Exchanger Designed to Condense Flue Gas Water

The Use of Restored Wetlands to Enhance Power Plant Cooling and Mitigate the Demand on Surface Water Use – Applied Ecological Services, Inc.

For this project, Applied Ecological Services (AES) is developing an understanding of the opportunity to restore wetlands for water cooling and make-up in existing low lying agricultural lands that were historic wetlands (see Figure 19).[34] These former wetlands have been drained by ditching and tilling to support agricultural uses. Restoring these fields to wetlands can reduce water usage, reduce the carbon emissions from the existing deteriorating soil carbon levels under the drained agricultural-uses of the land, and also reduce the energy penalty and resulting greenhouse gas (GHG) emissions associated with active water cooling strategies that employ cooling towers and other mechanical systems.

Figure 19: Restored Wetland

The activities for this project include:

- Produce an assessment of water cooling needs with a catalogue of various strategies that are operational where ponds, lakes, or wetlands are currently being used for cooling water and mitigating anthropogenic fossil fuel CO_2 emissions and other GHGs associated with reuse and cooling of heated waters from power plant operations.
- Develop a literature review on the use of restored wetlands for water cooling and heat management needs by various industries, including power producers.
- Complete a conceptual design, technical evaluation, and modeling of specific cooling strategies that employ wetlands.
- Construct a pilot-scale (five-acre) restored wetland at a host utility.
- Evaluate a range of issues, such as environmental efficacy, regulations, and public policies related to widespread adoption of wetland cooling practices.
- Create action plans to promote and guide region-wide implementation of conservation and wetland-based water cooling strategies with the incremental benefit of GHG mitigation practices.

Project accomplishments to date include completion of the base collection and inventory of relevant existing data and literature, substantial progress in compiling data, analyzing data, and defining variables, functions, and interactions relevant to the analysis of wetlands as components of power plant cooling systems and incorporating these variables and functions into a computational model, and laying groundwork for establishing the pilot project during the next phase of the project. This project is scheduled for completion in September 2012.

Transport Membrane Condenser for Water and Energy Recovery from Power Plant Flue Gas – Gas Technology Institute

Investigators at the Gas Technology Institute (GTI) are developing a membrane separation technology to recover water vapor from coal-fired power plant flue gas based on modifications to their patented Transport Membrane Condenser (TMC) technique originally developed for industrial gas-fired boilers.[35] In the new process, a small portion of the recovered water vapor can be directly added to the boiler feed water loop to replace fresh make-up water and at the same time improve power plant energy efficiency. The major portion of recovered water can be available for other plant use such as cooling tower water make-up or FGD. GTI estimates that up to 90 percent of the water vapor in the flue gas can be cost-effectively recovered, especially from flue gas of high-moisture content coals. It is particularly advantageous when applied to power plants that use FGD because of the increased moisture level in the flue gas. The TMC approach can also be used to recover water from the exhaust stream from drying high-moisture coals. There are three phases for the project. The objective for Phase I is to evaluate the membrane and develop the two-stage TMC design concept; the objective for Phase II is to design, build, and test the pilot-scale TMC at GTI's laboratory; and the objective for Phase III is to test the pilot-scale TMC on a power plant slipstream and develop a scaleup design and commercialization plan.

Figure 20 shows a conceptual layout for a TMC water recovery process for a typical power plant. GTI proposes a two-stage TMC process to maximize its function for recovering both water and heat; therefore, two separate cooling water streams would be used. On the water side, the first stage TMC inlet water is obtained from steam condensate from the condenser. Its outlet water with recovered water vapor and associated latent heat from flue gas goes to the deaerator for boiler water make-up. The second stage TMC inlet water is from part of the condenser cooling water stream. This outlet water goes back to the cooling water stream with extra recovered water from the flue gas. On the flue gas side, the TMC is situated between the FGD unit and the stack. This project will be completed in March 2011.

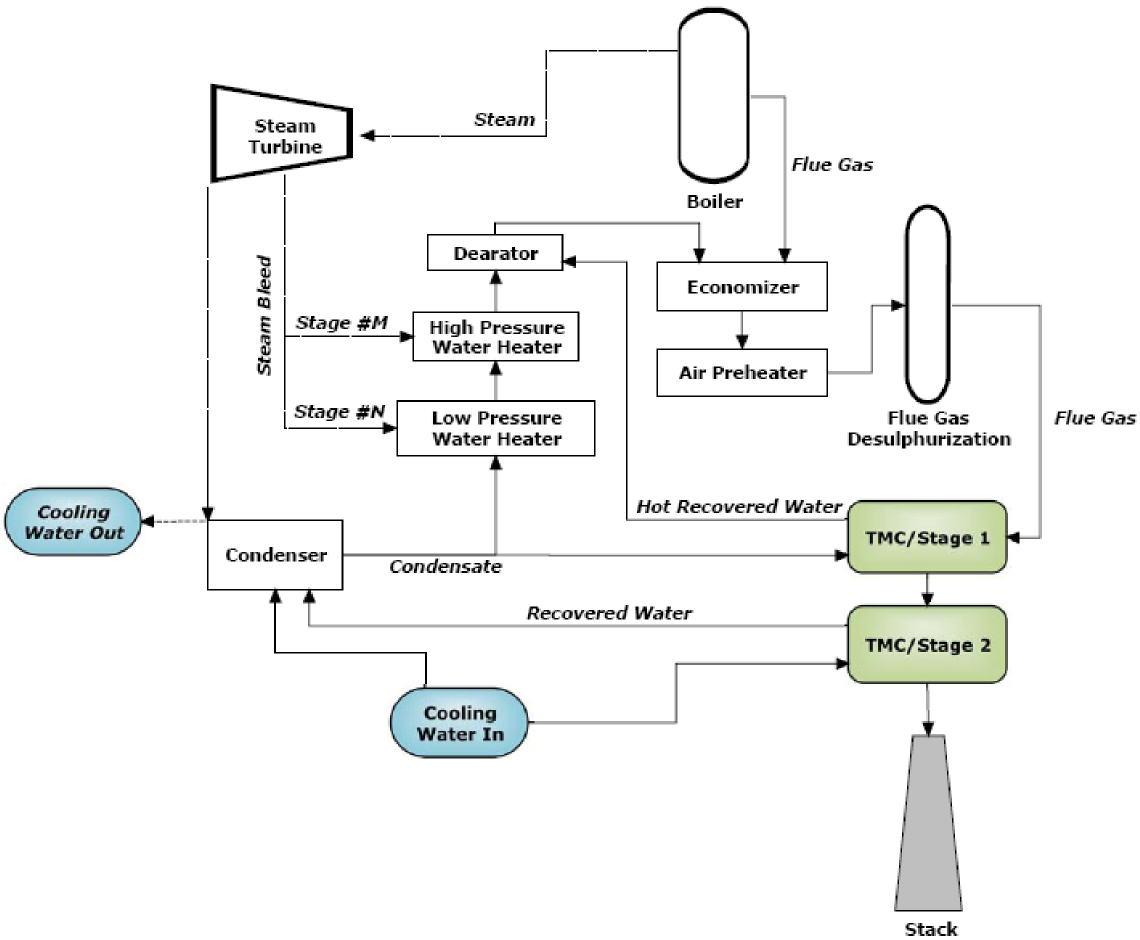


Figure 20: Power Plant Flue Gas Recovery with a Two-Stage TMC

Recovery of Water from Boiler Flue Gas Using Condensing Heat Exchangers – Lehigh University

Lehigh University researchers are developing condensing heat exchanger technology for coal-fired power plants for the recovery of water from flue gas (see Figure 21).[36] The project is a combination of pilot-scale tests, laboratory experiments, and heat exchanger design analyses and cost estimates. Pilot-scale tests are being performed using a slipstream of flue gas from a natural gas-fired boiler with sulfur trioxide (SO_3) injection. These tests are being performed to determine the extent to which the addition of more surface area at the high temperature end of the condensing heat exchanger will make it possible to restrict sulfuric acid condensation to a narrow region well upstream of the region over which water vapor condensation occurs. Pilot-scale tests are also being performed using slipstreams of flue gas from two coal-fired boilers. These tests will determine the effects of coal composition, inlet cooling water temperature, flue gas and cooling water flow rates and the amount of surface area in the high temperature end of the condensing heat exchanger on several different parameters. Characteristics expected to be impacted in the pilot tests include the kinetics of sulfuric acid condensation, rates of flue gas water recovery and Hg capture, and composition of the condensate collected from the low temperature heat exchangers. Laboratory experiments are being performed to measure rates of acid corrosion of candidate tube materials for condensate acid concentrations and temperatures obtained in the field studies. Finally, condensed flue gas water treatment needs are being determined, condensing heat exchanger designs are being developed, and their costs are being estimated for full-scale applications located both immediately downstream of an electrostatic precipitator (ESP) or baghouse, and downstream of a wet SO_2 scrubber.

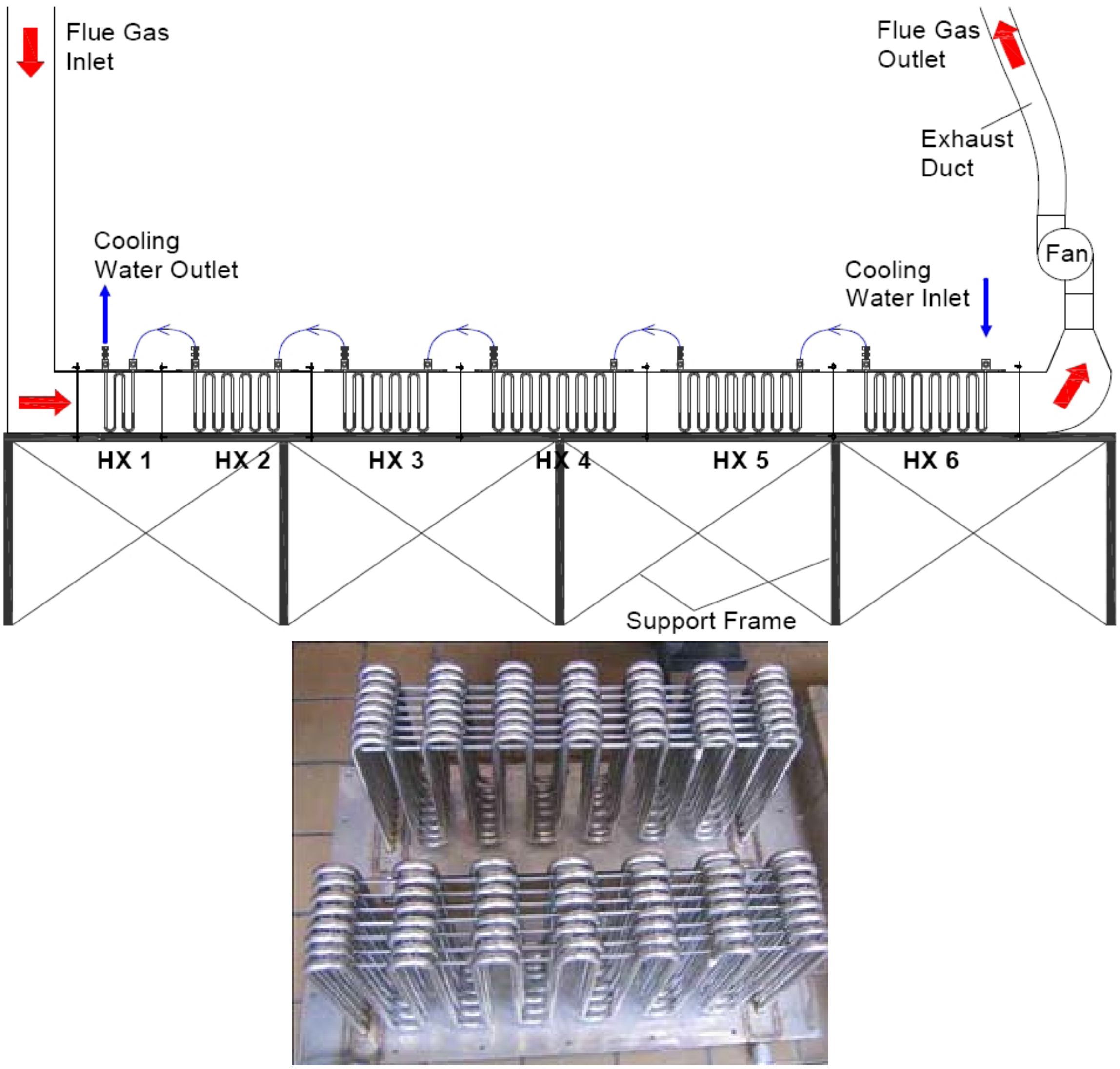


Figure 21: Diagram of Condensing Hear Exchanger Apparatus and Pilot-Scale Exchanger Tubing

Slipstream tests of the flue gas condensing heat exchanger system were performed at Southern Company's Plant Yates in June 2009. Plant Yates Unit 1 fires a bituminous coal and has a wet FGD. The tests were run over a range of flue gas and cooling water flow rates to simulate the effects of changes in unit load on acid and water vapor condensation kinetics. The average total water condensation rate ranged from 21.7 to 37.38 lb/hr, increasing with increased cooling water flow rate. The flue gas water vapor capture efficiency data exhibits some scatter, with mean values ranging from 23.1 to 34.2

percent. Without the use of acid traps, the sulfuric acid concentrations varied from one heat exchanger to the next, with a peak concentration of 1,400 mg/L and a minimum concentration of 33 mg/L. The presence of an acid trap resulted in reduced sulfuric acid flux on heat exchangers positioned just downstream of the trap, with reductions in flux averaging 33 and 42 percent for the two cases tested. This project will be completed in March 2011.

Advanced Cooling Technology

This component of the program is focused on research to 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. Projects in this focus area are briefly described in Table 6 and in greater detail below.

Table 6: 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

Project Title	Project Goals/Objectives	Approach/Results	Research Partners
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

Development of an Impaired Water Cooling System – Electric Power Research Institute

In conjunction with the produced water feasibility study conducted at the SJGS, EPRI also conducted pilot-scale testing of a hybrid cooling technology. The wet surface air cooler (WSAC) is a closed-loop cooling system coupled with open-loop evaporative cooling.[37] Warm water from the steam condenser flows through tubes that are externally drenched with spray water. Heat is removed through the evaporative effect of the spray water. The tubes are always covered in water, hence the name "wet surface." The WSAC is capable of operating in a saturated mineral regime because of its spray cooling configuration. A high spray rate is used to ensure that the tubes are constantly flooded and helps the spray nozzles from becoming plugged. Co-current flow of air and spray water eliminates dry spots on the underside of the tubes where fouling often occurs. The tubes have no fins and are spaced far enough apart that solids or precipitates from the poor quality water are washed into the basin.

At SJGS this system was used as auxiliary cooling for condenser cooling water. The spray water was blowdown water from the existing cooling towers. Testing was performed to determine to what extent the WSAC could concentrate untreated cooling tower blowdown before thermal performance was compromised. It was also used as a pre-concentrating device for the cooling tower blowdown that is typically evaporated in a brine concentrator or evaporation pond at this zero discharge facility. The pilot test unit was skid mounted and consisted of three separate tube bundles. Each bundle was constructed of a different metal to evaluate the corrosion potential of the degraded water. The pilot unit was instrumented to monitor thermal performance, conductivity of the spray water, and corrosion. This project was completed in 2006.

Environmentally-Safe Control of Zebra Mussel Fouling – New York State Education Department

The objective of this project was to investigate mechanisms for controlling zebra mussel populations in an environmentally-benign way. Zebra mussels are small, fingernail-sized bivalves that can live in rivers and lakes in enormous densities. Native to Europe, these mussels were first discovered in Lake St. Clair, near Detroit, in 1988 and have since spread as far south as Louisiana and as far west as Oklahoma. They can attach to almost any hard surface with their adhesive basal threads. Figure 22 shows zebra mussels inside a pipe. The colonization of zebra mussels on cooling water intake structures can lead to significant plant outages. There is a need for economical and environmentally safe methods for zebra mussel control where this invasive species has become problematic. Researchers with the New York State Education Department conducted a three-year study to evaluate a particular strain of a naturally occurring bacterium, *Pseudomonas fluorescens,* that was shown to be selectively lethal to zebra mussels but benign to non-target organisms.[38] Testing was conducted on the house service water treatment system for Rochester Gas and Electric Corporation's Russell Station that withdraws 4 to 5 MGD from Lake Ontario.

The research suggests that this method for zebra mussel control will pose less of an environmental risk than the current use of biocides like chlorine. However, if this method is to be widely adopted, it must be cost competitive. Laboratory experiments were conducted to define key nutrients required to produce more toxin per bacterial cell. This project was finalized in 2007.

Figure 22: Zebra Mussels Inside a Pipe

Enhanced Performance Carbon Foam Heat Exchanger for Power Plant Cooling – Ceramic Composites, Inc.

Ceramic Composites, Inc. partnered with SPX Corporation to develop high thermal conductivity foam to be used in an air-cooled steam condenser for power plants in place of traditional aluminum fins (see Figure 23).[39] Foam fins could significantly decrease energy consumption while enhancing water conservation within the power industry. Researchers evaluated a variety of fin width to channel width ratios. Additionally, researchers evaluated and tested wavy, chevron, straight, and Harmon fin designs, comparing air velocity, the overall heat transfer coefficient, and performance ratios.

Research into optimizing the manufacturing process for the foam fins was also conducted, including optimization of structural enhancement, optimization of bonding, optimization of machining, and economic evaluation. This project was completed in 2007.

Figure 23: Carbon Foam Heat Exchanger Fins

Use of Air2Air™ Technology to Recover Fresh-Water from the Normal Evaporative Cooling Loss at Coal-Based Thermoelectric Power Plants – SPX Cooling Systems, Inc.

SPX Cooling Systems evaluated the performance of its patented Air2Air™ condensing technology in cooling tower applications at a coal-fired electric power plant.[40] Researchers quantified Air2Air™ water conservation capabilities and determined the pressure drop and energy use during operation, examined freezing condition operation and plume abatement, and developed a wet/dry air mixing system for plume abatement and dissipation. Additionally, SPX Cooling Systems developed a collection method for the recovered water, analyzed water quality, and identified potential onsite processes capable of utilizing the recovered water. The water savings potential of Air2Air™ condensing technology is expected to average approximately 20 percent.

The technology was tested at SJGS in New Mexico (see Figure 24). The project was completed in September 2009. Analysis of the results shows significant promise for the technology, and a follow-on project was initiated, as described below.

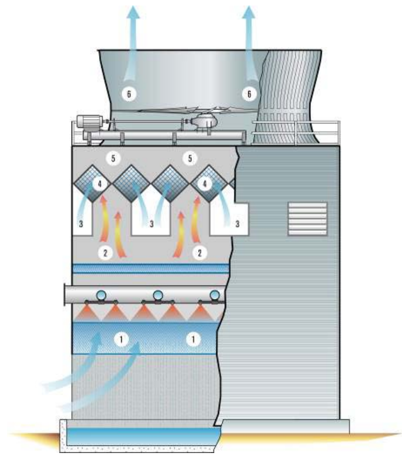


Figure 24: Illustration of Air2Air cooling technology. The tower on the far left includes Air2Air Technology. Note the steam from the other towers is effectively eliminated in the Air2Air tower.

Improvement to Air2Air® Technology to Reduce Freshwater Evaporative Cooling Loss – SPX Cooling Technologies, Inc.

Air2Air® technology has the potential to reduce freshwater withdrawal and consumption by recovering 15 to 25 percent of water from cooling tower evaporation. In this project, SPX Cooling Technologies is further developing Air2Air® condensing technology, enabling it to become a cost-effective and viable water savings technology.[41] Researchers are focusing on solving issues of economy as they relate to superstructure volume, pack cost, and costly ducting details (see Figure 25). A more efficient heat transfer pack with water-tight wet path seals is also being developed.

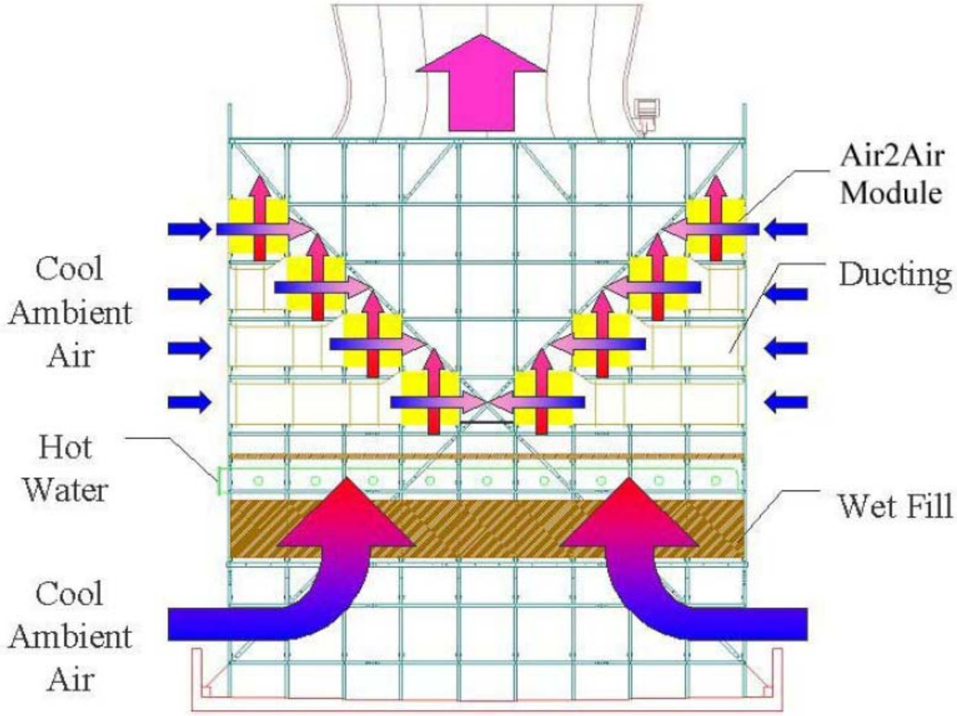


Figure 25: Diagram of Air2Air™ Water Conservation Cooling Tower

The Air2Air® technology involves contacting warm, wet air from the cooling tower with relatively drier and cooler ambient air. This is done in an air-to-air heat exchanger made up of plastic sheets with two discreet air pathways. As the warm, moist air from the tower is cooled, water condenses out and is collected. This water is high quality and can be used either as an offset to cooling water or in another application where high quality water is needed, thus offsetting water treatment costs. The Air2Air® also acts as plume abatement for the cooling tower. This project will be completed in December 2010.

Application of Pulsed Electrical Fields for Advanced Cooling in Coal-Fired Power Plants – Drexel University

Drexel University is developing a scale prevention technology based on a novel filtration method and an integrated system of physical water treatment in an effort to reduce the amount of water needed for cooling tower blowdown.[42] The filter is a self-cleaning metal membrane. Pulsed electric fields dislodge particles on the filter (see Figure 26).

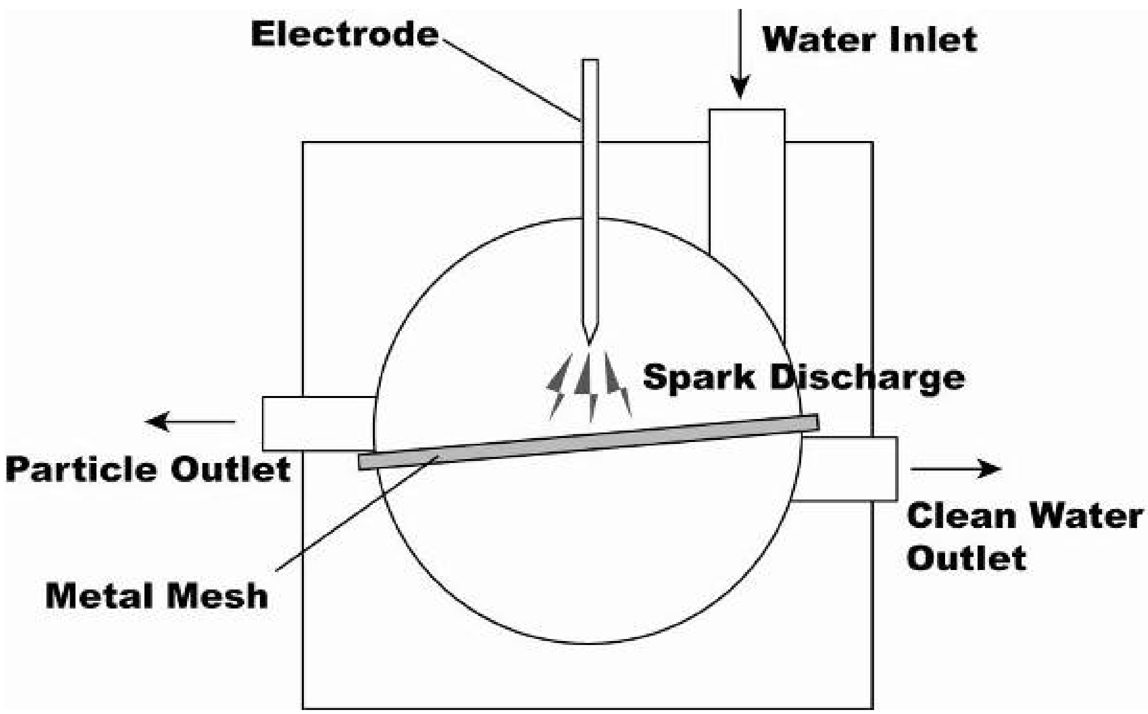


Figure 26: Schematic Diagram of a Self-Cleaning Filter Using Spark Discharges in Water

The researchers developed a filtration system and an integrated physical water treatment method. The filtration method utilizes electrical pulses to rapidly polarize water molecules on the filter membrane such that the water molecules are pulled to the membrane, pushing out the attached particles, which are then removed by reject flow. Development of the system was followed with validation testing.

Benefits from this research include the ability to operate at a higher cycle of concentration, which will reduce cooling tower blowdown water requirements (which also reduces the amount of freshwater make-up needed). This project was completed in 2009, and a follow-on project is ongoing.

Application of Pulse Spark Discharges for Scale Prevention and Continuous Filtration Methods – Drexel University

In this project, Drexel researchers are developing a new scale-prevention technology by continuously precipitating and removing dissolved mineral ions in cooling water.[43] Removal of the dissolved mineral ions would allow power plants to increase the number of times that the water could be recycled (known as cycles of concentration [COC]) before it would be discharged, which would effectively reduce the amount of make-up water needed for the plant. It is anticipated that the technology could double the COC thereby reducing the plant's blowdown by approximately 25 percent.

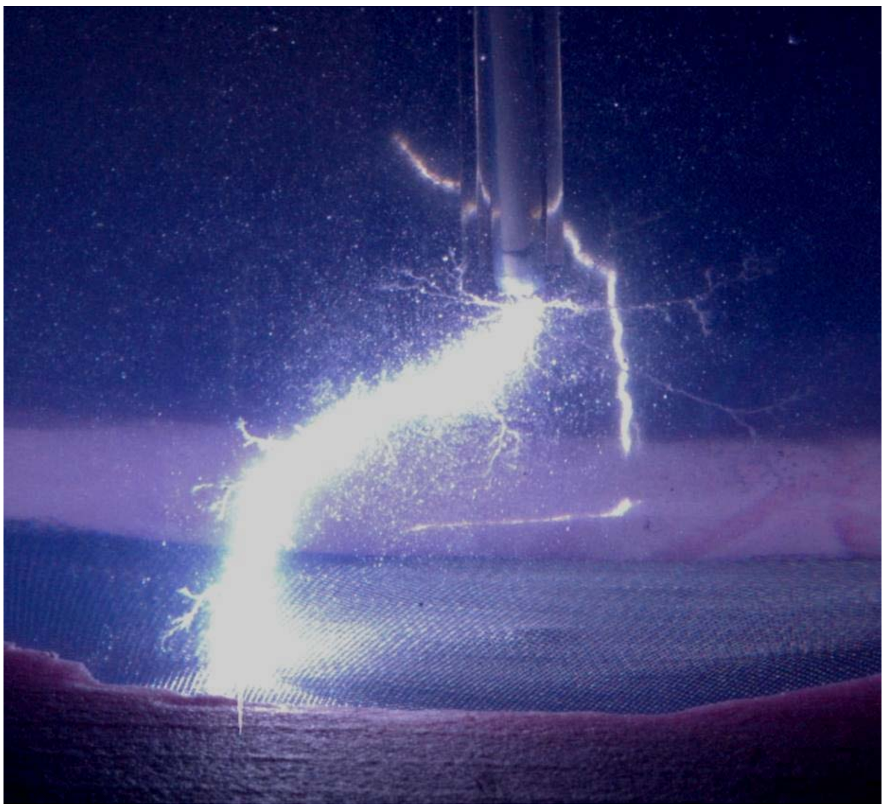


Figure 27: Pulse Stark Discharge in Water

The innovative water treatment technology utilizes spark discharges in water for scale prevention (see Figure 27). The key issue is how to precipitate and remove dissolved calcium ions in recirculating cooling water so that $CaCO_3$ scaling can be avoided and COC can be increased. The project utilizes spark discharges in water to precipitate dissolved mineral ions in circulating cooling water in a simulated laboratory cooling tower and continuously remove precipitated mineral salts using a self-cleaning filter.

A parametric study of the calcium ion precipitation process in the power supply side was completed, including experimental tests of calcium precipitation in hard water. In addition, a new plasma discharge system for the treatment of a large volume of water was developed and successfully tested. The completion date for this project is September 2011.

A Novel Concept for Reducing Water Usage and Increasing Efficiency in Power Generation – University of Pittsburgh

The objective of the project was to apply a unique ice thermal storage (ITS) technology to cooling the intake air to gas turbines used for power generation (see Figure 28).[44] The work included theoretical analysis, computer simulation, engineering design, and cost evaluation of this novel ITS technology.

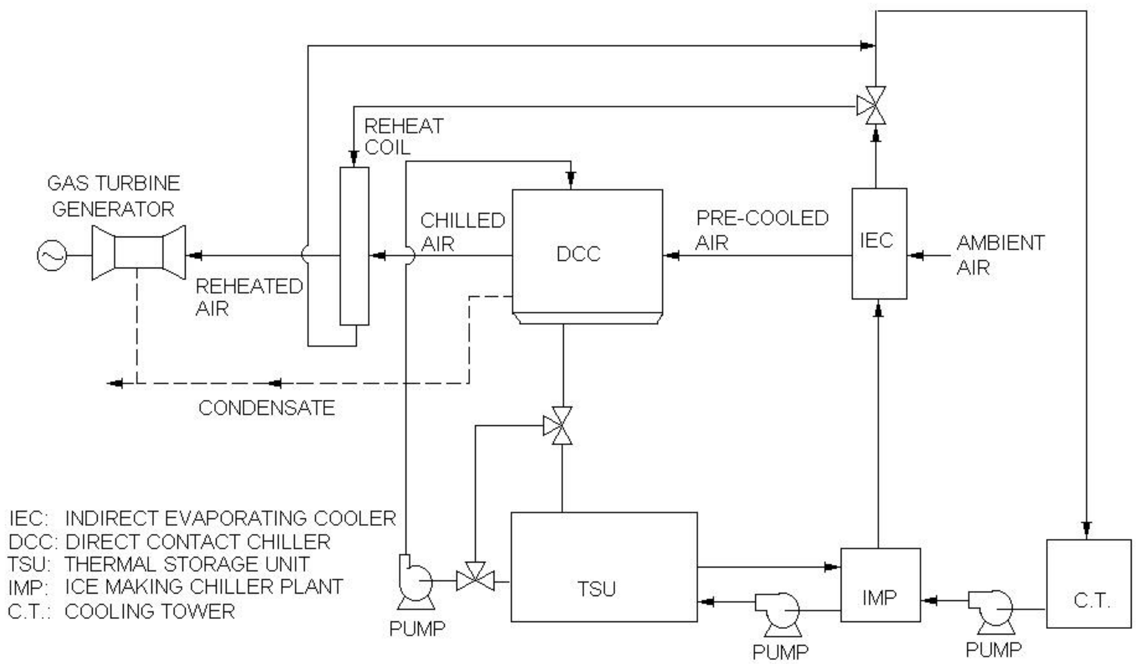


Figure 28: Ice thermal storage system for intake air cooling to gas turbine generator. The condensate from the DCC represents recovered water.

The study included two typical gas turbines (an industrial and an aeroderivative type gas turbine) operated at two different geographic locations: Phoenix, Arizona, and Houston, Texas.

Simulation runs were performed to generate data for both power output (KW) and heat rate (British thermal units [Btu]/KWh), as well as water recovery (acre ft/yr) in terms of intake air temperature and humidity based on weather data and turbine performance curves. Preliminary engineering design of a typical equipment arrangement for turbine inlet air-cooling operation using the ITS system was conducted. A cost analysis was performed to demonstrate the market viability of the ITS technology.

When the ITS technology is applied to gas turbines, a net power gain up to 40 percent and a heat rate reduction as much as seven percent can be achieved. In addition, a significant amount of water can be recovered (up to 200 acre-ft of water per year for a

50-MW turbine). The total cost saving is estimated to be $500,000/yr for a 50-MW gas turbine generator. These results have clearly demonstrated that the use of ITS technology to cool the intake-air to gas turbines is an efficient and cost-effective means to improve the overall performance of its power generation capacity with an important added benefit of water recovery in power plant operation. This project was completed in September 2003.

Improved Performance of an Air Cooled Condenser (ACC) Using SPX Wind Guide Technology – SPX Cooling Technologies, Inc.

SPX investigators are developing wind guide technology for air-cooled condensers (ACCs) to improve power plant efficiency.[45] Major drawbacks to the application of dry cooling have included efficiency variation and reduction, and capital and operating costs of the ACC units. SPX is working to reduce the efficiency variation in windy conditions by developing physical enhancements to the base ACC. The efficiency improvement for the cooling process is being evaluated by adding the new technology to an existing ACC cooling process at a selected coal-fired power plant.

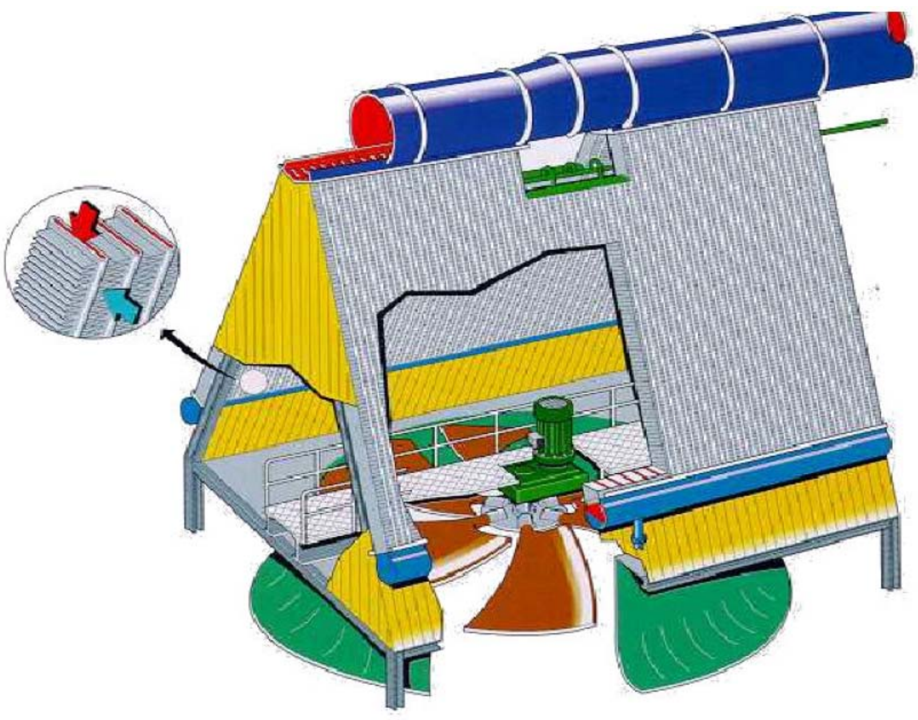


Figure 29: Wind Guide Technology for Improving Air Flow of an Air Cooled Condenser

Wind guide technology consists of guide vanes and wind screens that reduce crosswind effects by improving air flow distribution to and through the ACC fan (see Figure 29). This technology increases the flow of air in no wind and windy conditions. Degradation of fan performance during windy conditions is a common problem in ACCs, resulting in decreased cooling performance that causes a higher backpressure in the turbine and an overall lower plant efficiency.

For this project, a coal-fired power unit using an ACC will be selected to test the wind guide technology. Performance of the wind guide technology on the power plant will be determined by monitoring the steam temperature and pressure and condensate flow rate for the plant. Fan pressure and horsepower, and inlet/outlet air dry-bulb temperatures will be examined before and after the wind guide installation. The extent of performance gains that can be realized in both no wind and windy conditions will be determined. This project will be completed in December 2010.

Advanced Water Treatment and Detection Technology

In the early years of the energy water program, several projects were funded to evaluate water treatment and detection technologies. Projects are no longer being funded in this focus area, but the projects that were conducted are described below.

Fate of As, Se, and Hg in a Passive Integrated System for Treatment of Fossil Plant Waste Water – Tennessee Valley Authority and Electric Power Research Institute

Mercury, As, and selenium (Se) are pollutants often present at trace-levels in power plant flue gas and wastewater. In addition, ammonia "slip" from selective catalytic reduction systems (SCRs) for reduction of NO_X emissions can appear in wastewater streams such as FGD effluents and ash sluice water. The Tennessee Valley Authority (TVA) and EPRI conducted a three-year study of a passive treatment technology to remove trace levels of As, Se, and Hg, as well as ammonia and nitrate from fossil power plant wastewater at the Paradise Fossil Plant near Drakesboro, Kentucky.[46] An extraction trench containing zero-valent iron was evaluated as an integrated passive treatment system for removal of these trace compounds and wetlands were used for denitrification.

Objectives of this project included to: (1) design and install an extraction trench; (2) monitor the movement of As, Se, and Hg through the treatment system; (3) assess the removal efficiency of As, Se, and Hg from power plant wastewater by each component of the treatment system; and (4) determine the effect of each component of the treatment system on the speciation of As, Se, and Hg. This project was completed in 2006.

Demonstrating a Market-Based Approach to the Reclamation of Mined Lands in West Virginia – Electric Power Research Institute

EPRI demonstrated a market-based approach to abandoned mine land (AML) reclamation by creating marketable water quality and carbon emission credits.[47] The project involved the reclamation of thirty acres of AML in West Virginia through (1) installation of a passive system to treat acid mine drainage, (2) application of fly ash as a mine soil amendment, and (3) reforestation for the capture and sequestration of atmospheric CO_2. The watershed where research was conducted is displayed in Figure 30. Water quality and CO_2 uptake were measured and conventional economic principals were used to develop the costs and environmental benefits of the remedial treatments. Potential environmental credits included water quality credits due to decreased acid mine drainage and other benefits resulting from the soil amendment, as well as potential credits for CO_2

sequestration due to the more than 36,000 seedlings planned for the site. This project was completed in 2005.

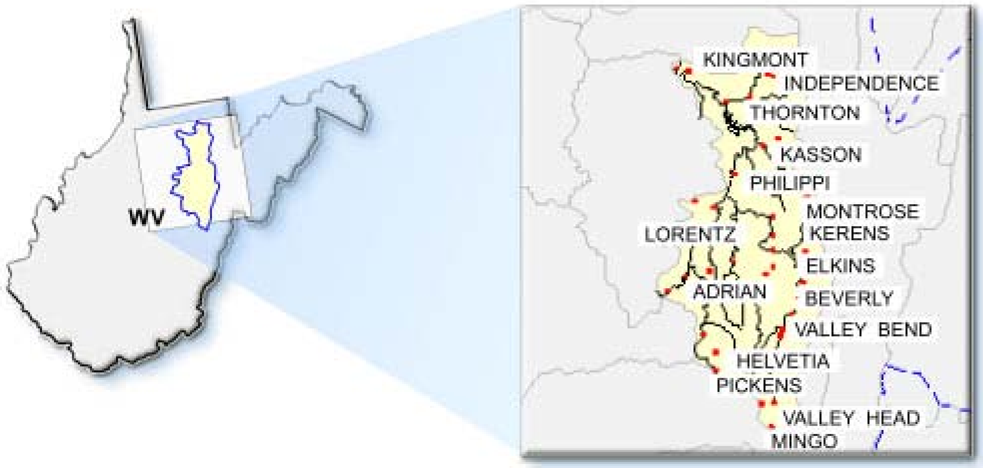


Figure 30: Location of the Tygart Valley Watershed in West Virginia

<u>Novel Anionic Clay Adsorbents for Boiler-Blow Down Waters Reclaim and Reuse – University of Southern California</u>

The University of Southern California studied the utilization of novel anionic clay sorbents for treating and reusing power plant effluents.[48] Concerns exist about heavy metals, such as As and Se, which can be found at low levels in power plant effluents. Since the waste stream flow rates are high and the metals concentrations are at trace levels, it is difficult to effectively clean the water. As a result, highly efficient treatment techniques are required. The University of Southern California studied the feasibility of applying novel sorbents to treat, recycle, and reuse boiler blowdown streams. The goal of this project was to develop an inexpensive clay-based adsorbent that could be used to treat high-volume, low-concentration wastewater containing As and Se.

During the study, model blowdown streams were treated in batch experiments and adsorption pH/temperature isotherms were developed. Impacts of As/Se interaction and the competition from background anions on adsorption rates were also studied. Results indicated that As has a greater adsorption capacity than Se for sorbents tested, and the adsorption capacities of both metals increased with increasing temperature. Adsorption rates varied from fast to relatively slow depending on the sorbent used. This project was completed in 2005.

Specifically Designed Constructed Wetlands: A Novel Treatment Approach for Scrubber Wastewater – Clemson University

Clemson University evaluated specifically designed pilot-scale constructed wetland treatment systems for treatment of targeted constituents in coal-fired power plant FGD wastewater.[49] The overall objective of this project was to decrease targeted constituents, Hg, Se, and As concentrations, in FGD wastewater to achieve discharge limitations established by NPDES and the CWA. Specific objectives of this research were: (1) to measure performance of this treatment system in terms of decreases in targeted constituents (Hg, Se, and As) in the FGD wastewater; (2) to determine how the observed performance is achieved (both reactions and rates); and (3) to also measure performance in terms of decreased bioavailability of these elements (i.e., toxicity of sediments in constructed wetlands and toxicity of outflow waters from the treatment system). This project was completed in 2005.

NETL In-House Water Research

In addition to the competitively-funded projects described above, the EPEC Program provides funding for in-house research performed by the NETL Office of Research and Development (ORD). These in-house research projects are described briefly below.

Surface Coating of Condenser Tubing and CO_2 Sparging for Preventing Fouling and Water Use Reduction

This work consists of surface modification to both promote heat transfer and reduce deposit formation in heat exchanger tubes. If the deposition and fouling can be reduced, less cooling water will be required. To date, NETL-Institute for Advanced Energy Solutions (IAES) researchers have begun the study of deposits from a test recirculation loop using river water from the Monongahela River. These initial tests will be followed by studies using coated and uncoated samples, as well as a novel proposal to alter the pH of coolant water with injected CO_2. The CO_2 would not be captured in this scenario, but in the passage through the cooling system, the modest pH shift may be beneficial in reducing deposits.

High Fidelity CFD Model and Corresponding Reduced Order Model for General Cooling Tower and Associated Water Recovery Devices

This project is developing models that consider heat and mass transport in cooling towers, to be integrated as modules within plant-scale simulation models. This work fills a modeling void in present commercial models for cooling towers. By providing a detailed model of processes in the cooling tower, this work will allow researchers to investigate how placement of devices to enhance water condensation/droplet return could be incorporated in the cooling tower design. As an example, the patterned substrates described below may be optimally located in the cooling tower flow using the detailed CFD model.

Topographically and Chemically Patterned Substrates for Water Recovery

This project is conducting studies to examine efficiencies of patterned engineered hydrophobic/hydrophilic surfaces in mist recovery and collection. The technical approach uses patterned superhydrophobic/superhydrophilic textured surfaces to increase the capture of draft-borne droplets on superhydrophilic, or "H_2O+" regions), collect them into larger droplets, and transport them under the influence of gravity and superhydrophobic, or "H_2O-" regions to effectively increase water recovery in the system. Recent discoveries in natural systems have found such a system under use by beetles in arid environments to collect morning fog as consumptive water. As of August 2009, potential substrates with the needed patterns have been selected and are being prepared by photolithography.

Oxy-Combustion of Fossil Fuels With Carbon Capture

In most CO_2 capture concepts, the flue gas is scrubbed of CO_2 and subsequently compressed. Especially for oxy-fuel systems, this compression step includes needed water condensation. Impurities associated with the condensed water have not been widely considered in evaluating the overall compression process, but are being investigated by ORD as part of ongoing studies of the Integrated Pollutant Removal (IPR) process.

NETL is developing IPR for processing the combustion products of oxy-combustion and generating a CO_2 product that meets pipeline and sequestration specifications (~2,200 psi; impurity limitations required by regulation). The products of oxy-combustion contain 30 percent or more of water, and the final CO_2 product will have a maximum water content (five to 20 parts per million [ppm]) to inhibit corrosion in the transportation and sequestration operations. IPR removes water from the flue gas and polishes the product to meet the required specifications. The water removed contains heat energy that is recovered and returned to the power plant to ameliorate the costs of producing oxygen and compressing the CO_2 product.

NETL researchers are also addressing the processing of the water recovered in IPR to prepare it for reuse in the plant. Capture and reuse of the water contained in the oxy-combustion flue gas has the potential to replace about 20 percent of the freshwater withdrawn to meet plant requirements. The approach to this research includes modeling, lab-scale experimental studies, and field tests to evaluate and demonstrate techniques. The locations of water recovery and chemical and physical characteristics at each location are being evaluated and compared to water specifications for plant operations. Multiple processes may be integrated into IPR in order to maximize water and heat recovery, minimize environmental impacts, and optimize economics. Development of an optimized water recovery and reuse process will take all of these factors, and possibly more, into account. It is important to note that the findings in this study may also benefit water reduction for different types of CO_2 capture technology, not just IPR. The research findings should benefit general studies of removing and purifying water produced during the compression stages of moist CO_2 recovered from the flue gas of any oxy-fuel power plant, and will likely be relevant to integrated gasification combined cycle (IGCC) systems as well where water is condensed during CO_2 removal.

Systems Modeling of Water Use

NETL/ORD is conducting a study to minimize water use under uncertainty. The majority of water loss occurs in the cooling tower. The amount of water lost is highly dependent on the conditions of air entering the tower. Thus, one of the major goals of this project has been to characterize the uncertainty in water use arising from variable atmospheric conditions. For a representative location, weather data has been analyzed to determine probability distributions for wet-bulb and dry-bulb air temperatures for four distinct seasons. In addition, an improved cooling tower model was developed. Applying a minimization algorithm (BONUS) to a process simulation incorporating this uncertainty indicates the potential for reducing water consumption by approximately 10 percent. To ensure that water resources are allocated most efficiently, plant-wide models need to be able to provide input to regional water resource planning models. NETL initiated a project in 2009 to survey global water management-related studies and to evaluate the benefits of integrating the plant level models under development by NETL/ORD with a global model and to develop a model requirements document. The simulation and modeling framework includes links to such regional water resource models.

Argonne National Laboratory Research

The EPEC Program also provides funding to ANL to conduct water-energy related studies. The ANL studies typically involve analysis and integration of data to provide insights on particular issues related to water use in power generation. The research conducted covers a wide range of topics. The project titles and brief descriptions of the ANL efforts are presented below.

Produced Water Volumes and Management Practices in the United States

This report provides a current estimate for the volume of produced water generated from oil and gas production in the United States.[50] The volume estimate represents a compilation of data obtained from numerous state oil and gas agencies and several Federal agencies for 2007. The total volume of produced water estimated for 2007 is about 21 billion bbl. This equals an average of 57.4 million bbl/day. Produced water is generated from most of the nearly 1 million actively producing oil and gas wells in the United States. Argonne contacted state oil and gas agencies in the 31 states with active oil and gas production to obtain detailed information on produced water volumes and management.

Impact of Drought on U.S. Steam Electric Power Plant Cooling Water Intakes and Related Water Resource Management Issues

The purpose of this project was to estimate the impact on generation capacity of a drop in water level at U.S. steam electric power plants due to climatic or other conditions.[51]

While the temperature of the water can impact decisions to halt or curtail power plant operations, this report specifically examines impacts as a result of a drop in water levels below power plant submerged cooling water intakes.

An Analysis of the Effects of Drought Conditions on Electric Power Generation in the Western United States

During the summer and fall of 2007, a serious drought affected the southeastern United States. River flows decreased, and water levels in lakes and other impoundments dropped. In a few cases, water levels were so low that power production had to be stopped or reduced. It is likely that, in coming years, competing water demands will increase. It is also possible that climatic conditions will become warmer or at least more variable, thereby exacerbating future droughts. This report attempts to identify the system-wide impacts on the power system that could arise from various decreases in surface water levels.[52]

Baseline and Projected Water Demand Data for Energy and Competing Water Use Sectors

The links between energy and water and the growing concerns about the adequacy of U.S. water supplies point to the need for data on water consumption by potentially competing economic sectors. Projected water consumption estimates can help identify possible locations and time periods in which energy production could be constrained because of competition for limited water resources. This report provides estimates of domestic freshwater demand, as expressed by consumption, to the year 2030 in five-year increments at the national and regional levels for energy and non-energy uses.[53]

Use of Reclaimed Water for Power Plant Cooling

This report provides information about an opportunity to reuse an abundant water source – treated municipal wastewater, also known as "reclaimed water" – for cooling and process water in electric generating facilities.[54] This report represents a unique reference for information on the use of reclaimed water for power plant cooling.

Beneficial Use of Mine Pool Water for Power Generation

The intent of this project was to evaluate some of the technical, policy, and regulatory issues surrounding the use of mine pool water as cooling water in power plants, with a particular focus on mines in Pennsylvania and West Virginia. The final report for the initial project was completed in 2003. The project and report were updated in 2006.[55] The most significant example of mine pool water use is at a nuclear power plant in southeastern Pennsylvania.

Use of Mine Pool Water for Power Plant Cooling

This report provides preliminary information about an opportunity to reuse ground water accumulated in underground coal mines for cooling and process water in electric generating facilities.[56] Six small power plants and one large power plant in Pennsylvania are currently using mine pool water.

Identification of Incentive Options to Encourage the Use of Produced Water, Coal Bed Methane Water, and Mine Pool Water

The objective of this project was to identify a limited set of scenarios involving combinations of water resources, applications, and incentives that might define the range of near-term opportunities for developing these resources.[57] A subset of the scenarios were selected and subjected to quantitative analyses to estimate the benefits attributable to the assumed incentives and to determine which might be most effective in promoting the development and use of these resources.

SUMMARY

Freshwater resources and reliable electrical energy are inextricably linked. Thermoelectric generation requires a sustainable, abundant, and predictable source of water. Power plants will increasingly compete for freshwater with the domestic, commercial, agricultural, industrial, and in-stream use sectors. There will be increasing pressure to deny permits for new power plants due to water quantity and quality issues.

In response to this challenge to national energy sustainability, DOE's FE/NETL is carrying out an R&D program focused on the development and application of advanced technologies to better manage how power plants use and impact freshwater**.** 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. Research is currently underway to assess and develop non-traditional sources of cooling and process water, advanced cooling water technologies, and innovative water reuse and recovery technologies. It is anticipated that this research will provide thermoelectric generators with the tools needed to reduce their freshwater withdrawal and consumption. Reduced water use will help to alleviate potential conflicts between growing demands for electricity and increasing pressures on the Nation's freshwater resources. For more information on NETL's power plant water R&D activities, please visit: http://www.netl.doe.gov/technologies/coalpower/ewr/water/index.html.

REFERENCES

[1] U.S. Department of Energy, 2006. *Department of Energy/Office of Fossil Energy's Water-Energy Interface Research Program*, U.S. Department of Energy, National Energy Technology Laboratory, April, 2006. http://www.netl.doe.gov/technologies/coalpower/ewr/pubs/IEP%20Power%20Plant%20Water%20R%26D%20Updated%200406.pdf

[2] Energy Information Administration, *Annual Energy Outlook 2010*, May 2010. http://www.eia.doe.gov/oiaf/aeo/

[3] U.S. Department of Energy, 2009. *Water Requirements for Existing and Emerging Thermoelectric Plant Technologies*, U.S. Department of Energy, National Energy Technology Laboratory – 402/080108, April, 2009. http://www.netl.doe.gov/energy-analyses/pubs/WaterRequirements.pdf

[4] Ciferno, J.P., R.K. Munson, J.T. Murphy, and B.S. LaShier. 2010. *The Relationship Between Carbon Capture and Sequestration and Water Use: Department of Energy Research and Development Programs,* Power Magazine, March 2010.

[5] Electric Power Research Institute, A Survey of Water Use and Sustainability in the United States with a Focus on Power Generation, EPRI Report No. 1005474, November 2003

[6] U.S. Department of Energy, 2009. *The Energy-Water Research and Development Technology Roadmap and Program Plan*, U.S. Department of Energy, National Energy Technology Laboratory, November, 2009. http://www.netl.doe.gov/technologies/coalpower/ewr/water/pdfs/Technology%20Roadmap%20and%20Program%20Plan.pdf

[7] Kenny, J.F., N.L. Barber, S.S Hutson, K.S. Linsey, J.K. Lovelace, and M.A. Maupin, *Estimated Use of Water in the United States in 2005*, U.S. Geological Survey Circular 1344, 2009.

[8] U.S. Geological Survey. *Estimated Use of Water in the United States in 1995*; USGS Circular 1200; 1999.

[9] U.S. Department of Energy, 2008. *Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements – 2008 Update*, U.S. Department of Energy, National Energy Technology Laboratory – 400/2008/1339, September, 2008. http://www.netl.doe.gov/energy-analyses/pubs/2009%20Water%20Needs%20Analysis%20-%20Final%20%289-30-2009%29.pdf

[10] U.S. Environmental Protection Agency, *Technical Development Document for the Final Regulations* (EPA-821-R-01-036), November 2001.

[11] SAIC. *Water-Energy RD&D Scoping Study;* Final Report to the U.S. Department of Energy, NETL; September 2003.

[12] United States General Accounting Office. *Freshwater Supply, States'Views of How Federal Agencies Could Help Them Meet the Challenges of Expected Shortages*; GAO Report No. GAO-03-514; July 2003.

[13] Electric Power Research Institute. *A Survey of Water Use and Sustainability in the United States With a Focus on Power Generation*; EPRI Report No. 1005474; November 2003.

[14] U.S. Department of the Interior. *Water 2025 – Preventing Crises and Conflict in the West*; May 2003.

[15] U.S. Department of Energy, 2005. *Addressing the Critical Link Between Fossil Energy and Water*, U.S. Department of Energy, National Energy Technology Laboratory, October 2005. http://www.netl.doe.gov/technologies/coalpower/ewr/pubs/NETL_Water_Paper_Final_Oct.2005.pdf

[16] *Strategies for Cooling Electric Generating Facilities Utilizing Mine Water: Technical and Economic Feasibility Project*. Final Report to the U.S. Department of Energy under Cooperative Agreement No. DE-PS26-03NT41719; West Virginia Water Research Institute – West Virginia University, September 30, 2004. http://www.netl.doe.gov/technologies/coalpower/ewr/pubs/WVU%20WRI%20Strategies%20for%20Mine%20Water%20Cooling%20Final%20Report.pdf

[17] *Use of Produced Water in Recirculating Cooling Systems at Power Generating Facilities*. Semi-Annual Technical Progress Reports to the U.S. Department of Energy under Cooperative Agreement No. DE-

FC26-03NT41906; Electric Power Research Institute, August-December 2004. http://www.netl.doe.gov/technologies/coalpower/ewr/water/pp-mgmt/epri.html

[18] *Mine Water for Thermoelectric Power Generation: A Modeling Framework* http://www.netl.doe.gov/technologies/coalpower/ewr/water/pp-mgmt/mine.html

[19] *A Synergistic Combination of Advanced Separation and Chemical Scale Inhibitor Technologies for Efficient Use of Impaired Water in Coal-Based Power Plant*s http://www.netl.doe.gov/technologies/coalpower/ewr/water/pp-mgmt/nalco.html

[20] *Reuse of Treated Internal or External Wastewaters in the Cooling Systems of Coal-based Thermoelectric Power Plant*. Final Report to the U.S. Department of Energy under Cooperative Agreement No. DE-FC26-06NT42722; University of Pittsburgh, September 2009. http://www.netl.doe.gov/technologies/coalpower/ewr/water/pp-mgmt/pubs/06550/42722FSRFG063009.pdf

[21] *Use of Treated Municipal Wastewater as Power Plant Cooling System Makeup Water: Tertiary Treatment versus Expanded Chemical Regimen for Recirculating Water Quality Management* http://www.netl.doe.gov/publications/factsheets/project/Proj525.pdf

[22] *Study of the Use of Saline Formations for Combined Thermoelectric Power Plant Water Needs and Carbon Sequestration at a Regional-Scale.* http://www.netl.doe.gov/technologies/coalpower/ewr/water/pp-mgmt/sandia.html

[23] *Thermoelectric Power Plant Water Demands Using Alternative Water Supplies: Power Demand Options in Regions of Water Stress and Future Carbon Management.* http://www.netl.doe.gov/technologies/coalpower/ewr/water/pp-mgmt/regional.html

[24] *Nanofiltration Treatment Options for Thermoelectric Power Plant Water Treatment Demands.* http://www.netl.doe.gov/technologies/coalpower/ewr/water/pp-mgmt/nanofiltration.html

[25] *Internet-Based, GIS Catalog of Non-traditional Sources of Cooling Water for Use at Coal-Fired Power Plants* http://www.netl.doe.gov/publications/factsheets/project/Proj522.pdf

[26] *Reuse of Produced Water from CO_2 Enhanced Oil Recovery, Coal-Bed Methane, and Mine Pool Water by Coal-Based Power Plants* http://www.netl.doe.gov/publications/factsheets/project/Proj526.pdf

[27] Dastgheib, S.A. 2008. *Reuse of Produced Water from CO_2 Enhanced Oil Recovery, Coal-Bed Methane, and Mine Pool Water by Coal-Based Power Plants,* Presentation, DOE/NETL –Existing Plants Water Projects Meeting, October 27-28, 2008, Pittsburgh, Pennsylvania. http://www.netl.doe.gov/technologies/coalpower/ewr/water/ppmgmt/pubs/05343/Kickoff%20NETL%20mtg_rev1_NT0005343.pdf

[28] *Technology to Facilitate the Use of Impaired Waters in Cooling Towers* http://www.netl.doe.gov/publications/factsheets/project/Proj523.pdf

[29] *Use of Coal Drying to Reduce Water Consumed in Pulverized Coal Power Plants*. Final Report to the U.S. Department of Energy under Cooperative Agreement No. DE-FC26-03NT41729; Energy Research Center - Lehigh University, March 2006 http://www.netl.doe.gov/technologies/coalpower/ewr/water/pp-mgmt/pubs/lehigh/41729%20Final.pdf

[30] *Lignite Fuel Enhancement* http://www.netl.doe.gov/publications/factsheets/project/Proj219.pdf

[31] James F. Klausner, Yi Li, Mohamed Darwish, and Renwei Mei. 2004. *Innovative Diffusion Driven Desalination Process*. ASME Journal of Energy Resources Technology., 2004, 126, pp. 219–225 http://www.netl.doe.gov/technologies/coalpower/ewr/water/pp-mgmt/pubs/desalination_paper.pdf

[32] *Water Extraction from Coal-Fired Power Plant Flue Gas,* Final Report to the U.S. Department of Energy under Cooperative Agreement No DE-FC26-03NT41907; University of North Dakota Energy and Environmental Research Center, December 2006. http://www.netl.doe.gov/technologies/coalpower/ewr/water/pp-mgmt/pubs/41907/41907%20Final.pdf

[33] *Recovery of Water From Boiler Flue Gas,* Final Report to the U.S. Department of Energy under Cooperative Agreement No DE-FC26-06NT42727; Lehigh University, December 2008. http://www.netl.doe.gov/technologies/coalpower/ewr/pubs/NT42727_Lehigh_FinalRpt.pdf

[34] *The Use of Restored Wetlands to Enhance Power Plant Cooling and Mitigate the Demand on Surface Water Use* http://www.netl.doe.gov/publications/factsheets/project/Proj518.pdf

[35] *Transport Membrane Condenser for Water and Energy Recovery from Power Plant Flue Gas* http://www.netl.doe.gov/publications/factsheets/project/Proj524.pdf

[36] *Recovery of Water from Boiler Flue Gas Using Condensing Heat Exchangers* http://www.netl.doe.gov/publications/factsheets/project/Proj521.pdf

[37] *Development of an Impaired Water Cooling System* http://www.netl.doe.gov/technologies/coalpower/ewr/water/pp-mgmt/pubs/41906/41906%20WSAC.pdf

[38] *Environmentally Safe Control of Zebra Mussel Fouling,* Final Report to the U.S. Department of Energy under Cooperative Agreement No DE-FC26-03NT41909; New York State Education Department, May 2008. http://www.netl.doe.gov/technologies/coalpower/ewr/pubs/NT41909_NY%20Dept%20of%20Educ_Final%20Report.pdf

[39] *Enhanced Performance Carbon Foam Heat Exchanger for Power Plant Cooling.* Final Report to the U.S. Department of Energy under Cooperative Agreement No DE-FG02-03ER83627; Ceramic Composites, Inc., 2007. http://www.netl.doe.gov/technologies/coalpower/ewr/pubs/ER83627_Ceramic%20Composites_Phase2%20FinalRpt.pdf

[40] *Use of Air2Air Technology to Recover Fresh-Water from the Normal Evaporative Cooling Loss at Coal-Based Thermoelectric Power Plants.* Final Report to the U.S. Department of Energy under Cooperative Agreement No DE-FC26-06NT42725; SPX Cooling Technologies, Inc., September 2009. http://www.netl.doe.gov/technologies/coalpower/ewr/pubs/NT42725_SPX%20Cooling_Final%20Report.pdf

[41] *Improvement to Air2Air® Technology to Reduce Freshwater Evaporative Cooling Loss* http://www.netl.doe.gov/publications/factsheets/project/Proj520.pdf

[42] *Application of Pulsed Electrical Foe;ds for Advanced Cooling and Water Recovery in Coal-Fired Power Plants.* Final Report to the U.S. Department of Energy under Cooperative Agreement No DE-FC26-06NT42724; Drexel University., June 2009 http://www.netl.doe.gov/technologies/coalpower/ewr/pubs/NT42724_Drexel_Final%20Rpt.pdf

[43] *Application of Pulse Spark Discharges for Scale Prevention and Continuous Filtration Methods* http://www.netl.doe.gov/publications/factsheets/project/Proj517.pdf

[44] *A Novel Concept for Reducing Water Usage and Increasing Efficiency in Power Generation,* Final Report to the U.S. Department of Energy under Cooperative Agreement No DE-FG26-02NT41544; University of Pittsburgh, March 2004. http://www.netl.doe.gov/technologies/coalpower/ewr/water/pp-mgmt/pubs/41544%20Final%20Report.pdf

[45] *Improved Performance of an Air Cooled Condenser (ACC) Using SPX Wind Guide Technology* http://www.netl.doe.gov/publications/factsheets/project/Proj519.pdf

[46] *Fate of As, Se, and Hg in a Passive Integrated System for Treatment of Fossil Plant Waste Water,* Final Report to the U.S. Department of Energy under Cooperative Agreement No DE-FC26-03NT41910; Tennessee Valley Authority, February 2007. http://www.netl.doe.gov/technologies/coalpower/ewr/water/pp-mgmt/pubs/41910/41910%20Final.pdf

[47] *Demonstrating a Market-Based Approach to the Reclamation of Mined Lands in West Virginia,* Report to the U.S. Department of Energy under Cooperative Agreement No DE-FC26-03NT41899R01; Electric Power Research Institute, July 2006 http://www.netl.doe.gov/technologies/coalpower/ewr/pubs/Reclamation%20WV%20Mine%20Lands.pdf

[48] *Novel Anionic Clay Adsorbents for Boiler-Blow Down Waters Reclaim and Reuse,* Final Report to the U.S. Department of Energy under Cooperative Agreement No DE-FG26-04NT42177; University of Southern California, December 2005. http://www.netl.doe.gov/technologies/coalpower/ewr/pubs/Novel%20Anionic%20Clay%20Adsorbents.pdf

[49] *Specifically Designed Constructed Wetlands: A Novel Treatment Approach for Scrubber Wastewater,* Final Report to the U.S. Department of Energy under Cooperative Agreement No DE-FG26-04NT42178; Clemson University, September 2005. http://www.netl.doe.gov/technologies/coalpower/ewr/pubs/Wetland%20Treatment%20Scrubber%20Wastewater.pdf

[50] *Produced Water Volumes and Management Practices in the United States,* Final Report to the U.S. Department of Energy under Cooperative Agreement No DE-AC02-06CH11357; Argonne National Laboratory, September 2009.

http://www.netl.doe.gov/technologies/coalpower/ewr/water/pdfs/anl%20produced%20water%20volumes%20sep09.pdf

51 *Impact of Drought on U.S. Steam Electric Power Plant Cooling Water Intakes and Related Water Resource Management Issues*, Final Report to the U.S. Department of Energy under Cooperative Agreement No DE-AC02-06CH11357; Argonne National Laboratory, April 2009. http://www.netl.doe.gov/technologies/coalpower/ewr/water/pdfs/final-drought%20impacts.pdf

52 *An Analysis of the Effects of Drought Conditions on Electric Power Generation in the Western United States*, Final Report to the U.S. Department of Energy under Cooperative Agreement No DE-AC02-06CH11357; Argonne National Laboratory, April 2009. http://www.netl.doe.gov/technologies/coalpower/ewr/water/pdfs/final%20%20WECC%20drought%20analysis.pdf

53 *Baseline and Projected Water Demand Data for Energy and Competing Water Use Sectors*, Final Report to the U.S. Department of Energy under Cooperative Agreement No DE-AC02-06CH11357; Argonne National Laboratory, November 2008. http://www.ead.anl.gov/pub/doc/ANL-EVS-TM08-8_water_demand_report.pdf

54 *Use of Reclaimed Water for Power Plant Cooling*, Final Report to the U.S. Department of Energy under Cooperative Agreement No DE-AC02-06CH11357; Argonne National Laboratory, August 2007. http://www.netl.doe.gov/technologies/coalpower/ewr/pubs/reclaimed%20water.pdf

55 *Update on Use of Mine Pool Water for Power Generation*, Final Report to the U.S. Department of Energy under Contract W-31-109-Eng-38; Argonne National Laboratory, September 2006. http://www.ead.anl.gov/pub/doc/ANL-EVS-R6-06MinePoolUpdate.pdf

56 *Use of Mine Pool Water for Power Generation*, Final Report to the U.S. Department of Energy under Contract W-31-109-Eng-38; Argonne National Laboratory, September 2003. http://www.netl.doe.gov/technologies/coalpower/ewr/pubs/mine%20pool%20report%20FINAL_1.pdf

57 *Identification of Incentive Options to Encourage the Use of Produced Water, Coal Bed Methane Water, and Mine Pool Water*, Final Report to the U.S. Department of Energy under Contract W-31-109-Eng-38; Argonne National Laboratory, September 2004. http://www.netl.doe.gov/technologies/coalpower/ewr/pubs/final%20report%20on%20incentives%20Oct%201%202004_1.pdf