Department of Energy/Office of Fossil Energy's Water-Energy Interface Research Program

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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 over 12 million gallons per hour of water for cooling and other process requirements[a]. The United States Geological Survey (USGS) estimates that thermoelectric generation[b] accounts for approximately 136 billion gallons per day (BGD) of freshwater withdrawals[c], ranking only slightly behind agricultural irrigation as the largest source of freshwater withdrawals in the United States.[1] As U.S. population and associated economic development continue to expand, the demand for electricity increases. The Energy Information Administration's (EIA) latest forecast estimates U.S. coal-fired generating capacity will grow from approximately 305 GW in 2004 to 453 GW in 2030.[2] As such, 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. 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 Innovations for Existing Plants (IEP) program directed at technologies and concepts to reduce the amount of freshwater used by power plants and to minimize any potential impacts of plant operations on water quality. The goal of this effort is to provide the technology to allow power plants to reduce freshwater withdrawals and consumption by at least 5-10% by 2015. This paper 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 IEP program to address current and future water-energy issues.

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[a] Actual cooling water flow rate requirements for a particular plant will vary depending on type of cooling water system and design parameters.
[b] Thermoelectric generation includes coal, oil, natural gas and nuclear power generation. Coal-based generation represents approximately 58% of total U.S. thermoelectric generation based on EIA AEO 2005 estimates.
[c] This includes both surface and ground water withdrawals.

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 USGS water use survey data, thermoelectric generation accounted for 39% (136 BGD) of all freshwater withdrawals in the nation in 2000, second only to irrigation, see Figure 1. Each kWh of thermoelectric generation requires the withdrawal of approximately 25 gallons of water[d], primarily used for cooling purposes. However, power plants also use water for operation of flue gas desulfurization (FGD) devices, ash handling, wastewater treatment, and wash water. When discussing water and thermoelectric generation, it is important to distinguish between water withdrawal and water consumption. Water withdrawal represents the total water taken from a source 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 presented in Figure 2.[3] Freshwater consumption for thermoelectric uses appears low (only 3%) when compared to other use categories (irrigation was responsible for 81% of water consumed). However, even at 3% consumption, over 3 BGD were consumed. It is expected that the percent of water consumed by thermoelectric generation is higher today than in 1995.

Figure 1. U.S. Freshwater Withdrawal (2000)

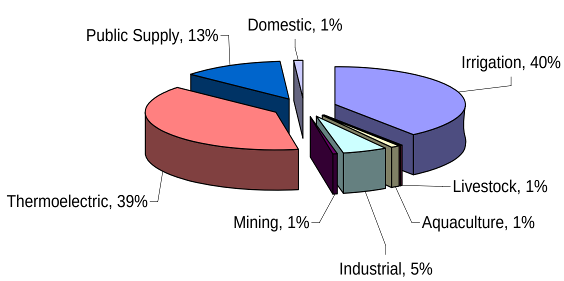
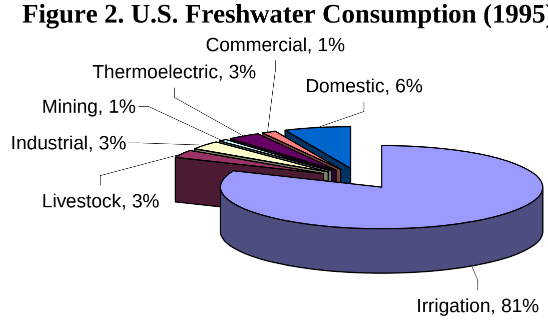


Figure 2. U.S. Freshwater Consumption (1995)



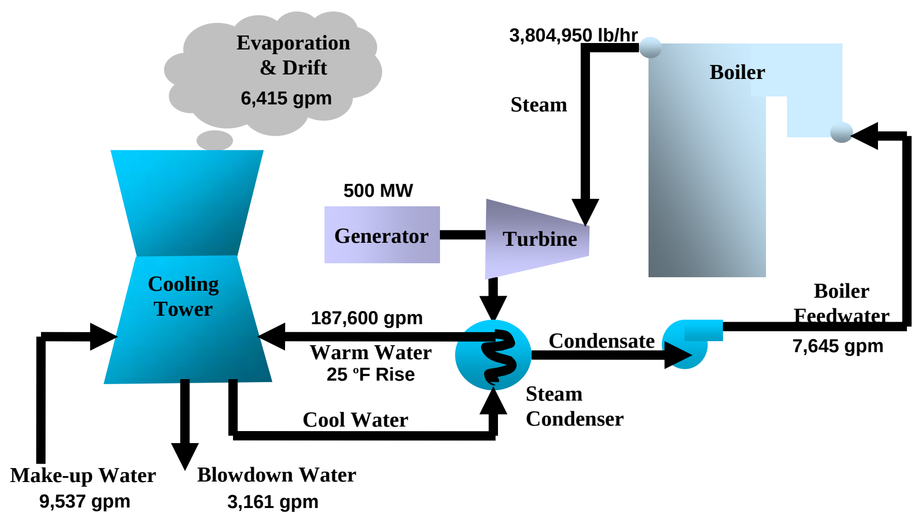
Large quantities of cooling water are required for thermoelectric power plants to support the generation of electricity. Thermoelectric generation relies on a fuel source (fossil or nuclear) to heat water to steam that is used to drive a turbine-generator. Steam exhausted from the turbine is condensed 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 – typically 15-25ºF. There are basically two types of cooling water

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

system designs – once-through (open loop) or recirculating (closed loop). In once-through systems the cooling water is withdrawn from a local water body such as a lake, river, or ocean and the warm cooling water is subsequently discharged back to the same water body after passing through the condenser. As a result, plants equipped with once-through cooling water systems have relatively high water withdrawal, but low water consumption. 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 the warm cooling water is typically pumped from the condenser to a cooling tower where the heat is dissipated directly to ambient air by evaporation of the water and heating the air. The cooling water is then recycled back to the condenser. In addition to cooling towers, cooling ponds or lakes can also be used to accomplish evaporation in recirculating systems.

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. 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 3.

Figure 3 - Process Flow Schematic for Wet Recirculating Cooling Water System



Wet recirculating 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 second type of recirculating cooling system is known as dry cooling. 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, EPA estimated capital costs for a dry cooling tower to be 6.5% of total plant capital costs (versus 2.0% for a wet cooling tower)[4].

Of the 136 BGD of freshwater withdrawal by thermoelectric generators in 2000, USGS estimated approximately 88% 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 EIA's Form 767 report.[5] Once-through systems have very 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% of thermoelectric generating units were equipped with wet cooling towers, representing approximately 38% 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

It is difficult to estimate future freshwater withdrawal and consumption by thermoelectric generation due to changes in the type of generation, method of cooling, and source of water. Based on EIA projections of thermoelectric generation in 2025, DOE/NETL estimates that daily freshwater withdrawals could decrease to 113 BGD or increase to 138 BGD, and that daily freshwater consumption could remain at 3.3 BGD or increase to 8.7 BGD.[6]

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 ten years (2003 – 2013) under normal water conditions, and 46 states expect water shortages under drought conditions.[7] Water supply and demand estimates by EPRI for the years 1995 and 2025 also indicate a high likelihood of local and regional water shortages in the United States.[8] 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. Competition over water in the western United States, including water needed for power plants, led to a 2003 Department of Interior initiative to predict, prevent, and alleviate water-supply conflicts.[9] Other areas of the United States are also susceptible to freshwater shortages as a result of drought conditions, growing populations, and increasing demand.

Concern about water supply, expressed by state regulators, local decision-makers, and the general public, is already impacting power projects across the United States. For example, in March 2006, an Idaho state House committee unanimously approved a 2-year moratorium on construction of coal-fired power plants in the state based on environmental and water supply concerns.[10] Arizona recently rejected permitting for a proposed power plant because of concerns about how much water it would withdraw from a local aquifer.[11] In early 2005, Governor Mike Rounds of South Dakota called for a summit to discuss drought-induced low flows on the Missouri River and the impacts on irrigation, drinking-water systems, and power plants.[12] Residents of Washoe County, Nevada expressed opposition to a proposed coal-fired power plant due to concerns over how much water the plant would use.[13] A coal-fired power plant to be built in Wisconsin on Lake Michigan has been under attack from environmental groups because of potential effects of the facility's cooling-water-intake structures on the Lake's aquatic life.[14] In February 2006, Diné Power Authority reached an agreement with the Navajo Nation to pay $1,000 per acre foot and a guaranteed minimum total of $3 million for water for its proposed Desert Rock Energy Project.[15] In an article discussing a 1,200 MW proposed plant in Nevada, opposition to the plant stated, "There's no way Washoe County has the luxury anymore to have a fossil-fuel plant site in the county with the water issues we now have. It's too important for the county's economic health to allow water to be blown up in the air in a cooling tower."[16]

Such events point towards a likely future of increased conflicts and competition for the water the power industry will need to operate their thermoelectric generation capacity. 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 and the impacts of chronic and sporadic drought. In the east, current and future environmental requirements, such as the Clean Water Act's intake structure regulation, could be the most significant impediment to securing sufficient water, although local drought conditions can also impact water availability. Key environmental regulations that can potentially impact power plants are summarized below.

Environmental Regulations Affecting Thermoelectric Power Generation Water Use

The U.S. Environmental Protection Agency (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 Clean Water Act and the Safe Drinking Water Act 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 Clean Water Act (CWA) provides for the regulation of discharges to the Nation's surface waters. The CWA 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 §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 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. Regulations for Phase III are due to be finalized in 2006 and will apply to other industrial sources and new offshore and coastal oil and gas extraction facilities.

The Safe Drinking Water Act – The Safe Drinking Water Act (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, arsenic, and other trace metals could also affect how power plants dispose of coal by-products.

INNOVATIONS FOR EXISTING PLANTS PROGRAM

DOE/NETL's IEP Program is a comprehensive R&D effort directed at the development of advanced technologies that can enhance the environmental performance of the existing fleet of coal-fired power plants. In response to the growing recognition of the inter-dependence between freshwater availability and quality and electricity production, the IEP program was broadened in 2002 to include research directed at coal-fired power plant related water management issues and awarded five water-energy projects under competitive solicitation in August of 2003. In November 2005, the IEP program awarded seven new water-energy projects under a second competitive solicitation. The overall goal of this effort is to reduce the amount of freshwater needed for power plant operations and to minimize potential impacts on water quality. More specifically, the program is directed at providing the technology to allow power plant's to reduce freshwater withdrawals and consumption by at least 5-10% by 2015. The research encompasses assessments, analyses, and laboratory through pilot-scale testing and is performed in partnership with industry, academia, technology developers, and other government organizations. The program is built around four specific areas of research:

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

- Advanced Cooling Technology
- Advanced Water Treatment and Detection Technology

The following is a brief summary of several recently completed, on-going, and recently awarded R&D projects in these four research areas. Several water-related projects funded under the University Coal Research and the Clean Coal Power Initiative programs are also discussed.

Non-Traditional Sources of Process and Cooling Water

Research and analysis 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. Examples include surface and underground mine pool water[17], water displaced by geological carbon sequestration, coal-bed methane produced waters, and industrial and/or municipal wastewater.

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

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.[18] 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, 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 makeup 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) makeup 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 mg/L equivalent concentration of $CaCO_3$ − 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 that utilization of mine pool water as a source of cooling water makeup can be cost competitive with freshwater makeup systems. Table 2 provides a summary of the capital and operating cost estimates for mine pool water collection and treatment systems at the three sites.

Table 2 – 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

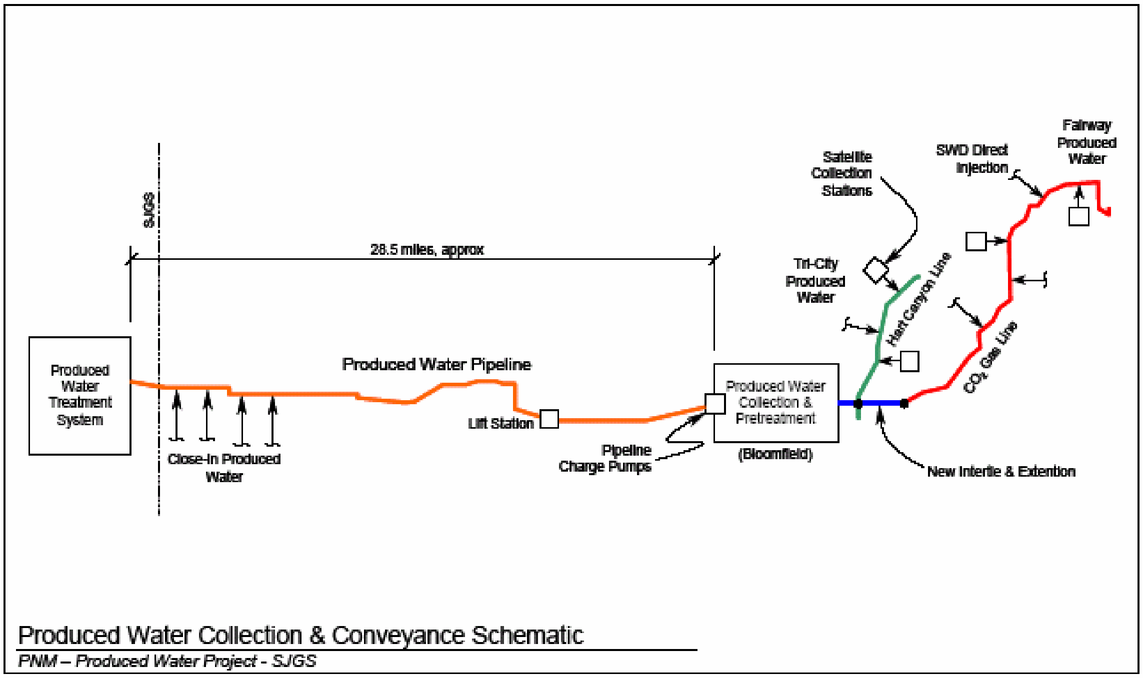
Based on fluid and heat flow modeling of the second scenario, it was determined that interconnection of two adjoining mines would be necessary to provide sufficient heat transfer residence time to adequately cool the recirculating water flow. As a result, the study identified only one potential site 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)

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.[19] Two major issues associated with this use of produced water are the following: (1) collection and transportation of the produced water to the plant and (2) 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 over 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 4). 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 4 – 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 with a brine concentrator distillation unit was found to be the most economical treatment method. This project will be finalized 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

A 300 megawatt 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 5). The plans called for use of public water at the rate of 2,000 to 3,000 gallons per minute (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 will be located, sampled, and their flow will be determined under wet and dry weather conditions. This data will be 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 5. Beech Hollow Power Plant Site

Using the data and decision-making process derived in the earlier portion of this project, as well as any appropriate data and information obtained from other thermoelectric plants utilizing mine water, a computer-based design tool will be developed for estimating the cost of water acquisition and delivery to the power plant. The cost of using mine water by power plants will be compared to the cost of using traditional water supplies, including surface water and public water supplies. In addition, the potential environmental improvements resulting from the utilization of mine water that is currently contaminating area streams will be documented. This project will be completed in December of 2007.

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 Argonne National Laboratory, is to develop advanced-scale control technologies to enable coal-based power plants to use impaired water in recirculating cooling systems. 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 will focus on methods to economically manage scaling issues (see Figure 6). The overall approach will be 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 6. Example of Pipe Scaling

Research will be conducted in three parts with laboratory research and development and small pilot scale field demonstration. Initially researchers will work to establish quantitative technical targets, develop scale inhibitor chemistries for high stress conditions, and determine the feasibility of the membrane separation technologies to minimize scaling. Subsequently, researchers will develop additional novel scale inhibitor chemistries, develop selected separation processes, and optimize the compatibility of technology components at the laboratory scale. Finally, integrated technologies will be tested using selected pilot scale model sites to validate the performance.

If the project is successful, the technology developed will make the use of impaired waters by coal-fired power plants more feasible. Benefits of the new technologies would be the following: 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 fresh water. This project will be completed in 2009.

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, is to assess the potential of three types of impaired waters for cooling water makeup in coal-based thermoelectric plants. The impaired waters to be studied include: secondary treated municipal wastewater; passively treated coal mine drainage; and ash pond effluent (Figure 7). Researchers plan to use a combination of pilot and laboratory scale studies, engineering and regulatory assessments, and mathematical modeling efforts.

To determine the feasibility of impaired water use, a variety of activities will be conducted, including: assessment of the availability and proximity of impaired waters at twelve 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.

Figure 7. Examples of Impaired Waters

(1) Ash Pond Effluent **(2) Secondary Treated Municipal Wastewater** **(3) Passively Treated AMD**

If the project is successful, the technology developed will make use of impaired waters by coal-fired power plants more feasible by providing necessary information on geographic proximity, pretreatment requirements, available quantities, and regulatory and permitting issues that are relevant for application of these impaired waters. Additionally, key design and operating parameters will be determined that will aid in successful use of the impaired waters without detrimental impact on cooling system performance. This project will be completed in June of 2009.

Innovative Water Reuse and Recovery

Research is currently underway to develop advanced technologies to reuse power plant cooling water and associated waste heat and investigate methods to recover water from coal and power plant flue gas. Such advances have the potential to reduce fossil fuel power plant water withdrawal and consumption.

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 the plant's cooling water system.[19] 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.

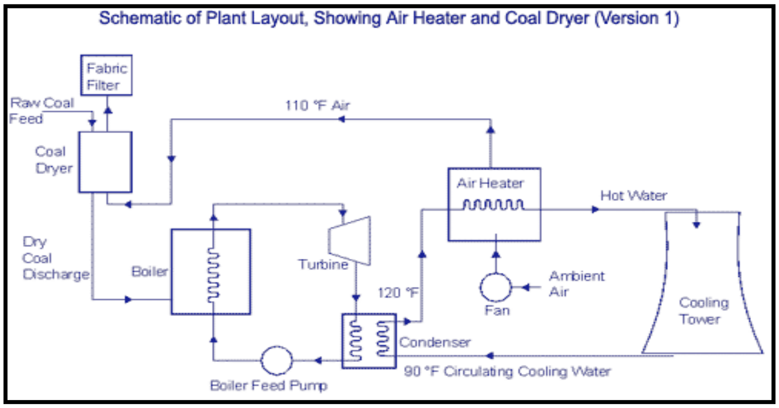
The desiccant selection and characterization evaluation was conducted by ranking the merits of potential desiccants based on physical and chemical data along with laboratory testing. One of the desiccants was selected for initial pilot-scale testing. Data from the pilot-scale testing showed that the 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 will be finalized in 2006.

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.[20] While bituminous coals have minimal moisture content (less than 10%), low-rank coals contain significant amounts of water – subbituminous and lignite coals range from 15-30% and 25-40% 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.

In addition, drying the coal prior to combustion can improve the plant heat rate, and in return reduce overall air emissions. Figure 8 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 is being 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. The Coal Creek project is being funded under DOE/NETL's Clean Coal Power Initiative. Lehigh's project will be finalized in 2006.

Figure 8 - Schematic of Lehigh Coal Drying Process



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. 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 fresh water 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 fresh water 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 reverse osmosis and flash-evaporation technologies. This project will be finalized in 2006.

Recovery of Water from Boiler Flue Gas – Lehigh University

Conducted by Lehigh University, this project will be a combination of laboratory and pilot scale experiments and computer simulations that will investigate the use of condensing heat exchangers to recover water from boiler flue gas at coal-fired power plants. 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 makeup, would be able to supply from 25% (for PRB) to 37% (for lignite) of the makeup water using this approach.

Researchers will conduct computational fluid mechanics analyses to aid in the design of the compact fin tube heat exchanger that will condense water vapor from flue gas. 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 will be determined via laboratory and pilot plant experiments. Additional experiments will be conducted to measure the heat transfer effectiveness of the fin-tube bundle designed for condensing water vapor. Analyses of the boiler and turbine cycle will be carried out to estimate potential reductions in heat rate due to recovering sensible and latent heat from the flue gas.

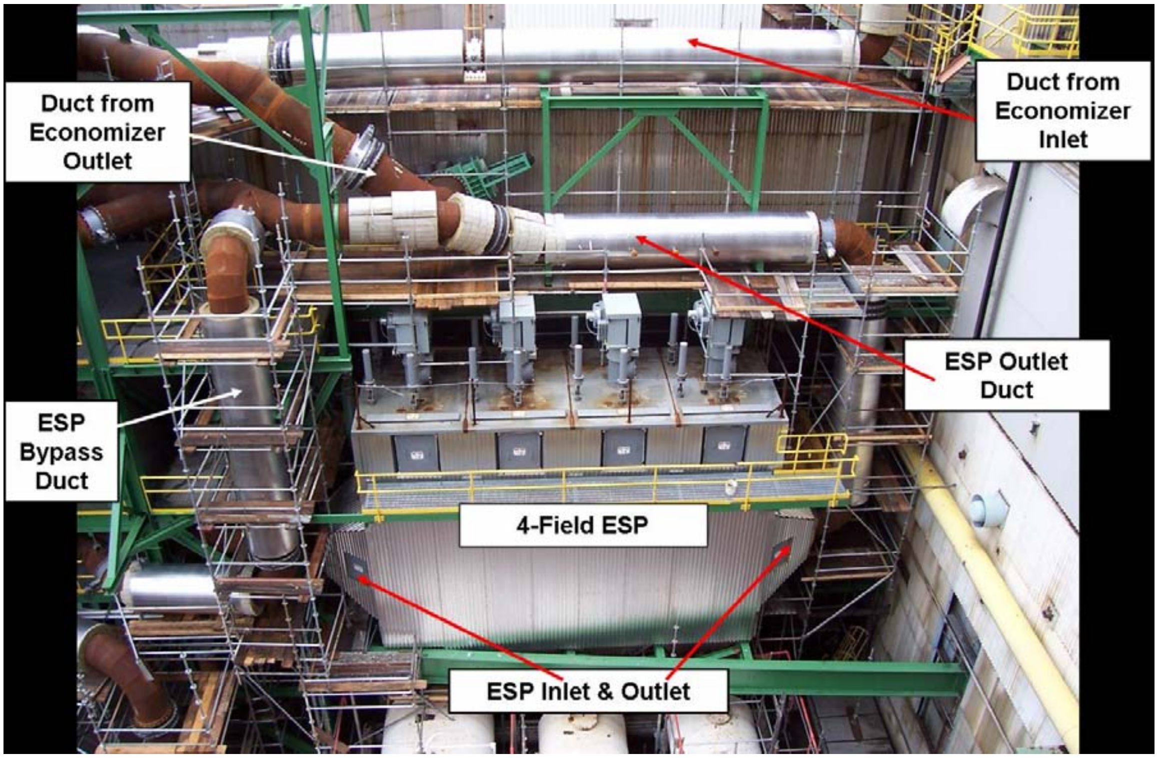
If the project is successful, the technology developed will provide coal-fired utilities a method of producing water from flue gas that would otherwise be evaporated from the stack. This water would then be available for power plant operations such as cooling tower or flue gas desulfurization make-up water. An added benefit of cooling the flue gas to remove water is the potential to remove vapor phase sulfur trioxide/sulfuric acid (SO_3/H_2SO_4) and to utilize the rejected sensible and latent heat in the boiler or turbine cycle resulting in increased boiler efficiency. This project will be completed in June of 2008.

Reduction of Water Use in Wet FGD Systems – URS Group, Inc.

The project team will attempt to demonstrate the use of regenerative heat exchange to reduce flue gas temperature and minimize evaporative water consumption in wet FGD systems on coal-fired boilers. Most water consumption in coal-fired power plants occurs due to evaporative water losses. For example, a 500-megawatt (MW) power plant will loose approximately 5,000 – 6,000 gallons per minute (gpm) to evaporation and 500 gpm in the wet FGD system. Installation of regenerative reheat on FGD systems is expected to reduce water consumption to one half of water consumption using conventional FGD technology.

Researchers will conduct pilot-scale tests of regenerative heat exchange to determine the reduction in FGD water consumption that can be achieved and assess the resulting impact on air pollution control (APC) systems. The project team consists of URS Group, Inc. as the prime contractor, the Electric Power Research Institute (EPRI), Southern Company, Tennessee Valley Authority (TVA), and Mitsubishi Heavy Industries (MHI). The team will conduct an analysis of the improvement in the performance of the APC systems and the resulting reduction in capital and operating costs. The tests are intended to determine the impact of operation at cooler flue gas temperatures on FGD water consumption, electrostatic precipitator (ESP) particulate removal (see Figure 9), SO_3 removal, and Hg removal. Additionally, tests will be conducted to assess the potential negative impact of excessive corrosion rates in the regenerative heat exchanger.

Figure 9. Electrostatic Precipitator



If successful, this project will demonstrate the ability to use regenerative heat exchange to cut evaporative consumption in half by cooling the flue gas entering the FGD system. Additionally, the project will demonstrate possible benefits due to the flue gas being cooled upstream of the ESP, such as: control of SO_3 emissions by condensation on fly ash; improved particulate control by the ESP due to reduced gas volume and lower ash resistivity; avoided costs associated with flue gas reheat or wet stacks; and potential additional reduction in native Hg removal in the ESP due to operation at a cooler flue gas temperature. This project will be completed in August of 2008.

Advanced Cooling Technology

This component of the program is focused on research to develop technologies that improve performance and reduce costs associated with wet cooling, dry cooling, and hybrid cooling technologies. In addition, the research area covers innovative methods to control bio-fouling of cooling water intake structures as well as advances in intake structure systems.

Development of an Impaired Water Cooling System – EPRI

In conjunction with the produced water feasibility study conducted at the San Juan Generating Station, 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. 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 will consist 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 will be finalized in 2006.

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

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.[21] Figure 10 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 are conducting a three-year study to evaluate a particular strain of a naturally occurring bacteria, *Pseudomonas fluorescens,* that has shown to be selectively lethal to zebra mussels but benign to non-target organisms. Testing is being 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.

Figure 10. Zebra Mussels Inside a Pipe

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 to define key nutrients required to produce more toxin per bacterial cell are underway. This is a long-term experiment and an accurate measurement of this increase in cell toxicity will not be available until design of the entire chemically-defined culture medium and culturing protocol is finalized. This project will be finalized in 2006.

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

Ceramic Composites, Inc. has 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. Foam fins could significantly decrease energy consumption while enhancing water conservation within the power industry. Researchers have evaluated a variety of fin width to channel width ratios. Additionally, researchers have 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 is being conducted including: optimization of structural enhancement, optimization of bonding, optimization of machining, and economic evaluation. If successful, this project will allow air cooled condensers to be smaller and more efficient at heat rejection. This project will be complete in July 2006.

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

SPX Cooling Systems, formerly Marley Cooling Technologies, Inc., will evaluate the performance of its patented Air2Air™ condensing technology in cooling tower applications at coal-fired electric power plants. Researchers will quantify Air2Air™ water conservation capabilities with results segmented by season and time of day. They will determine the pressure drop and energy use during operation. Additionally, SPX

Cooling Systems will develop a collection method for the recovered water, analyze water quality, and identify potential on-site processes capable of utilizing the recovered water.

Research conducted will also examine freezing condition operation and plume abatement. Cold weather applications concerns will be examined by determining if the Air2Air™ modules freeze to any extent and if freezing causes any structural damage to modules or supports. A wet/dry air mixing system will be developed for plume abatement, and the dissipation of the plume discharged from the cooling tower fan will be studied.

If successful, the project could demonstrate significant water savings due to recovery using the condensing technology. SPX Cooling Systems lists a design annual average water recovery rate of 20% for their Air2Air™ condenser and estimates that the cooling water savings in condensed evaporate for the U.S. to be 1.56 billion gallons per day if all power and industrial towers were outfitted with the condensing technology. This project will be completed in December of 2008.

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

Drexel University will be conducting research with the overall objective of developing technologies to reduce freshwater consumption at coal-fired power plants. The goal of this research is to develop 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. The filter will be a self-cleaning metal membrane, using pulsed electric fields to dislodge particles on the filter.

The researchers will develop a filtration system and an integrated physical water treatment method. The filtration method will utilize 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 will then be removed by reject flow. Development of the system will be followed with validation testing. Drexel University will utilize a flow loop consisting of: a cooling tower; a rectangular heat transfer test section with a window for visualization of crystal growth; electric heater for hot water; main circulating loop; and side-stream loop.

Potential 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). Additional environmental benefits are expected due to the reduction in the use of chemicals for scaling and bio-fouling prevention. This project will be completed in 2009.

Advanced Water Treatment and Detection Technology

Future controls on the emission of mercury and possibly other trace elements have raised concerns about the ultimate fate of these contaminants once they are removed from the flue gas. Preventing these “air pollutants” from being transferred to surface or ground waters will be critical. In addition, ammonia from selective catalytic reduction systems used to control nitrogen oxide emissions can appear in a power plant's wastewater streams. Research is needed for advanced technologies to detect and remove mercury, arsenic, selenium and other components from the aqueous streams of coal-based power plants should effluent standards be tightened in the future.

Fate of As, Se, and Hg in a Passive Integrated System for Treatment of Fossil Plant Waste Water – Tennessee Valley Authority (TVA) & EPRI

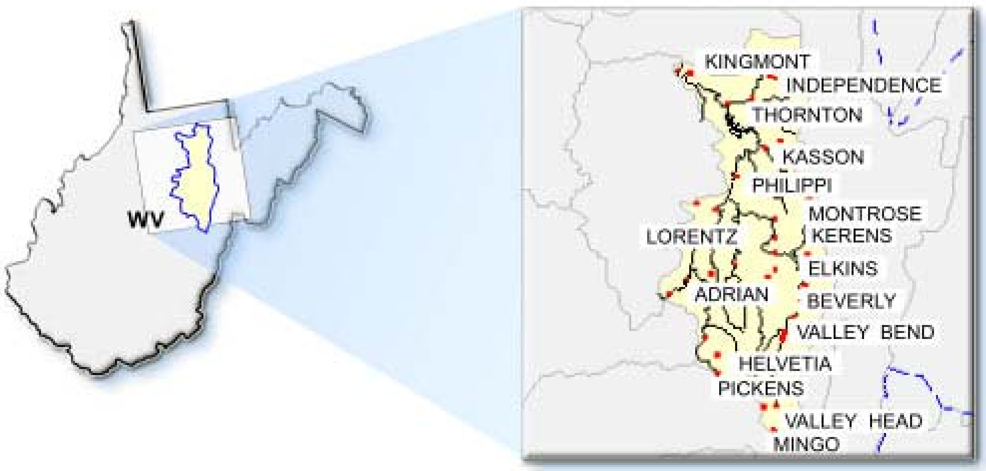
Mercury, arsenic, and selenium are pollutants often present at trace-levels in power plant flue gas and wastewater. In addition, ammonia "slip" from selective catalytic reduction systems (SCRs) for reduction of NOx emissions can appear in wastewater streams such as FGD effluents and ash sluice water.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

Objectives of this project include 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 componenet of the treatment system on the speciation of As, Se, and Hg. This project will be completed in 2006.

Demonstrating a Market-Based Approach to the Reclamation of Mined Lands in West Virginia – EPRI

EPRI demonstrated a market-based approach to abandoned mine land (AML) reclamation by creating marketable water quality and carbon emission credits. 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 carbon dioxide (CO_2). The watershed where research was conducted is displayed in Figure 11. 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 11. Location of the Tygart Valley Watershed in West Virginia



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

The University of Southern California studied the utilization of novel anionic clay sorbents for treating and reusing power plant effluents.[22] Concerns exist about heavy metals, such as arsenic (As) and selenium (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 blow-down 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 arsenic and selenium.

During the study, model blow-down 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

This research evaluated specifically designed pilot-scale constructed wetland treatment systems for treatment of targeted constituents in coal-fired power plant FGD wastewater. The overall objective of this project was to decrease targeted constituents, mercury, selenium, and arsenic concentrations, in FGD wastewater to achieve discharge limitations established by NPDES and 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).

Integration with Other Coal Research Programs

In addition to the research being conducted under the IEP program, NETL is developing an advanced power system known as Integrated Gasification Combined Cycle (IGCC) that can reduce overall thermoelectric power plant water withdrawals and consumption. IGCC is a technology that efficiently converts coal to a synthesis gas that may be used in a gas turbine for power production. Roughly two-thirds of power generated in an IGCC is in the gas turbine. The waste heat from the gas turbine is used to produce steam in a heat recovery steam generator that is used to power a steam turbine which produces the remaining one-third of power. Pulverized coal (PC) plants, on the other hand, generate all power with the steam turbine. Since the gas turbine doesn't require cooling water, IGCC plants require appreciably less cooling water on a gallons/kWh output basis compared to a similar capacity PC plant.

SUMMARY

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

In response to this challenge to national energy sustainability and security, DOE's Office of Fossil Energy/NETL is carrying out an R&D program focused on the development and application of advanced technologies and concepts to better manage how power plants use and impact freshwater. The goal of this effort is to provide the technology to allow power plant's to reduce freshwater withdrawals and consumption by at least 5-10% by 2015. Research is currently underway to assess and develop non-traditional sources of cooling and process water, advanced cooling water technologies, innovative water reuse and recovery technologies, and advanced wastewater treatment and detection 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.

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DISCLAIMER

Reference in this article to any specific commercial product or service is to facilitate understanding and does not imply endorsement by the U.S. Department of Energy.

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