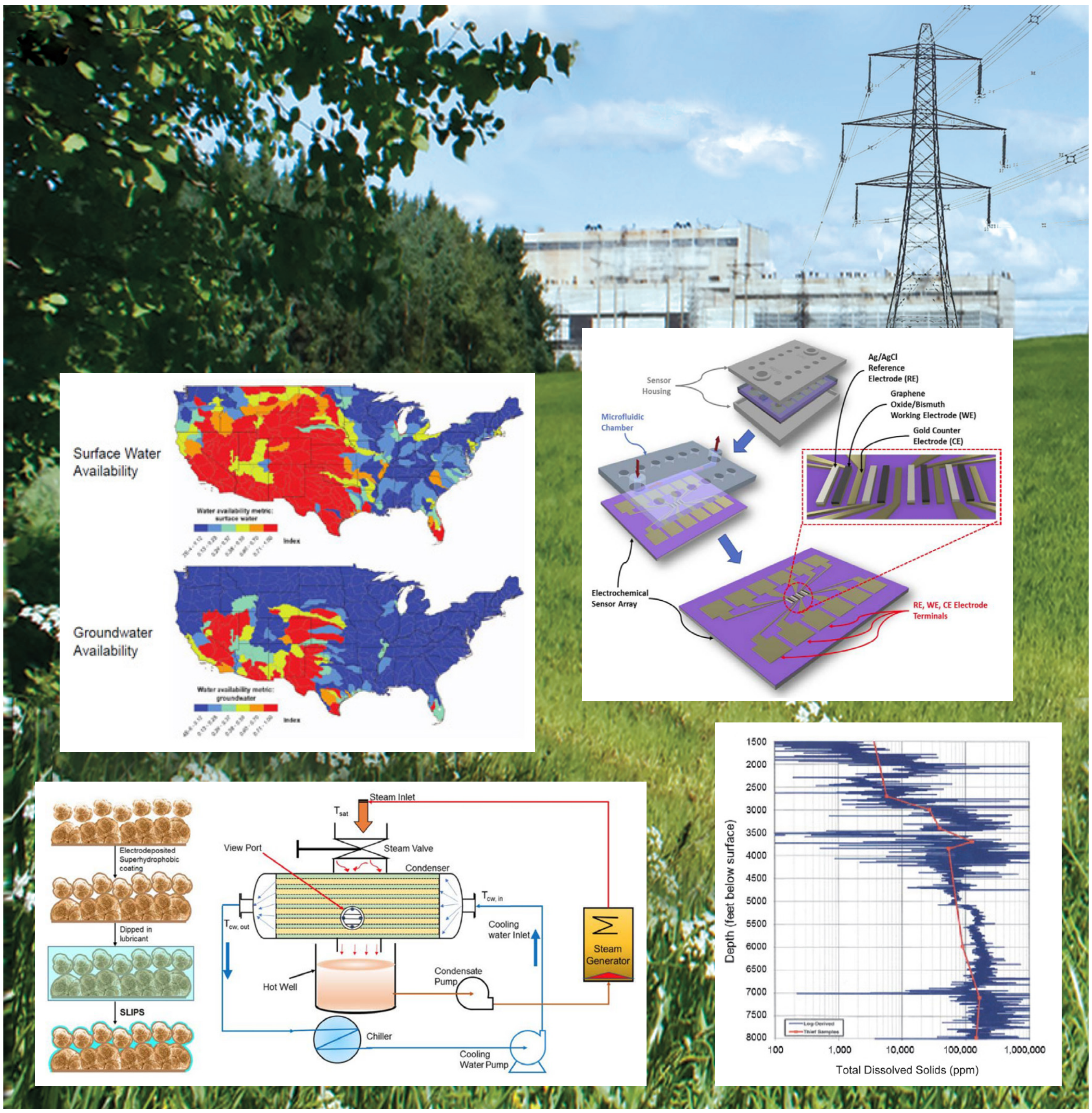
NATIONAL ENERGY TECHNOLOGY LABORATORY

CROSSCUTTING RESEARCH PROGRAM
WATER MANAGEMENT RESEARCH AND DEVELOPMENT PROJECT PORTFOLIO



April 2018

U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY

DISCLAIMER

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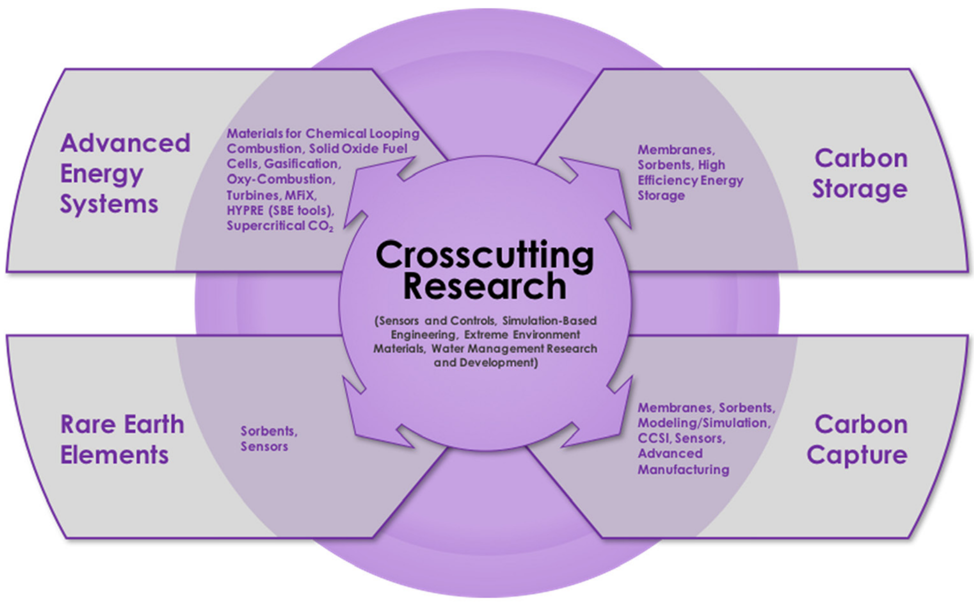
INTRODUCTION

The Crosscutting Research Program develops a range of innovative and enabling technologies that are key to improving existing power systems and essential for accelerating the development of a new generation of highly efficient, environmentally benign fossil fuel-based power systems. The mission space is focused on bridging the gap between fundamental and applied research and development (R&D) efforts. Technologies that successfully bridge this gap are intended to offer viable step-change improvements in power system efficiency, reliability, costs, and environmental impacts.

The research fundamental to the Crosscutting Research Program overlaps and benefits other Office of Fossil Energy (FE) program areas—rare earth elements, carbon capture, carbon storage, and advanced energy systems—as shown in the figure below.



Crosscutting Research technology overlaps with other Fossil Energy Program Areas.

The Crosscutting Research Program executes R&D efforts by partnering and collaborating with research institutions and the power generation industry throughout the United States and in select international locations. The Crosscutting Research Program also sponsors one of the longest running and most important university training and research programs to reinforce the research-based education of students at U.S. universities and colleges with emphasis on fossil energy science. The major objective for this program is to produce tools, techniques, and technologies that map to the Clean Coal Research Program efforts.

The Crosscutting Research Program is comprised of three focus areas: Coal Utilization Sciences, Plant Optimization Technologies, and University Training and Research. A description of each area follows.

Coal Utilization Sciences: The Coal Utilization Sciences technology area research effort is focused on modeling and simulation technologies that lead to a suite of products capable of designing and simulating the operation of next-generation, near-zero-emissions power systems such as gasification and oxy-combustion. Models can also solve current plant operational and lifetime issues. These products are based on validated models and highly detailed representations of equipment and processes.

Plant Optimization Technologies: The Plant Optimization Technologies technology area exists to improve availability, efficiency and environmental performance of coal-based fossil energy power generation plants. Research is focused on sensors and control systems, materials, and water management as the basis for successful implementation of advanced power generation systems in the harsh coal-fired environment. This area also explores novel concepts such as direct power extraction and the application of additive manufacturing towards constructing complex components (e.g., turbine blades with embedded sensing capabilities).

University Training and Research: The University Training and Research (UTR) program awards research-based educational grants to U.S. universities and colleges in areas that benefit the FE and the Crosscutting Research Program. UTR is the umbrella program under which the University Coal Research (UCR) and Historically Black Colleges and Universities (HBCU) and Other Minority Institutions (OMI) initiatives operate. These grant programs address the scientific and technical issues key to achieving Fossil Energy's goals and build our nation's capabilities in energy science and engineering by providing hands-on research experience to future generations of scientists and engineers. The program also coordinates with and seeks opportunities to partner with State and Tribal governments and engage industry, universities, and non-governmental organizations (NGOs) on the responsible use of fossil fuels nationally and internationally.

In addition to the Crosscutting Research Program listed above, the National Energy Technology Laboratory (NETL) uses its participation in the U.S. Department of Energy's (DOE) Office of Science **Small Business Innovation Research (SBIR) Program** to leverage funding, enhance the research portfolio, and, most importantly, facilitate a pathway to commercialization. SBIR is a highly competitive program that encourages small businesses to explore technological potential and provides the incentive to profit from commercialization. By including qualified small businesses in the nation's R&D arena, high-tech innovation is stimulated and the United States gains entrepreneurial spirit to meet specific research and development needs. SBIR targets the entrepreneurial sector because that is where most innovation and innovators thrive. By reserving a specific percentage of Federal R&D funds for small business, SBIR protects small businesses and enables competition on the same level as larger businesses. SBIR funds the critical startup and development stages and encourages the commercialization of the technology, product, or service which, in turn, stimulates the U.S. economy. Since its inception in 1982 as part of the Small Business Innovation Development Act, SBIR has helped thousands of small businesses compete for Federal research and development awards. These contributions have enhanced the nation's defense, protected the environment, advanced health care, and improved our ability to manage information and manipulate data.

The Crosscutting Research Program fosters the development of innovative power systems by conducting research in these key technology areas:

Sensors and Controls: The basis for this research area is to make available new classes of sensors and measurement tools that manage complexity; permit low cost, robust monitoring; and enable real-time optimization of fully integrated, highly efficient power-generation systems. Sensor development focuses on measurements to be made in high temperature, high pressure, and/or corrosive environments of a power system or underground injection system. Harsh environment sensing concepts and approaches focus on low cost, dense distribution of sensors; exploration of sensor networking using passive and active wireless communication; and thermoelectric and vibration energy harvesting approaches. Advanced manufacturing techniques focus on how to lower cost and improve fabrication of sensors. Controls research centers on self-organizing information networks and distributed intelligence for process control and decision making.

High Performance Materials: Materials development under the Crosscutting Research Program focuses on structural materials that will lower the cost and improve the performance of fossil-based power-generation systems and on functional materials, which are designed to perform specified non-structural tasks (e.g., shape memory materials or barrier coatings). Computational tools in predictive performance, failure mechanisms, and molecular design of materials are also being developed to support highly-focused efforts in materials development and reduce the time and cost to develop new materials. Advanced manufacturing development is represented under High Performance Materials in two capacities: first, the need for advancements in feedstocks such as metal powders for superalloys and second, as a set of methods for producing high-performance materials.

Simulation-Based Engineering: This key technology area comprises the expertise and capability to computationally represent the full range of energy science from reactive and multiphase flows up to a full-scale virtual and interactive power plant. Science-based models of the physical phenomena occurring in fossil fuel conversion processes and development of multiscale, multi-physics simulation capabilities are just some of the tools and capabilities in Simulation-Based Engineering. This key technology area enables the development of innovative, advanced energy systems by developing and utilizing advanced process systems, engineering tools and approaches, and the transformation of computationally intensive models into reduced order, fast, user-enabled models for the purposes of study, development, and validation. These tools will be used to optimize data handling and exploit information technology in the design of advanced energy systems with carbon capture.

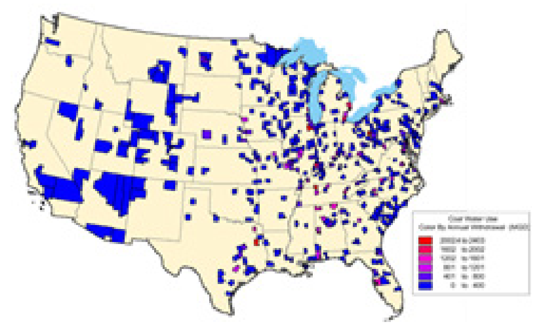
Water Management Research and Development: Water research encompasses the need to reduce the amount of freshwater used by power plants and to minimize any potential impacts of plant operations on water quality. Research in effluent treatment and water quality sensing, field testing of technologies and processes for treating water produced by injection of carbon dioxide into deep saline aquifers, and exploration of water-limited cooling and innovative multi-stage filtration technologies are being conducted. Data modeling and analysis is being employed to examine existing water availability data on a regional basis. The vision for this program area is to develop 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. To accomplish this, Crosscutting Research is needed to lead a critical national effort directed at removing barriers to sustainable, efficient water and energy use, developing technology solutions, and enhancing our understanding of the intimate relationship between energy and water resources.

WATER MANAGEMENT RESEARCH AND DEVELOPMENT

This Project Portfolio report showcases 23 Water Management Research and Development projects within the Crosscutting Research Program. Each project page clearly describes the technology, project goals, and anticipated overall benefits.

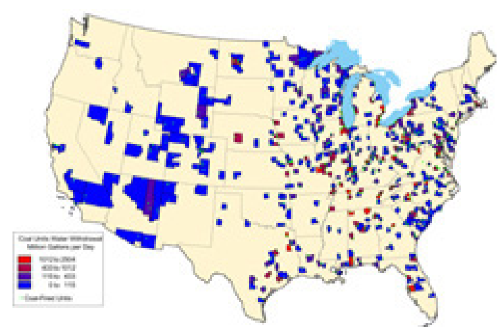
Water is a vital resource that is inextricably linked to our quality of life. The role water plays in generating power is well documented and national efforts are underway to minimize water demands.

In concert with the Energy-Water Nexus initiative, the Water Management Research and Development technology area focuses on reducing water use and consumption for thermoelectric power generation. Thermoelectric power generation accounts for over 40 percent of freshwater withdrawals (143 billion gallons of water per day) and over 3 percent of freshwater consumption (4 billion gallons per day) in the United States. Thermoelectric power plant water consumption is slated to increase from 3 percent (1995 USGS data) to as high as 10 percent given the expansion of closed loop cooling and cooling towers. To further exacerbate the problem, projected water consumption for the power generation sector will dramatically increase with the implementation of carbon capture technologies. As the cost associated with water consumption increases, so too will the cost of water treatment, recovery, and reuse.



U.S. Water Withdrawal
Coal Fired Units – County Level.

The Crosscutting Research Program has supported water research over the past decade. The current goal is to identify projects which will develop a range of technologies to optimize and/or reduce freshwater use for energy processes through improved waste heat recovery, alternative heat transfer technologies, and new sources of water (i.e., utilizing treated wastewater). Acquisition of these research projects is based on a comprehensive, multipronged R&D approach with a portfolio of technologies on multiple paths to enhance the probability of success of research efforts that are operating at the boundaries of current scientific understanding. The R&D covers a wide range, integrating advances and lessons learned from fundamental research, technology development, and large-scale testing. The success of this effort will enable cost-effective implementation of technologies throughout the power generation sector. These projects are being developed on three- to five-year timelines.



U.S. Water Consumption
Coal Fired Units – County Level.

The Water Management Research and Development project portfolio is categorized into three core technologies:

Process Efficiency and Heat Utilization

Greater process efficiency and heat utilization will be needed to reduce water utilization as improvements in heat transfer technology and better thermal integration of power plant systems (particularly new plants that include carbon capture technologies) are made.

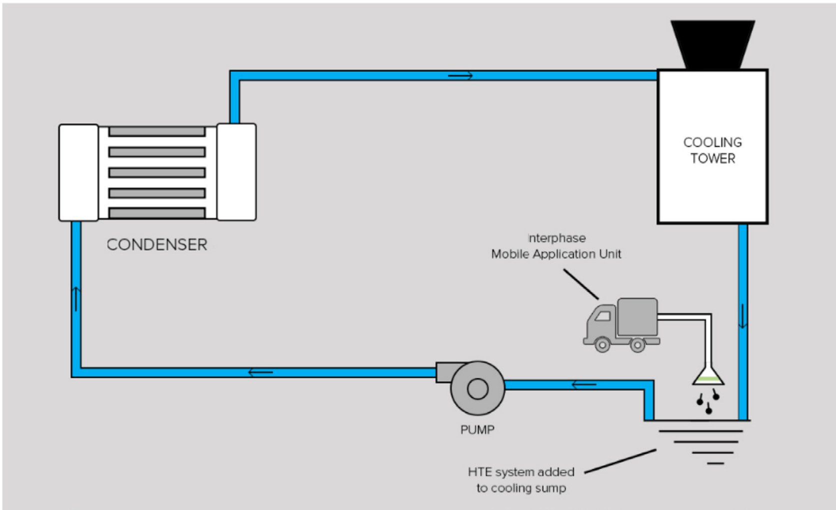
Water Treatment and Reuse

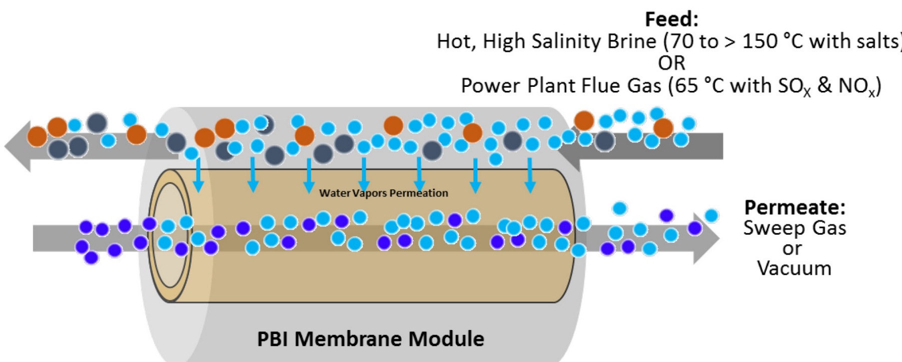
Research on water treatment and reuse is being performed to develop advanced technologies to reuse power plant cooling water and associated waste heat and to investigate methods to recover water from power plant flue gas. Considering the quantity of water withdrawn and consumed by power plants, any recovery or reuse of this water can significantly reduce the plant's water requirements. Water treatment research is focused on power plant effluent streams and briny water containing high total dissolved solids (TDS) associated with the geologic sequestration of carbon dioxide.

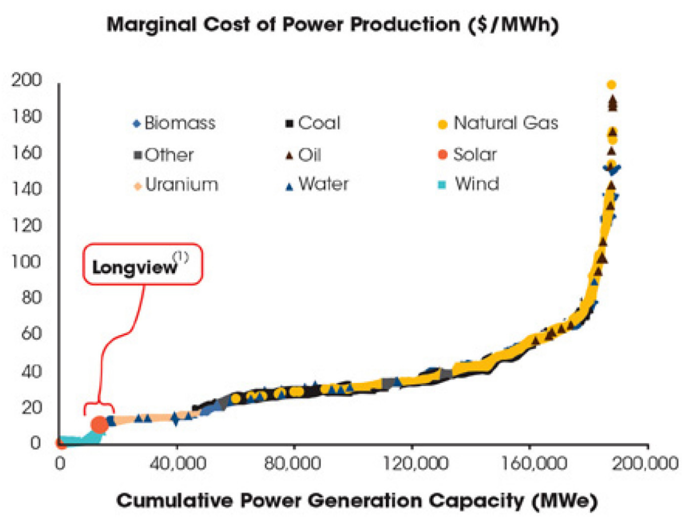
Data Modeling and Analysis

Data modeling and analysis is being undertaken to improve the quality and amount of data collected, conduct comprehensive modeling efforts of complex systems, and provide crosscutting analyses to help decisionmakers and support policy development. Stakeholder decision making must target qualitative and quantitative scenarios, probabilistic approaches, insights into system shocks and extremes, and improved uncertainty characterization.

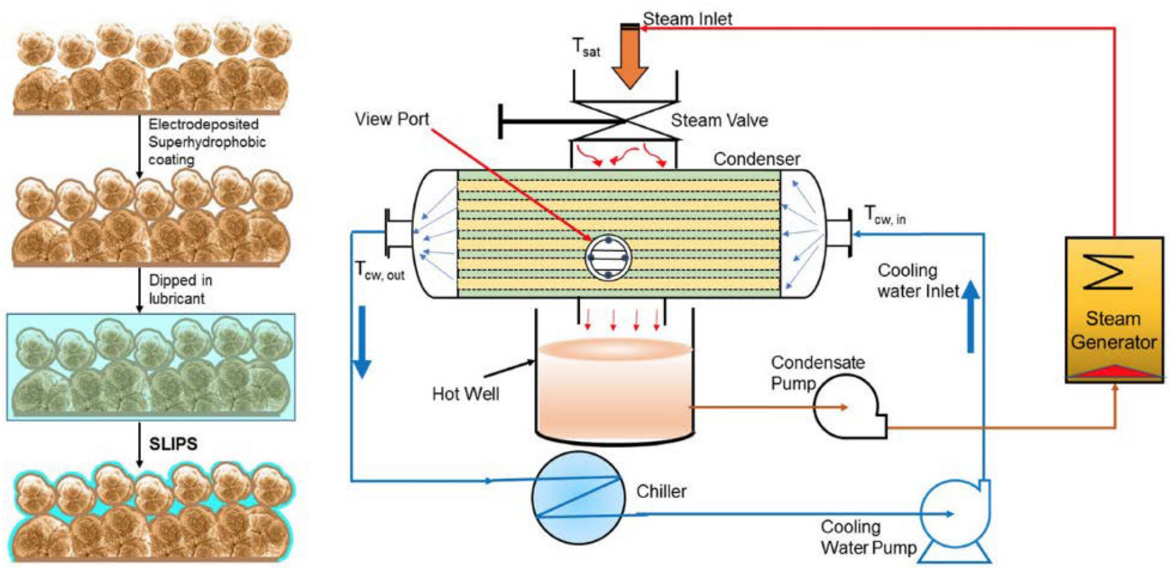
PROJECTS BY RESEARCH AREA







PROCESS EFFICIENCY AND HEAT UTILIZATION



Application of Heat Transfer Enhancement (HTE) System for Improved Efficiency of Power Plant Condensers

Performer	Interphase Materials, Inc.
Award Number	FE0031561
Project Duration	02/01/2018 – 01/31/2020
Total Project Value	$ 961,915
Technology Area	Plant Optimization Technologies

NETL is partnering with Interphase Materials, Inc. to determine the condenser efficiency improvements as well as the reduction of continuous-feed water treatment that coal-fired plants could realize by utilizing Interphase's heat transfer enhancement technology (HTE system). Previous lab-scale work has demonstrated that the HTE system can inhibit biofouling, microbiologically induced corrosion, and scale build up as well as improve the baseline heat transfer efficiency of cooling systems in laboratory scale testing. By applying the HTE system first to field test rigs at the Longview site, and subsequently to the condenser at the Longview plant, Interphase and Longview will collect field data on the HTE system's potential to increase heat transfer efficiency in the condenser cooling systems of coal-fired power plants.

If the anti-biofouling and heat transfer enhancement properties of the HTE system are shown to be effective on in-service power plant condensers, there is an opportunity to lower the heat rate of the existing U.S. coal power generating fleet. Fouling prevention could result in a reduction of water treatment chemical volumes, which would help power plants meet requirements of the Environmental Protection Agency Clean Water Act. Reducing fouling will also reduce cleaning frequency and maintenance costs, increase hardware lifecycles, and help power plants maintain efficient long-term operation.

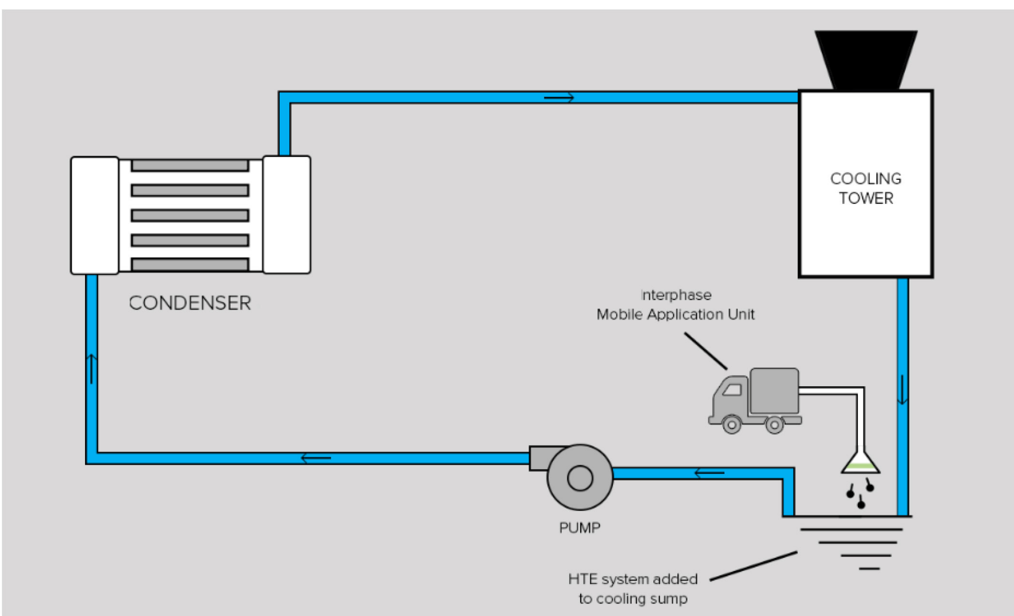


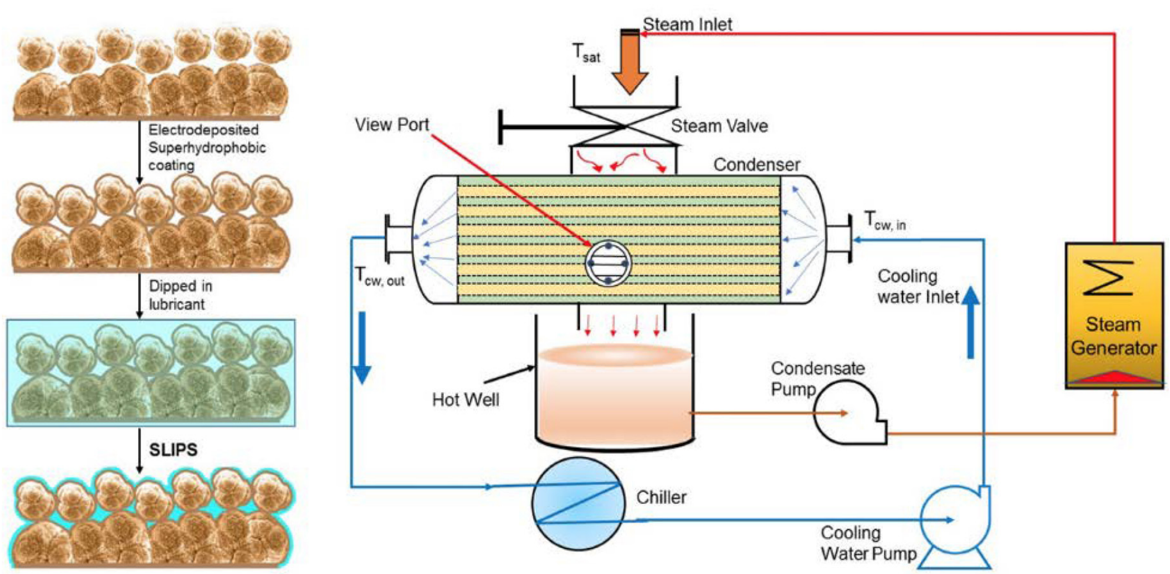
Diagram of HTE application to Longview cooling system.

Novel Patterned Surfaces for Improved Condenser Performance in Power Plants

Performer	Virginia Polytechnic Institute and State University
Award Number	FE0031556
Project Duration	12/15/2017 – 12/14/2020
Total Project Value	$ 938,470
Technology Area	Plant Optimization Technologies

NETL is partnering with Virginia Polytechnic Institute and State University to improve thermoelectric power plant performance through engineered superhydrophobic/slippery liquid infused porous surfaces (SLIPS) for condenser tube designs fabricated by a patented two-step electrodeposition technique. The electrodeposition process is a widely-used industrial process that is applicable to a variety of shapes, materials, and sizes. The project will demonstrate and characterize a variety of SLIPS coatings based on copper, nickel, copper/nickel, zinc, tungstite, and other materials on commonly used condenser tube surfaces—namely, copper, copper/nickel, stainless steel, and titanium alloys—through a facile and cost-effective electrodeposition process. The goal is to demonstrate overall condenser heat exchanger effectiveness that is at least 50 percent higher than that of current systems while reducing condenser pressure and improving power plant efficiency.

The research conducted will broaden both fundamental and applied scientific knowledge in the field of transport phenomena using SLIPS surfaces and the robust, scalable fabrication process of the structures. Meeting the project goal could lead to novel, industrially scalable, and low-cost fabrication of durable SLIPS coatings that will lead to improved plant efficiency and performance, and thereby to reduced carbon dioxide emissions.



Proposed SLIPS coating to enhance heat transfer and reduce drag on condenser surfaces.

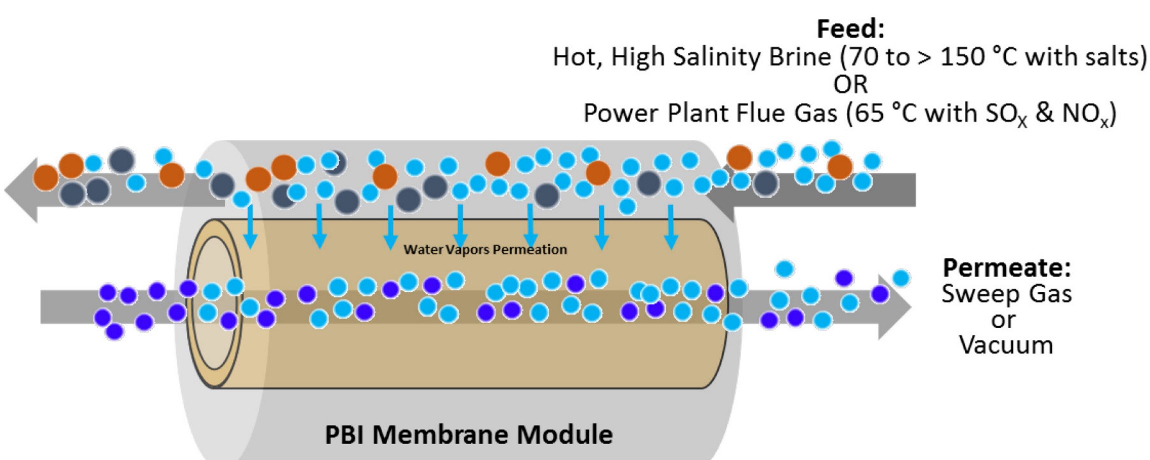
WATER TREATMENT AND REUSE

Water Treatment and Water-Vapor Recovery Using Advanced Thermally Robust Membranes Power Production

Performer	Los Alamos National Laboratory
Award Number	FWP-FE-844-17-FY17
Project Duration	09/25/2017 – 09/30/2018
Total Project Value	$ 400,000
Technology Area	Plant Optimization Technologies

Growing water and energy needs mandate implementation of technologies promoting water recovery and/or use of alternate water resources to provide clean water for power plant operations while reducing their reliance on fresh water. Water vapor capture from flue gas and non-conventional water resource utilization including extracted high salinity brines treatment and use provides a path-forward to meet the water needs of power production industry. The focus of this effort is to develop a thermally robust membrane separation technology for use in challenging corrosive flue gas and high-salinity brine environments for clean water production. Efficient process integration opportunities provided by such a thermo-chemically robust membrane technology would enable increased power production opportunities by co-utilization of heat/water derived from hot power plant waste streams and high salinity extracted waters.

Flue Gas Dehydration. A major source of water loss in power plants is due to release of water vapor-saturated flue gases. Besides water vapor, significant power plant heat is lost due to flue gas temperature requirements, as maintaining gas temperatures above the dew point is necessary to mitigate sulfur oxides (SO_X) and nitrogen oxides (NO_X) condensation with water, which causes stack corrosion issues. Flue gas water vapor recovery and latent heat utilization for heating combustion air or boiler water can significantly benefit power plants including improving power production efficiency. Membrane-based separation processes are advantageous for flue gas dehydration as membranes provide opportunities for continuous operation with no additional chemical substances required. Advanced membrane materials having higher rejection for nitrogen, carbon dioxide (CO_2), SO_X, and NO_X over water vapor are desired to improve the quality of produced water from flue gas.



Conceptual membrane process for high salinity brine treatment or flue gas dehydration leveraging highly selective water vapor permeation in PBI materials.

High Salinity Brine Treatment. Managing and deriving value from the large quantities of extracted waters generated by CO_2 storage operations poses major technical, economic, and environmental challenges. Treatment of the waters extracted from these sources is a significant challenge owing to their high concentration of total dissolved solids (TDS) and the potential presence of hydrocarbons and metals. These water resources have TDS concentrations ranging from that of seawater (greater than 40,000 milligrams per liter [mg/L]) to concentrations in excess of 300,000 mg/L, with the common range for reuse/concentration targeted here ranging from 40,000 to 150,000 mg/L. In addition, extracted hot brine temperatures can range from 70 to greater than 150 degrees Celsius (°C) depending on the geological formation. The temperatures and TDS characteristics of the extracted waters from these sources span broad ranges that lead to significantly more challenging separations problems than those encountered in non-extracted water desalination applications (e.g., sea and brackish waters). Whereas reverse osmosis is currently the most energy-efficient technology for desalination, it is inherently limited to lower-salinity brines such as those encountered in sea water treatment. Current commercial technologies for treating high-salinity brine streams for reuse applications (e.g., evaporative crystallization and mechanical vapor compression) are considered too costly and energy-inefficient to support their use in this application. Therefore, novel energy-efficient separation methods for treating high-salinity extracted water are of great interest.

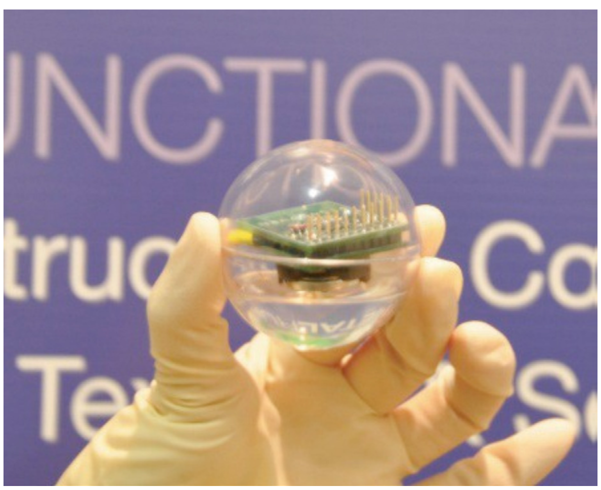
Polybenzimidazole (PBI)-based membranes are excellent candidates for these extreme environment water separations owing to their high water vapor transport characteristics and demonstrated thermo-chemical durability. Los Alamos National Laboratory has developed a suite of PBI materials and membrane platforms that have proven exceptional for harsh environment elevated temperature separations, e.g. CO_2 capture in pre-combustion syngas environments. The focus of this effort is to gather PBI membrane performance data and demonstrate durability at process-relevant operating conditions for flue gas dehydration (65 °C in presence of SO_X and NO_X) and high salinity extracted water treatment (50,000 to 300,000 mg/L TDS and up to 200 °C). This data is required to understand the PBI membrane separation technology utilization potential for power production applications.

Wireless Networked Sensors in Water for Heavy Metal Detection

Performer	NanoSonic, Inc.
Award Number	SC0013811
Project Duration	06/08/2015 – 07/31/2018
Total Project Value	$ 1,150,000
Technology Area	Plant Optimization Technologies

NanoSonic, Inc. will develop wireless sensors for use in analyzing heavy metal chemistry for power generation facilities and, more broadly, for commercial use. The company will develop wireless networked sensors using conformal nanomembrane-based chemical field effect transistors (ChemFETs) to detect heavy metals in water. NanoSonic will fabricate prototype nanomembrane ChemFET sensor elements, design and synthesize chemical-specific ionophores for selectively detecting targeted heavy metal elements, and demonstrate the performance of prototype sensor devices. NanoSonic will work with a local environmental monitoring company to produce a wireless sensor network for in situ environmental monitoring.

Project success will enable efficient monitoring of heavy metals in water for environmental surveillance, location of pollution sources using analysis from concentration gradients, and detection and mapping of chemical concentrations that are potentially harmful to people and/or destructive to agriculture.



Wireless sensor node.

Wireless sensor probe.

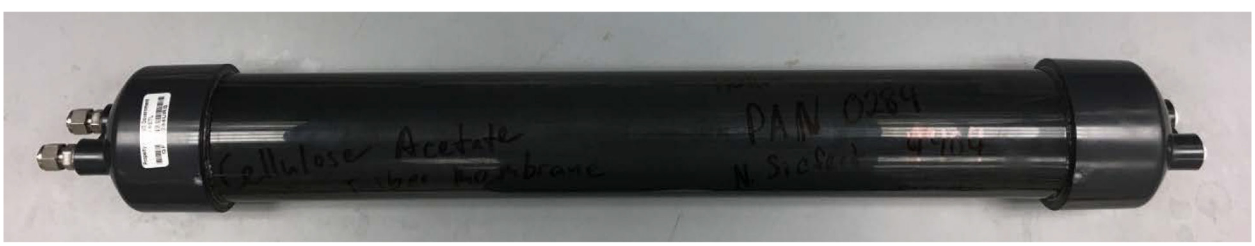
Water Management for Power Systems: Concentrating Wastewater Effluent Streams – Task 4

Performer	National Energy Technology Laboratory
Award Number	FY18 FWP 1022428: Task 4
Project Duration	04/01/2018 – 03/31/2019
Total Project Value	$ 278,000
Technology Area	Plant Optimization Technologies

The objective of this research is to experimentally demonstrate and numerically simulate a novel membrane process for concentrating effluent streams. Effluent waste streams from coal power plants contain heavy metal contaminants and hence cannot be discharged to local waterways and the cost to treat these effluent streams is currently very expensive. While there are cost-effective treatment processes for low salinity water, such as reserve osmosis, this process ends up generating a medium salinity brine that must be further concentrated. The Environmental Protection Agency estimates that the compliance costs are $480 million for the Final Rule limiting effluent waste streams at coal power plants, with estimated benefits of between $451 and $566 million. Hence, to increase net benefits, it is crucial to develop innovative technologies that can lower the cost of treating these heavy metal waste streams at coal power plants.

One option for treating these effluent streams is called zero liquid discharge (ZLD), which effectively concentrates the dissolved ionic species while separating out fresh water. Currently, ZLD is an expensive option for treating these effluent streams because of the high energy and capital cost associated with the brine concentration step in the ZLD process. As such, this task will demonstrate advanced technologies that can concentrate effluent streams to high concentrate while reducing energy consumption.

This brine concentration research has the potential to reduce capital cost and electricity consumption for treating and concentrating high salinity brines generated at coal-fired power plants by at least 50 percent compared to commercially-available, non-membrane technologies, such as mechanical vapor recompression.



Hollow fiber membranes for scale-up testing of osmotically assisted reserve osmosis process.

Water Management for Power Systems: Desalination of High Salinity Extracted Brines – Task 2

Performer	National Energy Technology Laboratory
Award Number	FY17 FWP 1022428: Task 2
Project Duration	01/01/2017 – 03/31/2018
Total Project Value	$ 238,000
Technology Area	Plant Optimization Technologies

A number of high-salt-concentration brines are extracted during carbon dioxide (CO_2) storage. The goal of this research is to concentrate brines extracted during CO_2 storage and generate fresh water for local use. This research would also be applicable and beneficial in managing effluent generated directly at coal power plants. There is a commercial application for convening extracted brines with approximately 10 percent (by weight) dissolved salt into two parts fresh water and one-part 30 percent (by weight) dissolved salt. This 30 percent (by weight) brine would be injected into a reservoir different from the one from which it was extracted, and the fresh water would be used locally or discharged safely to the environment. The goal of this project is to conduct research on membrane-based processes to convert high-salinity brine into a lower-salinity brine, such that conventional reverse osmosis (RO) membranes can be used. This project will measure water and salt flux from commercially available RO membranes under the high salinity conditions found in a multi-stage osmotically assisted reverse osmosis (OARO) process to treat high-salinity brines. The project will also build a working model of an OARO process and compare its performance to commercially available thermal technologies.

The goal of research conducted in FY16 was to develop a literature review of both commercial and state-of-the-art R&D technologies to generate fresh water from high-concentration brines produced during oil/gas development and extracted during CO_2 sequestration in saline aquifers. As part of the literature review, estimated electrical and financial costs to generate fresh water from high-concentration brines as a function of inlet and outlet salt concentration were determined. The capability to measure permeability and selectivity of membranes for high-salinity brine separation was developed at NETL. As part of the literature review, the team determined which separation technology to experimentally test in the new water-brine separation laboratory under construction at NETL.

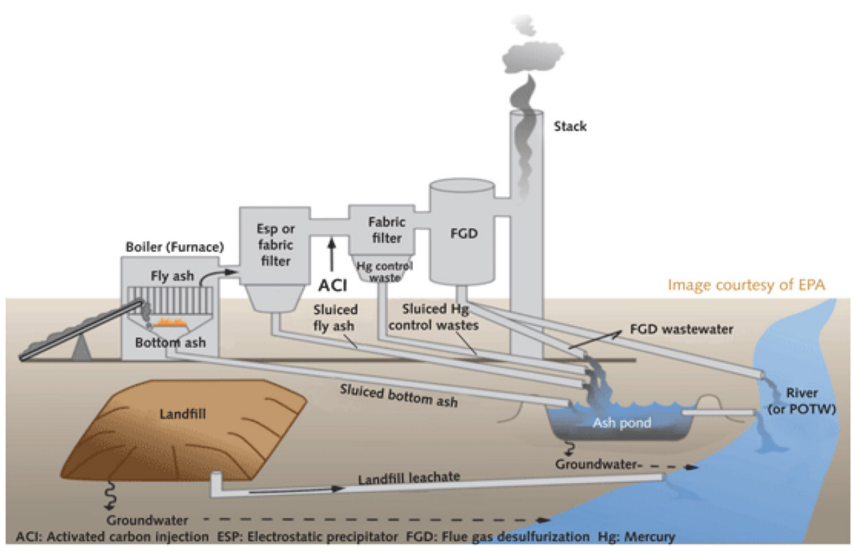
Laboratory test equipment.

Water Management for Power Systems: Guiding R&D for Treatment of Coal Power Plant Effluent Streams – Task 2

Performer	National Energy Technology Laboratory
Award Number	FY18 FWP 1022428: Task 2
Project Duration	04/01/2018 – 03/31/2019
Total Project Value	$ 820,000
Technology Area	Plant Optimization Technologies

The objective of this effort is to (1) evaluate effluent water-related issues at both existing and new coal power plants and (2) use the results obtained from techno-economic studies to help guide research in this area. Treatment of wastewater streams at coal-fired power plants is currently attracting significant inquiry and interest due to recent Environmental Protection Agency (EPA) regulations. Because discharge requirements for new and existing coal plants are different, treatment approaches of their wastewater streams will be different. This task will explore how the zero-liquid discharge (ZLD) systems required of new coal plants may change as a function of certain constituents in the coal, such as chlorine. Likewise, it is not clear if the wastewater treatment technology of choice for existing coal plants is applicable to coal plants burning low-rank coals (such as subbituminous or lignite), or how the technology will be required to perform. This task will also explore those issues as they relate to wastewater treatment systems at existing plants.

Technical information obtained from this task will identify water related research and development needs and provide management knowledge of current/future regulations and possible technologies to meet these regulations. The benefit to existing coal units will be greater knowledge of how heavy metals are divided amongst the various wastewater streams and how this information could inform the EPA's anticipated revision of the wet flue gas desulfurization wastewater portion of the effluent limitation guideline rule. In addition, the ZLD technologies that are being evaluated for new coal power plants may eventually be required for existing units, since environmental standards typically only become more stringent over time. Understanding current and future water issues related to power plants is critical to inform program direction, goals, and research.



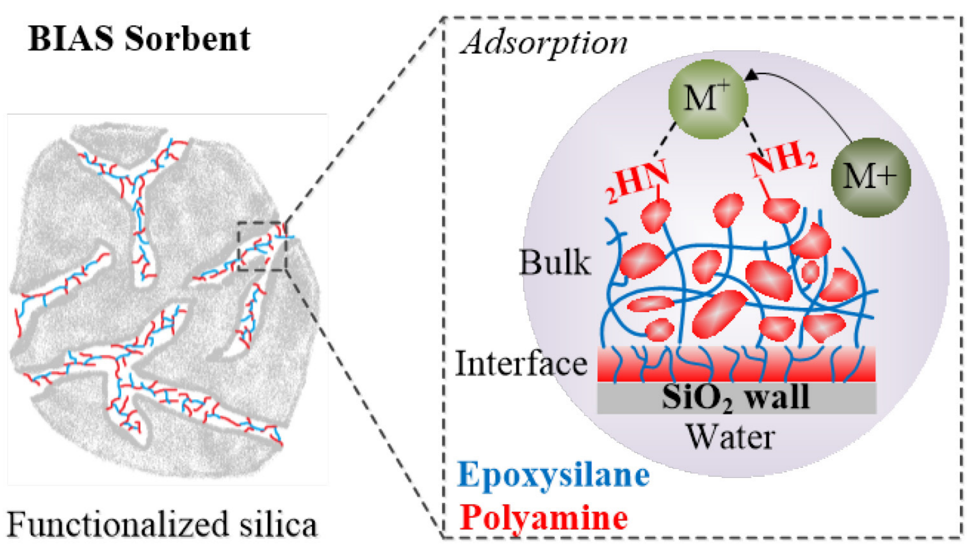
Coal-fired power plant.

Water Management for Power Systems: Selective Removal of Heavy Metals from Effluent Streams – Task 3

Performer	National Energy Technology Laboratory
Award Number	FY17/18 FWP 1022428: Task 3
Project Duration	01/01/2017 – 03/31/2019
Total Project Value	$ 1,130,000
Technology Area	Plant Optimization Technologies

The objective of this effort is to develop basic immobilized amine sorbent (BIAS) materials for the selective removal of heavy metals from industrial waste waters, with focus on those waste waters that are generated during coal combustion. Previous work on related BIAS sorbents shows that it is feasible to capture metals from complex mixtures with selectivity using this technology. Challenges with the flue gas desulfurization (FGD) system are centered upon the chemical form in which the metals persist in the FGD water, as opposed to feed sources that have been studied. NETL will expand on previous work to develop a sorbent material that can reduce both the regulated oxy-anionic heavy metals, as well as the regulated cationic metals to, at a minimum, the permissible discharge levels by using a flow-based treatment method. The effort will include fabrication of stabilized amine co-polymers on high surface area silica particles, screening for metal uptake, capacity testing, and treatment of authentic coal waste water samples. In all phases of the work, detailed characterization of the BIAS materials, the feed solutions and eluent solutions will be conducted. The target material will be designed to support waste water treatment in a flow-through application with a low pressure drop across the sorbent bed. For this task, FGD water will be used as a target matrix for evaluating sorbent performance.

The technology developed in this project has the potential to reduce the cost of treating FGD or other waste water treatments by 50 percent compared to commercially-available zero liquid discharge or chemical/biological treatment options.



New research into novel chemical treatment options.

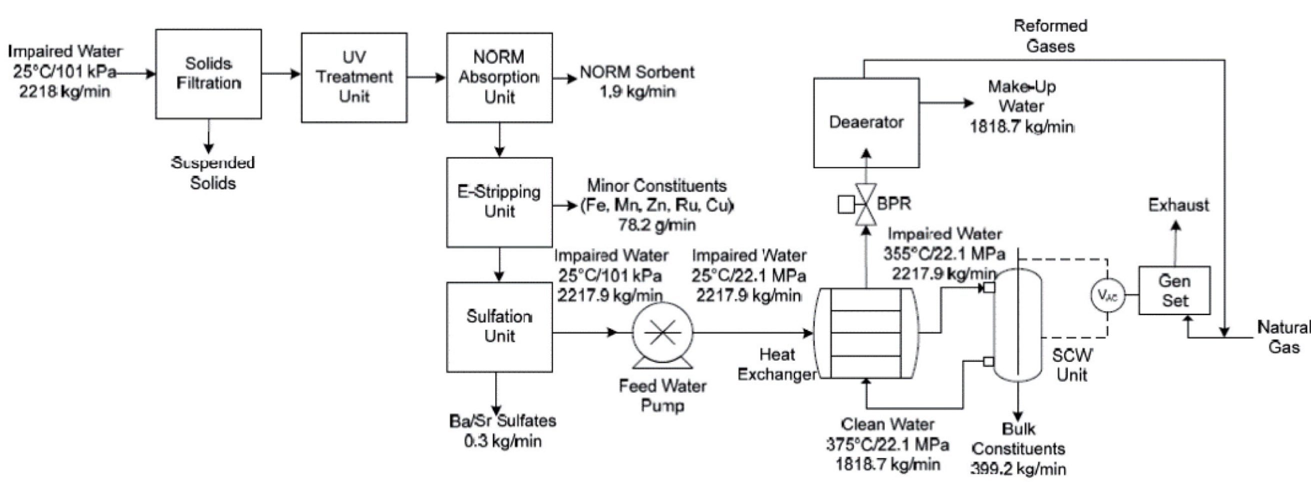
Advanced Integrated Technologies for Treatment and Reutilization of Impaired Water in Fossil Fuel-Based Power Plant Systems

Performer	Ohio University
Award Number	FE0026315
Project Duration	09/01/2015 – 08/30/2018
Total Project Value	$ 937,500
Technology Area	Plant Optimization Technologies

The objective of this project is to validate the technical/commercial promise of an advanced multi-stage process for treating and reutilizing impaired water as make-up water in fossil fuel-based power plants through small-scale testing and to prepare the technology for a future pilot-scale test effort. This process is based on an advanced multi-stage treatment process, which utilizes commercial solids filtering and ultraviolet light treatment to remediate bacteria; a low-cost natural zeolite to remove naturally occurring radioactive material (NORM) found in oil/gas-based impaired water; electrochemical stripping and selective sulfation to remove minor constituents; and a breakthrough supercritical water unit design, which utilizes internal Joule-based (resistive) heating to remove major constituents and hydrocarbons.

Both the electrical generation and the economic security of the United States rely on fossil fuel-based power plants having access to suitably clean water. To address competing societal and industry demands for available water and the effects of climate change, new water sources for these power plants are necessary to reduce the stress they exert on the existing water supply. In the near future, the United States is projected to generate significant quantities of impaired water from carbon dioxide (CO_2) storage, along with impaired water from existing oil and natural gas production. As such, these impaired water sources represent a potential water supply for fossil fuel-based power plants. However, the impaired water resources contain a host of components including suspended solids, dissolved solids or salts, and, in the case of oil/gas sources, may also contain hydrocarbons and NORM.

The impaired water treatment process developed under this project could be used to recover up to 95 percent of beneficially reusable water from impaired water and reduce water treatment costs. The method could meet the goal of developing a deployable process to cost-effectively treat 500 gallons per minute of impaired water from CO_2 storage or oil/gas operations to supplement make-up water used in power plant systems.



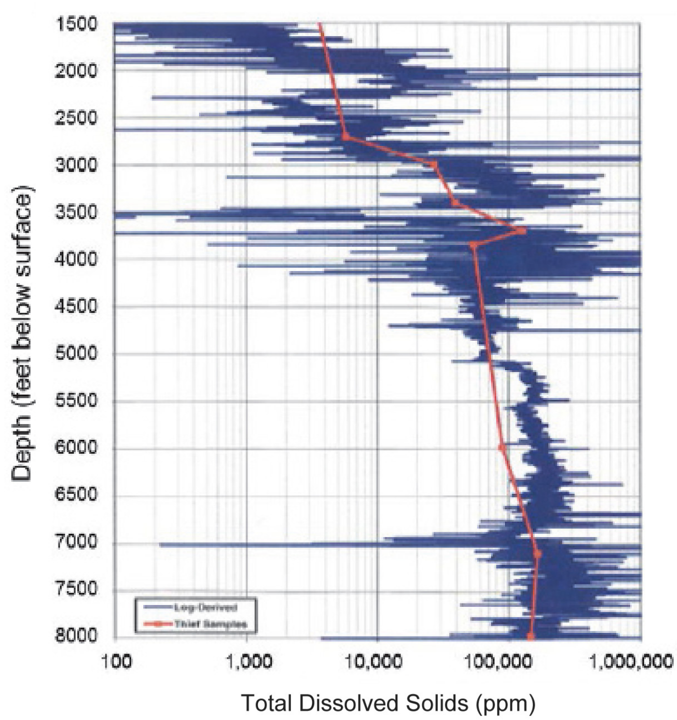
Schematic of impaired water treatment process.

Low-Energy Water Recovery from Subsurface Brines

Performer	Research Triangle Institute
Award Number	FE0026212
Project Duration	09/01/2015 – 12/31/2017
Total Project Value	$ 937,500
Technology Area	Plant Optimization Technologies

The objective of this project is to develop and demonstrate the feasibility of a bench-scale low-cost, low-energy water treatment process using non-aqueous solvents (NAS) for economically extracting clean water from high-total dissolved solids (TDS) brines. TDS is a measure of the amount of dissolved matter in water and an indication of the salinity. (The energy required for separation increases with salinity.) The high TDS levels in concentrated brines generated from CO_2 subsurface storage and fossil fuel extraction (often eight times higher than those of seawater) make the current state-of-the art approaches to water treatment/disposal such as reverse osmosis untenable. Specific project objectives are to identify candidate solvents that can absorb water under one condition and release it under another condition; test different solvents and/or mixtures of solvents for optimum water uptake and release to maximize water recovery from 180,000 parts per million TDS brine; develop optimum conditions to maximize the kinetics of the process; test water quality and, if necessary, develop a downstream process to satisfy potable water standards; and develop strategies to optimize the overall process and perform a techno-economic assessment for scale-up.

This water extraction technology approach addresses the two major challenges associated with treating this type of water: (1) the NAS can be used to treat water with very high TDS content and (2) the novel solvent method can be applied at large scale and low cost and energy. The successful development of this approach will provide a comprehensive solution to the water management issues encountered in high-TDS brine treatment, advancing expanded water reuse and discharge options beyond those that are currently feasible. This solvent technology will conserve precious water resources and reduce the environmental impact of concentrated brines. Some other anticipated benefits include low energy costs, low capital expenditure costs, high-quality effluent, and easy scale-up.



Subsurface plot showing the increasing TDS concentration in water with depth at a possible CO_2 storage site.

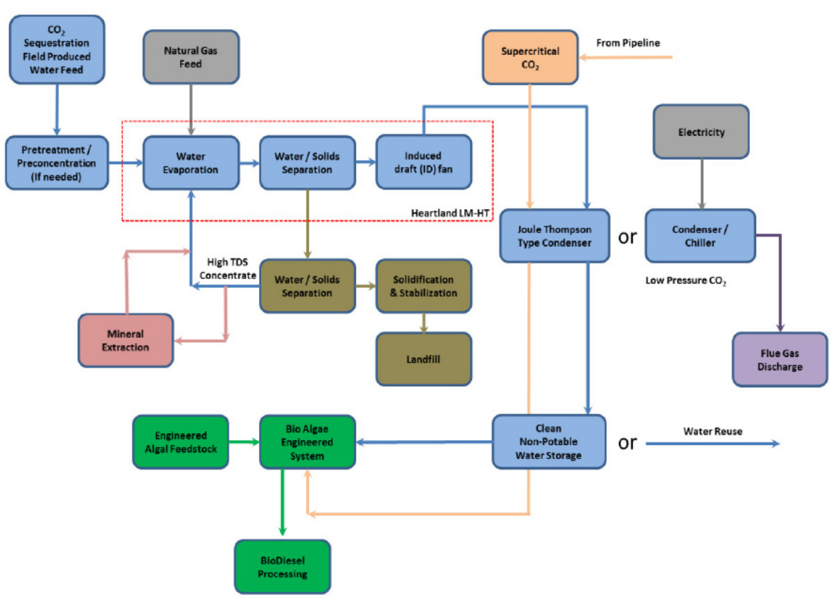
Treatment of Produced Water from Carbon Sequestration Sites for Water Reuse, Mineral Recovery and Carbon Utilization

Performer	Southern Research Institute
Collaborator	Advanced Resources International, Inc.
Award Number	FE0024084
Project Duration	10/01/2014 – 12/31/2017
Total Project Value	$ 653,686
Technology Area	Plant Optimization Technologies

The primary project objectives are to (1) select four representative CO_2 sequestration reservoirs based on water varying chemical and geologic properties; (2) develop an integrated and adaptable concentration system; (3) develop solidification and stabilization mixtures to immobilize residual contaminants; (4) evaluate opportunities to recover strategic and rare earth minerals and efficiently utilize CO_2 and extracted water; and (5) complete a technical readiness review, economic feasibility analysis, and environmental risk assessment. The extracted water volume and characteristics necessary to facilitate the injection of 3.5 million tons per year of CO_2 will be used for the mass and energy calculations and to determine long-term viability.

Early project work by Advanced Resources International led to the selection of the Tuscaloosa, Mount Simon, Sulphur Point and Keg River, and the Wasson Field formations for use in geochemical characterizations. The four formations provide concentrations ranging from 35,000 to 190,000 milligrams per liter (mg/L) total dissolved solids (TDS), 4,851 to 63,014 mg/L sodium, and 200 to 19,000 mg/L magnesium. The varied geochemistry will require a wide range of design considerations that must be addressed to optimize the use of low-temperature membrane treatment versus thermal concentration techniques.

Current project activities are focused on balancing the efficient treatment of low-to-medium TDS streams utilizing the New Logic Research vibratory shear enhanced processing process with the Heartland Technology Partner's thermal concentrator, which is very effective on high to very high TDS streams. Recent results indicate that an integrated approach has the potential to provide technically and economically feasible treatment solutions.



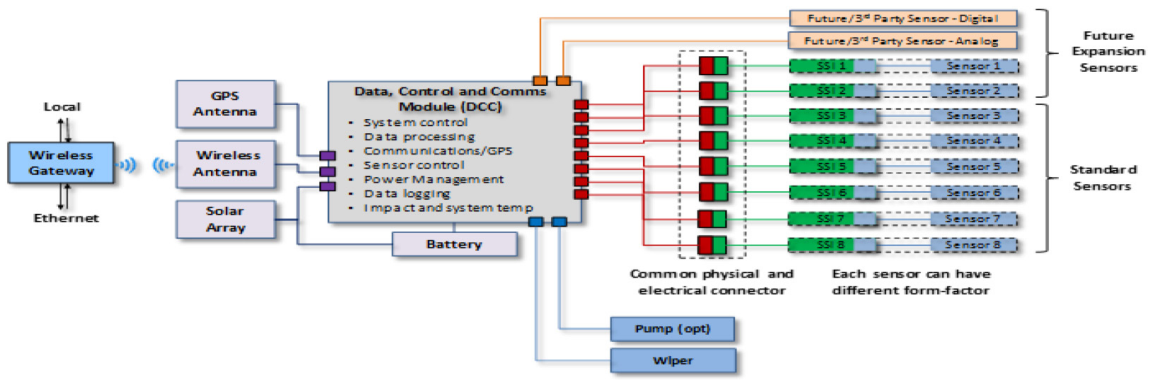
Integrated CO_2 sequestration produced water reuse system.

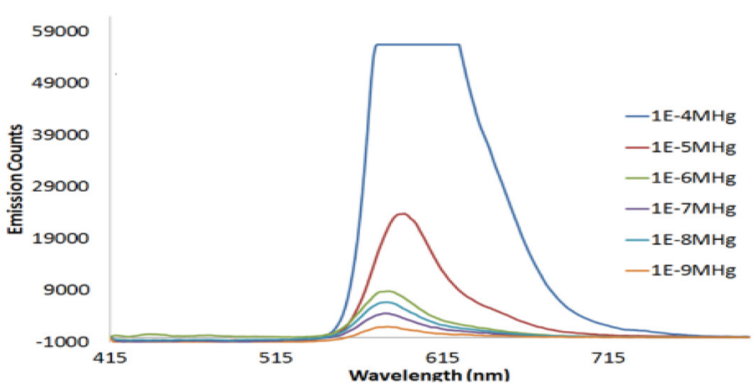
Integrated Sensors for Water Quality

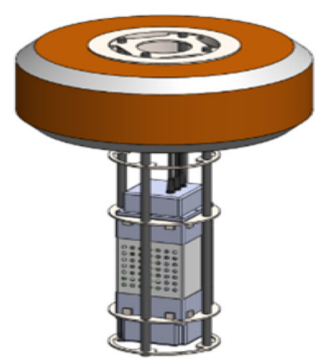
Performer	Sporian Microsystems, Inc.
Award Number	SC0013863
Project Duration	06/08/2015 – 07/31/2018
Total Project Value	$ 1,164,896
Technology Area	Plant Optimization Technologies

This Sporian Microsystems, Inc. project involves preparing, optimizing, and characterizing imprinted polymer (IP) systems, evaluating IP film fabrication methodologies, and experimentally evaluating/demonstrating IP sensing performance with Sporian's existing sensor system hardware. Sporian Microsystems will develop an integrated water sensor package that is low-cost, rapidly deployable, wireless, self-powered, and capable of relaying relevant in-situ water measurements in real-time.

This technology could support reducing or maintaining the water-use footprint in the energy sector, provide highly reliable real-time measurement-based data for water management, and be deployed at low-cost. In addition, this technology could be highly attractive for monitoring sanitary water for consumption or processes that affect water use and require sensors for ensuring proper contamination monitoring and abatement, especially in the energy, industrial/agricultural, municipal drinking water, and wastewater monitoring sectors.







Top: System architecture.

Bottom left: Molecularly imprinted polymer signaling versus mercury concentration.

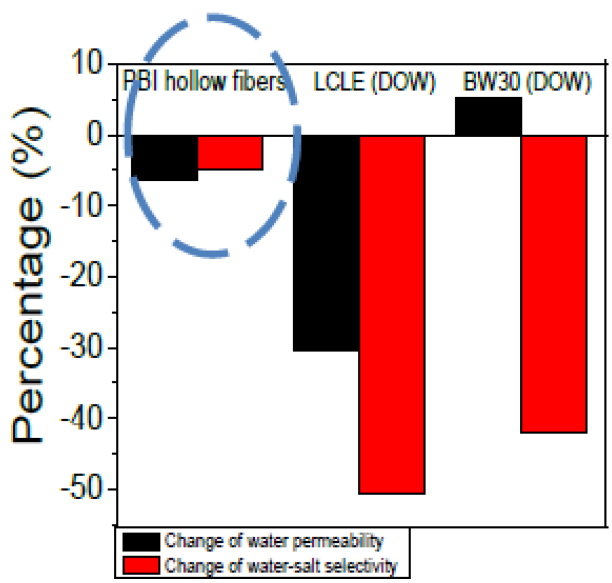
Bottom right: Buoy hardware design concept.

Development of a High Efficient Membrane-Based Wastewater Management System for Thermal Power Plants

Performer	SRI International
Award Number	FE0031552
Project Duration	12/19/2017 – 06/18/2020
Total Project Value	$ 799,949
Technology Area	Plant Optimization Technologies

The main goal of the proposed research is to develop innovative effluent water management practices at coal-fired energy plants. In particular, researchers plan to use SRI-based polybenzimidazole (PBI) hollow-fiber membrane (HFM) technology to remove selenium from flue gas desulfurization (FGD) wastewater below the effluent discharge limits (less than 5 parts per billion). The PBI membranes are resistant to fouling and can be operated under environments that are substantially harsher than tolerated by commercially available membranes. The fouling resistance of PBI-HFM based separation system under simulated FGD water discharge conditions will be tested.

The technology developed will allow the removal of toxic material in the FGD blowdown and other wastewater from the plant and provide an opportunity to develop methods for reducing water use within plant and thereby reducing freshwater withdrawals. Success of this project will result in development of a power plant effluent control system that can remove the hazardous compounds and also recover and reuse the water back into the plant to reduce freshwater withdrawal. In addition, energy use in effluent control systems in thermal power stations will be greatly reduced.



Demonstration of chlorine stability of PBI HFM compared to commercial membranes.

Continuous Water Quality Sensing for Flue Gas Desulfurization Wastewater

Performer	University of Alabama at Birmingham
Collaborator	Southern Research
Award Number	FE0027778
Project Duration	08/01/2016 – 06/30/2018
Total Project Value	$ 439,986
Technology Area	University Training and Research

The overall goal of this project is to develop an integrated water sensor package for continuous water quality monitoring of flue gas desulfurization (FGD) wastewaters to include concentration measurements of multiple contaminants (e.g., trace metals: selenium, arsenic, and mercury) and measurement of common water quality indicators (e.g., pH, total dissolved solids).

The proof-of-concept prototype will successfully demonstrate the key features of the technology through on-site processing of FGD wastewater including reliable in-field automated operation for extended periods (e.g., one week); accurate trace metal detection (e.g., selenium, arsenic, and mercury) using a proprietary FGD sample preparation technique; low cost, small footprint detection with a commercial off-the-shelf (COTS) voltammetry device, parts per trillion (ppt) limit of detection/qualification; continuous monitoring with high sampling frequency (i.e., more than one measurement per hour for trace metals); integration of COTS water quality indicators (e.g., pH, total dissolved solids); and wireless transmission of measurements to an on-site control room.

The project comprises three phases: Phase I Development of Sample Preparation Batch Process; Phase II Design and Development of Continuous Sample Preparation Prototype; and Phase III Demonstration Unit Integration and Field Testing. The resulting demonstration unit will be used for extended in-field testing at a coal-fired power plant at a partner's site and will be validated for accuracy and reliability through comparison with the gold-standard analysis method provided by onsite inductively coupled plasma mass spectrometry analysis.

Anticipated project benefits include (1) ability to monitor and detect contaminant concentration levels in FGD wastewater discharge in coal-fired power plants; (2) reduction in recurring operating and off-site laboratory analysis costs by minimizing required FGD wastewater treatment reagents and equipment; and (3) closed-loop control of contaminant concentrations in effluent discharge resulting in a high level of confidence of compliance with EPA discharge guidelines.

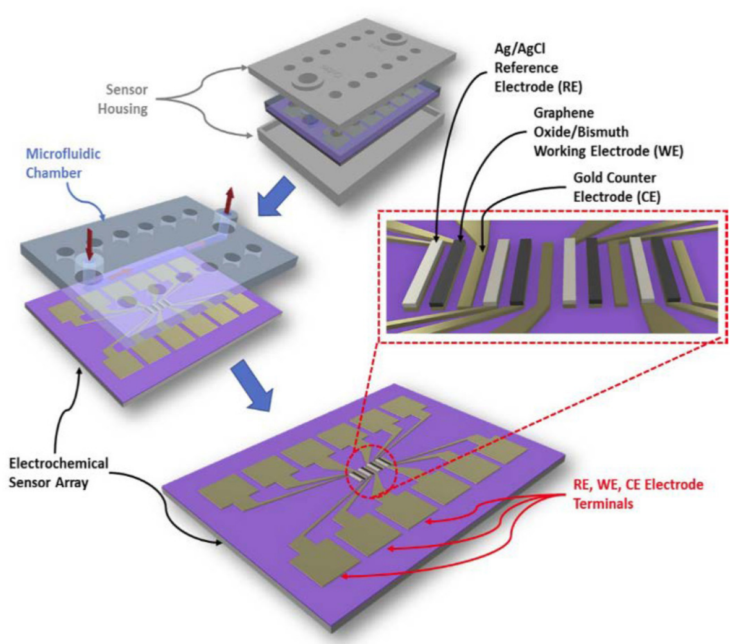
Multi-phase approach.

Applying Anodic Stripping Voltammetry to Complex Wastewater Streams for Rapid Metal Detection

Performer	University of California at Los Angeles
Collaborator	Regents of the University of California at Riverside
Award Number	FE0030456
Project Duration	08/01/2017 – 07/31/2020
Total Project Value	$ 400,000
Technology Area	University Training and Research

This project's objective is to develop a lab-on-a-chip (LOC) electrochemical sensor capable of accurately measuring heavy metal concentrations, including lead (Pb), cadmium (Cd), and arsenic (As), in complex aqueous streams such as wastewater. The sensor technology relies on anodic stripping voltammetry (ASV), which has been demonstrated to detect extremely low (sub ppm) concentrations of these metals. The technology will be capable of autonomously conducting metal measurements and report the findings remotely via cellular technology. Furthermore, using open-source hardware and software tools, the project team will construct sensor technology that operates with minimal human intervention and is capable of autonomously performing all of the pre-treatment steps needed to perform metal measurement activities. To accomplish this objective, the project team will concentrate on characterizing metal speciation in wastewater, develop appropriate pre-treatment methods that will allow analysis of this complex matrix on an LOC device, fabricate a range of electrodes specifically tailored to enhance the detection of the target metals, and finally, construct and test an autonomous LOC device that incorporates the pre-treatment steps and specialized electrodes for the detection of heavy metals in wastewater.

All pre-treatment steps will be integrated into the fully automated LOC device, which will conduct the metal analysis without the need for human intervention beyond periodically re-filling reagent reservoirs. Current heavy metal measuring methods are time-consuming and rely on grab sampling and expensive analytical instruments. Thus, the proposed technology would decrease costs and increase the frequency of measurements, enabling heavy metal contamination to be detected in near real time.



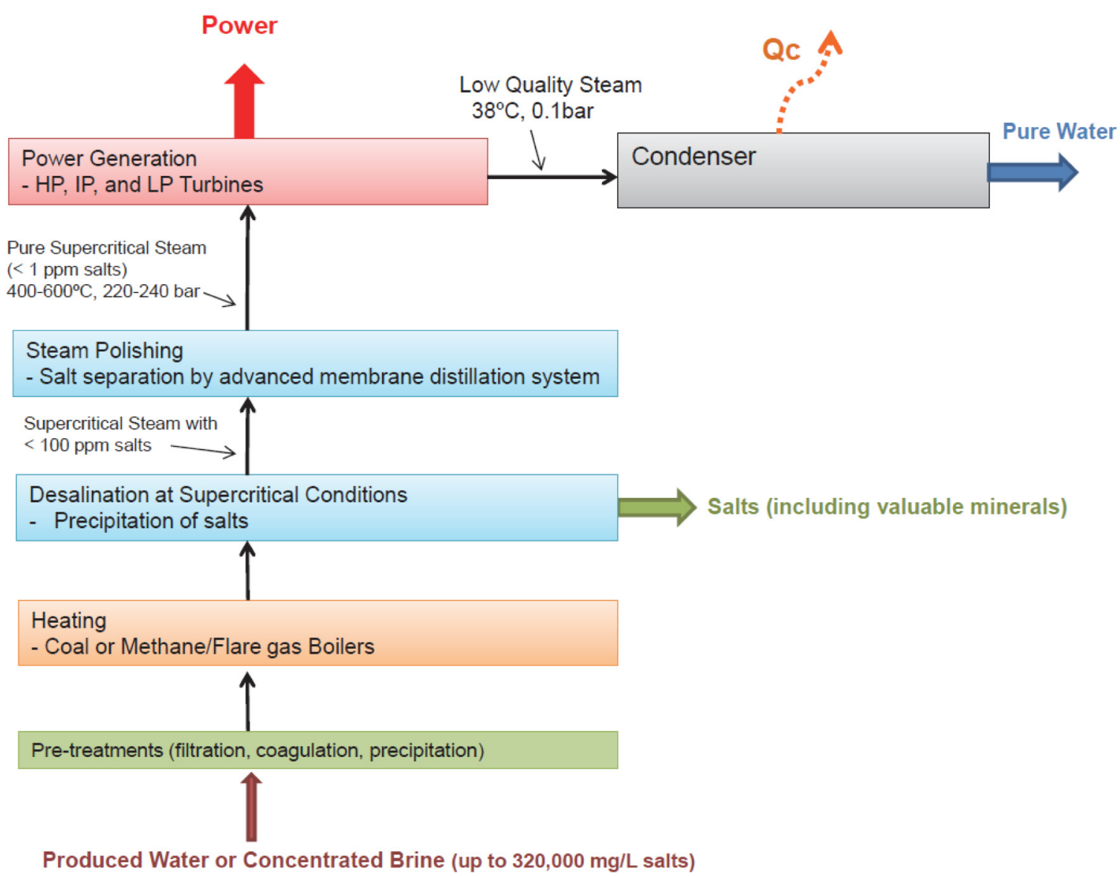
Schematic of electrochemical sensor arrays microanalyzer system.

An Integrated Supercritical System for Efficient Produced Water Treatment and Power Generation

Performer	University of Illinois at Urbana-Champaign
Award Number	FE0024015
Project Duration	01/01/2015 – 05/31/2018
Total Project Value	$ 656,311
Technology Area	Plant Optimization Technologies

The goal of this project is to evaluate the feasibility of an innovative, integrated supercritical cogeneration system for cost-effectively treating extracted waters resulting from carbon dioxide sequestration, oilfields, and coal-bed methane recovery. Methane or coal is used as an energy source to drive the proposed system that generates both electricity and pure water. Project tasks include process simulation, thermodynamic analysis, and techno-economic evaluation of the integrated system; design and assembly of supercritical salt precipitation and membrane distillation systems; development and characterization of advanced carbon membranes for supercritical membrane distillation; and desalination and purification of different extracted water samples with salt concentrations of 30,000 parts per million (ppm) to 200,000 ppm.

This project may provide a transformative approach to generating power from coal or natural gas, purifying high salinity saline or extracted water, and recovering valuable, strategic minerals in a zero liquid discharge plant. Extracted water is expected be treated at a much lower cost due to the higher efficiency of the proposed supercritical integrated system compared to existing cogeneration or evaporation/crystallization systems.



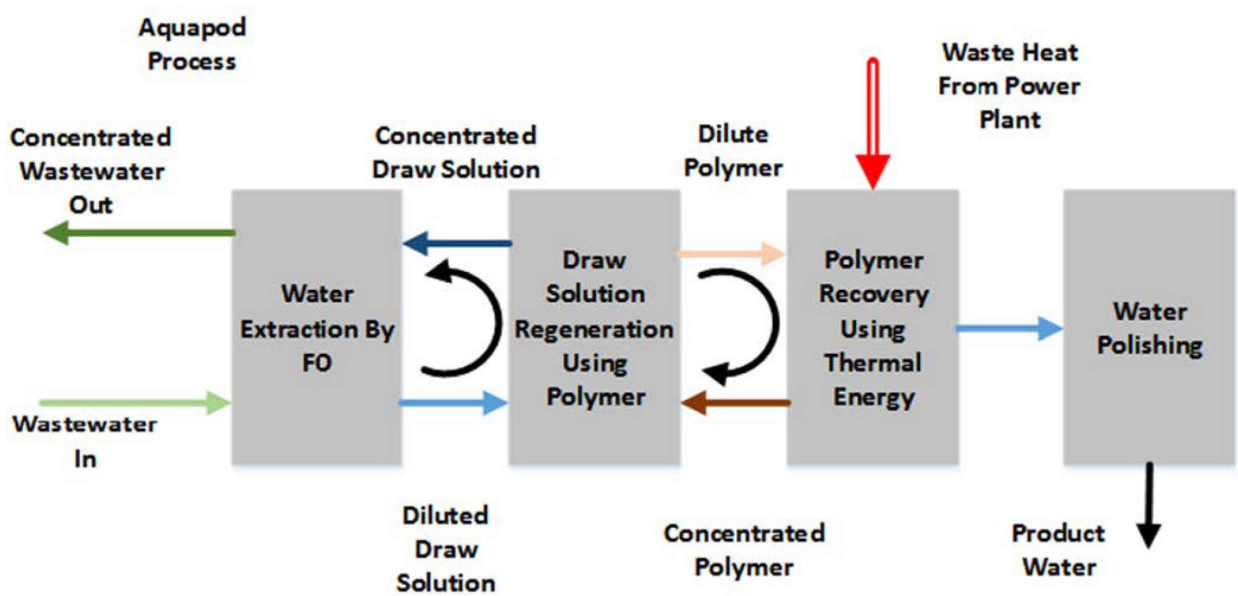
Conceptual diagram of the proposed supercritical extracted water desalination and energy generation system.

Energy Efficient Waste Heat Coupled Forward Osmosis for Effluent Water Management at Coal-Fired Power Plants

Performer	University of Illinois at Urbana-Champaign
Award Number	FE0031551
Project Duration	12/19/2017 – 12/31/2020
Total Project Value	$ 929,617
Technology Area	Plant Optimization Technologies

This project will evaluate a transformational low energy (less than 200 kilojoules/kilogram water) waste heat coupled forward osmosis (FO) based water treatment system (the Aquapod©), adapted to meet the complex and unique environment of a power plant, to manage effluents, meet cooling water demands and achieve water conservation. The target is to enable recovery of at least 50 percent of the water from highly degraded water sources without extensive pretreatment in a cost effective manner.

The use of the Aquapod© FO process can double-to-quadruple the amount of water recovery from power plant effluents per unit of input energy compared to the current state of the art. It is also an intrinsically safe process, unlike the current state of the art, which utilizes gaseous ammonia. Project outcomes will enable the early-stage evaluation of a transformational water treatment system adapted to the power plant environment. A partner utility is engaged early in the technology development to assure that results would be applicable to large-scale coal-fired power plants.



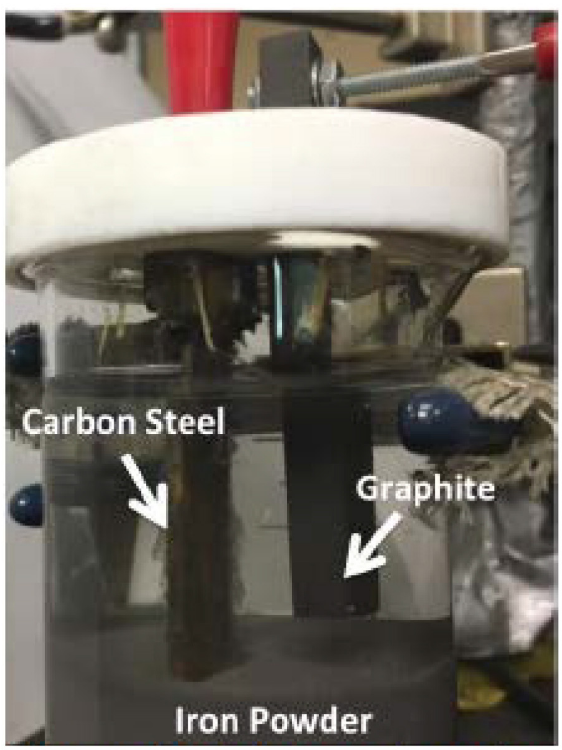
The process utilized by the University of Illinois.

Intensified Flue Gas Desulfurization Water Treatment for Reuse, Solidification, and Discharge

Performer	University of Kentucky
Award Number	FE0031555
Project Duration	01/22/2018 – 01/21/2020
Total Project Value	$ 928,666
Technology Area	Plant Optimization Technologies

This project will develop a process that is able to treat for reuse wastewater resulting from wet flue-gas desulfurization (FGD) scrubbing systems, leading to significant reductions in footprint and chemical consumption compared to the state-of-the-art water treatment technologies. To achieve this goal, the project will (1) evaluate the effectiveness of electrocoagulation with air-dissolved flotation in removing regulated species through design, construction, and testing of a one liter per hour sub-pilot unit, (2) examine a nanofiltration unit to achieve greater than 80 percent monovalent salt rejection, (3) conduct long-term operation of membrane-based filtration for FGD wastewater aimed at determining performance degradation, e.g., membrane fouling, (4) determine a practical salt concentration for solidification resulting in an acceptable leachate, and (5) apply continuous capacitive deionization as a polishing step to remove any remaining government-regulated species below the effluent limitation guidelines requirements for recycling or discharge.

Wastewater treatment is one of the most important and challenging environmental issues associated with coal-based power generation. Compared to existing state-of-the-art biological treatment methods based on several physical/chemical steps, the proposed process will result in a reduction in the footprint of a physical/chemical treatment process and withdrawals of fresh water at power generation plants.



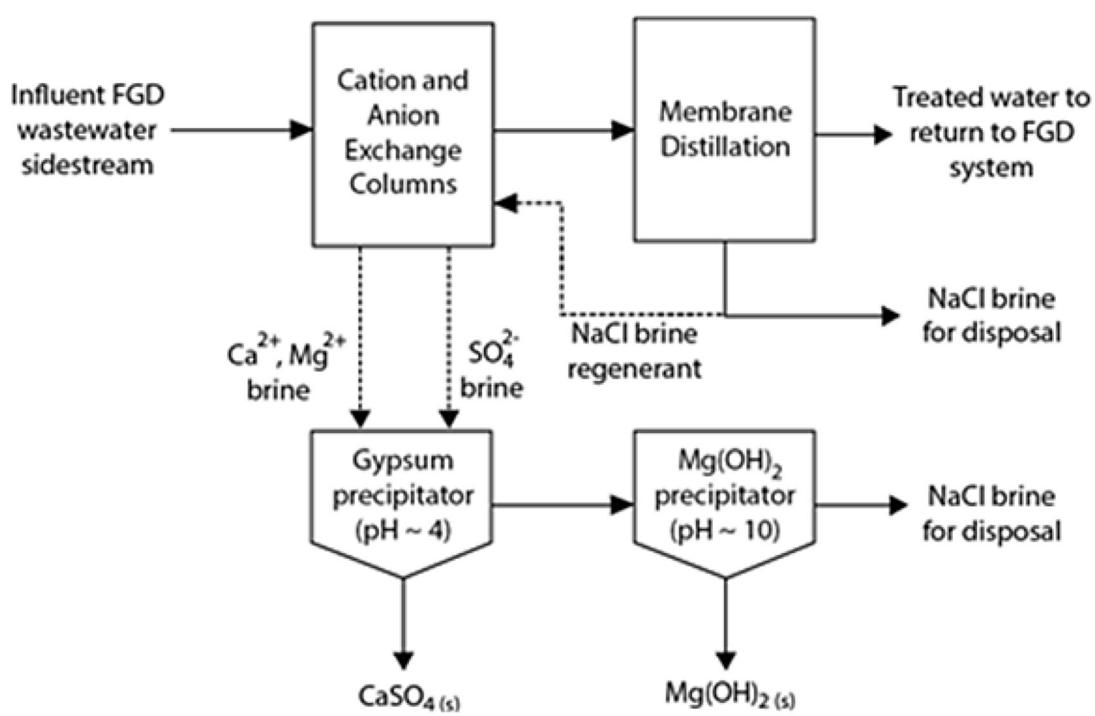
A lab-scale setup for electro-coagulation studies.

Flue Gas Desulfurization Wastewater Treatment, Reuse and Recovery

Performer	University of New Mexico
Award Number	FE0030584
Project Duration	08/01/2017 – 07/31/2019
Total Project Value	$ 249,536
Technology Area	University Training and Research

The objective of the proposed research is to develop a computer model of both the unit processes and overall treatment system. Model development will be supported by laboratory research addressing (1) the ability to concentrate divalent ions from high-salinity flue gas desulfurization (FGD) wastewater of varying chemistry, and (2) the ability to precipitate gypsum and magnesium hydroxide from concentrated ion-exchange brines. The model will calculate process performance, mass and liquid flow rates, and heat requirements; it will be used to evaluate the technical feasibility of a full-scale treatment process. The technology developed in this study will be relevant to utilities considering zero liquid discharge of FGD wastewaters. The project objectives will be achieved through a combined laboratory and modeling effort to develop a novel treatment process for FGD wastewater. Lab studies will be conducted to investigate divalent ion removal and precipitation of gypsum and magnesium hydroxide from brine solutions. The process model will enable performance to be predicted and optimized by calculating flow, mass, and energy balances.

This study will result in a new treatment process to recover water, commodities, and trace contaminants from FGD wastewater. The proposed treatment process will reduce water use by the FGD process, recycle treated wastewater, and use waste heat to improve process performance based on research at minority-serving institutions.



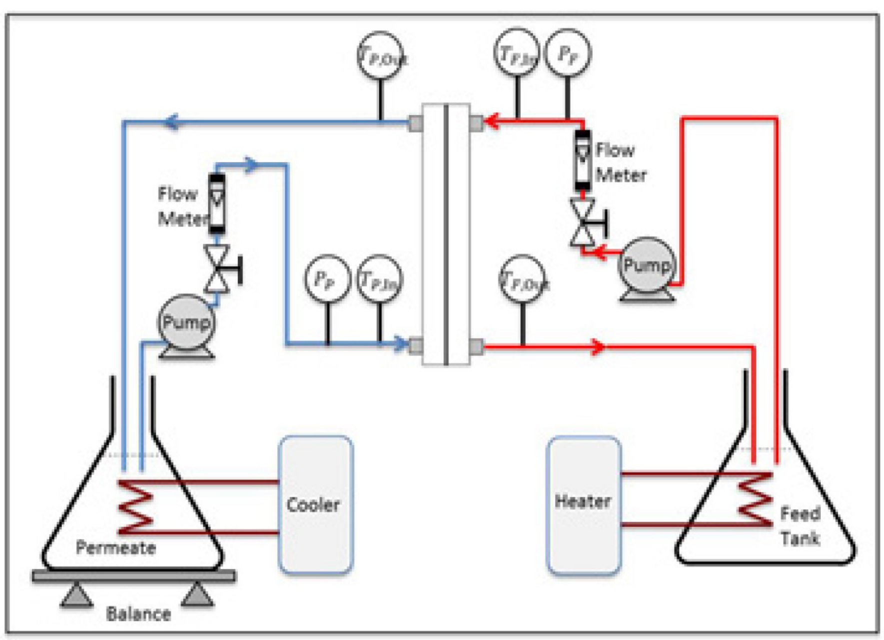
Process description.

Development of Membrane Distillation Technology Utilizing Waste Heat for Treatment of High Salinity Wastewaters

Performer	University of Pittsburgh
Award Number	FE0024061
Project Duration	10/01/2014 – 10/31/2017
Total Project Value	$ 654,183
Technology Area	Plant Optimization Technologies

The main objective of this study is to evaluate the feasibility of using membrane distillation (MD) technology to treat high salinity wastewater generated during unconventional gas production or CO_2 sequestration utilizing waste heat that is available in thermoelectric power plants or compressor stations (both natural gas [NG] and CO_2 compressors). Technical information obtained in these laboratory-scale studies will be utilized for a systems-level integration of the MD process with low-grade heat sources (i.e., thermoelectric power plants and NG and CO_2 compressor stations) or NG as a fuel source. The project's approach is to (1) examine the laboratory-scale performance of two MD schemes—direct contact membrane distillation and vacuum membrane distillation—along with operating conditions and process configurations in terms of productivity and permeate quality; (2) conduct laboratory-scale studies with synthetic and actual wastewaters to assess the capabilities and limitations of MD technology and define key design and operating parameters (high-salinity produced and extracted waters representative of several shale gas plays and geologic sequestration locations, respectively, are being used to study how water composition affects MD performance); (3) use this information for a systems-level analysis to assess the feasibility of integrating the MD process with low-grade heat sources (i.e., thermoelectric power plants and natural gas and CO_2 compressor stations); and (4) conduct a preliminary economic assessment of MD technology for saline wastewater treatment.

This project may advance the use of alternative sources of energy for wastewater treatment, promote the recycle and reuse of wastewater, reduce the energy footprint and enhance the mobility of treatment systems, and enhance the economic and environmental performance of MD technology.



Direct contact membrane distillation experimental set-up.

Developing Cost-Effective Biological Removal Technology for Selenium and Nitrate from Flue Gas Desulfurization Wastewater from an Existing Power Generating Facility

Performer	West Virginia State University
Award Number	FE0027893
Project Duration	10/01/2016 – 09/30/2019
Total Project Value	$ 249,999
Technology Area	University Training and Research

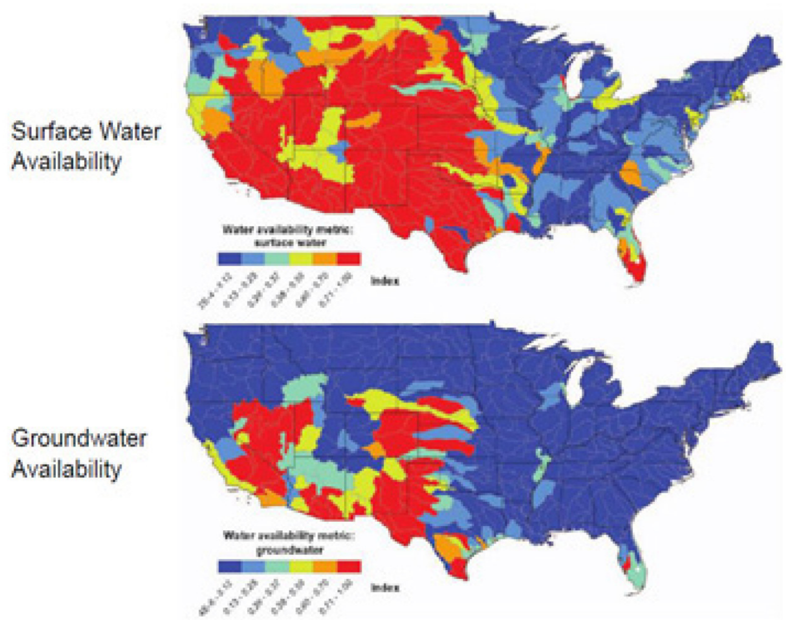
The overall goal of this project is to explore a variety of genomic, biochemical, genetic, and molecular approaches to understanding the molecular basis of selenium and nitrate sensing, uptake, and sequestration by algae and plants from flue gas desulfurization (FGD) wastewater. The ultimate objective of this project is to apply the knowledge gained to develop a cost-effective biological treatment to help reduce these compounds in FGD wastewater, reduce power plant use of freshwater, and increase biomass/crop production.

The work will focus on the following technical objectives: (1) investigate changes in transcripts and metabolism in algae and plants in response to FGD wastewater and (2) explore biotechnological strategies to increase sequestration of selenium and nitrates in biomass for agricultural productivity.

The project will develop transcriptomic and metabolomic data for basic and applied water research relating to algae, duckweeds, and mutants/transgenic plants derived using Arabidopsis transfer-DNA (T-DNA). Anticipated project benefits include maximizing sequestration of selenium and nitrates in biomass for FGD wastewater remediation, reduction of power plant use of freshwater resources, and enhanced agricultural production.

Candidate genes in model system.

DATA MODELING AND ANALYSIS

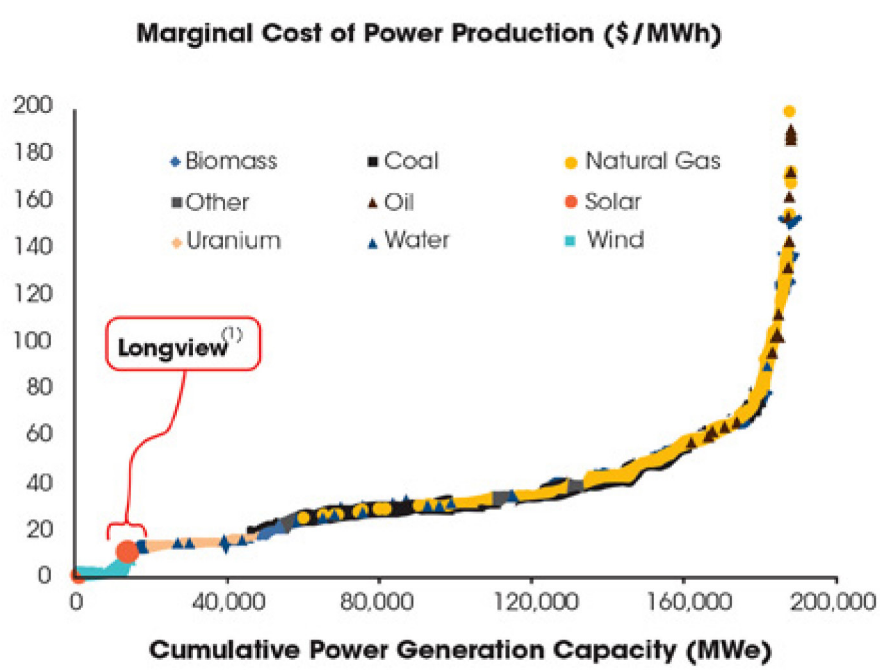


Water Management for Power Systems: Impact of Water Use of Power Systems – Task 5

Performer	National Energy Technology Laboratory
Award Number	FY18 FWP 1022428: Task 5
Project Duration	04/01/2018 – 03/31/2019
Total Project Value	$ 240,000
Technology Area	Plant Optimization Technologies

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. Understanding the intertwining 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. A summary comparison of water and energy issues shows a striking correspondence between issues on the water side and issues on the energy side. The immediacy of these issues lends urgency to the effort to understand and manage the water-energy nexus. The objective of this task is to obtain and investigate current water data on individual plant- and fleet-wide water use, water stresses due to power generation, and how water stresses impact power plant operations.

Models and software developed under this task will provide information on the impacts of water use by power plants that can be used by existing coal power plants to make investment decisions on when and what type of equipment to purchase to reduce water consumption. Understanding the impact of water use on power generating systems is critical to guide program direction, goals, and research.



Marginal cost of power production.

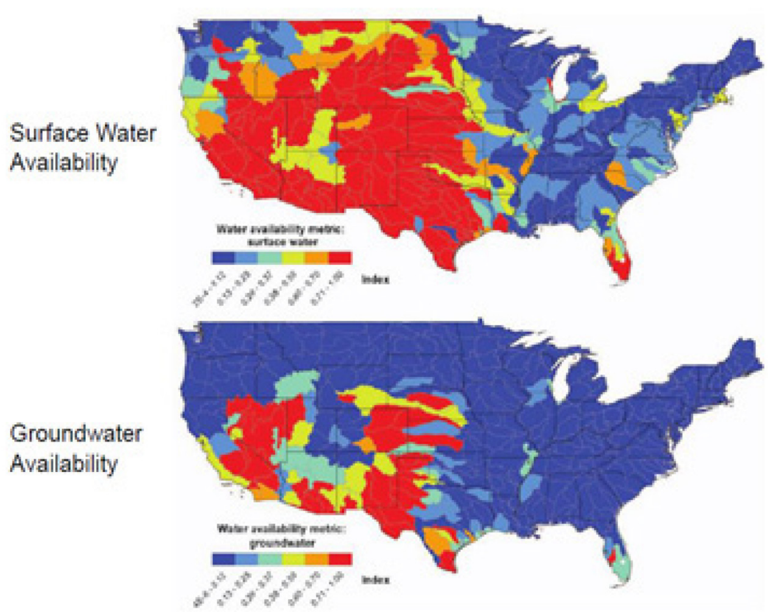
Exploring Energy-Water Issues in the United States

Performer	Sandia National Laboratories
Collaborator	Carnegie Mellon University
Award Number	FWP-14-017626
Project Duration	10/01/2014 – 12/31/2017
Total Project Value	$ 1,243,000
Technology Area	Plant Optimization Technologies

The objective of this work was to develop data and models to better understand the link between thermoelectric power generation and water. This effort involved two broad areas of research, one toward the development of the foundation for a water (for energy) atlas and the second involving an assessment of water use requirements of fossil-fueled electric power plants. The water (for energy) atlas task compiled estimates of water availability, cost, and projected future demand at the watershed level (8-digit Hydraulic Unit Code [HUC], corresponding to roughly 2,250 watersheds) for the lower 48 states. Water availability and cost metrics were developed for four sources of water: surface water, groundwater, municipal wastewater, and shallow brackish groundwater.

The second task enhanced the analytical capabilities of the Integrated Environmental Control Model (IECM) to assess water use requirements of fossil-fueled electric power plants to consider a variety of alternative water treatment and cooling technologies and processes for carbon capture and storage. The enhanced IECM resulted in an improved ability to analyze and assess water needs, costs, and impacts of fossil energy plants.

Work was recently completed to scope a path forward for developing a full-scale Water for Energy Decision Support Tool (WEDST). The tool would be used to inform technology and supply choices related to water for energy planning (e.g., cooling for thermoelectric power plants, water for unconventional oil/gas development). Such a tool could assist energy developers in design and siting decisions; support long-range planning by water and energy managers; and inform state and national policy assessment. It could also help inform expanded water modules within EIA's National Energy Modeling System.



Project relevancy to fossil energy.

ABBREVIATIONS

ASV . . . . anodic stripping voltammetry

BIAS. . . . . basic immobilized amine sorbent

ChemFET. . . . . .chemical field effect transistors

CO_2 . . . . carbon dioxide

COTS. . . . . .commercial off-the-shelf

DNA . . . . .deoxyribonucleic acid

DOE . . . .[U.S.] Department of Energy

EIA . . . . Energy Information Administration

EPA . . . . .Environmental Protection Agency

FGD . . . . flue gas desulfurization

FO . . . . .forward osmosis

HBCU. . . . . . . Historically Black Colleges and Universities

HFM . . . . .hollow-fiber membrane

HTE .heat transfer enhancement

HUC. . . . . .hydraulic unit code

ICP-MS . . . . .inductively coupled plasma mass spectrometry

IECM . . . . integrated environmental control model

IP . . . . .imprinted polymer

LOC . . . . lab-on-a-chip

MD . . . . membrane distillation

mg/L . . . . .milligrams per liter

NAS . . . . non-aqueous solvents

NETL . . . . National Energy Technology Laboratory

NG . . . . natural gas

NGO. . . . . non-governmental organization

NORM . . . . .naturally occurring radioactive material

NO_X . . . . .nitrogen oxides

OARO. . . . . osmotically assisted reverse osmosis

OMI . . . . .Other Minority Institutions

PBI . . . . polybenzimidazole

pH . . . . power of hydrogen (measure of acidity)

ppm . . . . parts per million

ppt . . . . .parts per trillion

R&D . . . . .research and development

RIC. . . . . Research & Innovation Center

RO . . . . reverse osmosis

SBIR. . . . . Small Business Innovation Research

SE&A . . . . systems engineering & analysis

SLIPS. . . . . superhydrophobic/slippery liquid infused porous surfaces

SO_X . . . . .sulfur oxides

T-DNA . . . . transfer-DNA

TDS . . . . total dissolved solids

U.S. . . . . United States

UCR . . . . University Coal Research

USGS. . . . . .United States Geological Survey

UTR . . . . University Training and Research

WEDST . . . . Water for Energy Decision Support Tool

ZLD . . . . .zero liquid discharge

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