# EFRI-RESIN: Alternative Cooling Water Technologies for Resilient and Sustainable Thermoelectric Power Generation

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The challenges of providing sustainable energy and water to burgeoning populations are exacerbated by interdependence of the nation's energy and water infrastructures. Conventional thermoelectric power generation requires large, stable cooling water supplies. Rising consumer demand for electric power is exacting severe water resource pressures as new thermoelectric plants are constructed in populous and arid regions of the western and southeastern U.S., intensifying competition between utilities and agriculture for scarce freshwater. Alternative power generation methods that capture and store carbon, or utilize coal gasification or biomass to reduce carbon emissions, are water-intensive and worsen energy-water interdependency.

In this project, environmental and chemical engineers, a climate change researcher, resource economist, and policy analyst will work together to develop tools that assist energy and water sector stakeholders and policymakers in making decisions that strengthen the resilience and sustainability of electric power generation. The project objectives are as follows. (1) Life cycle assessment will be conducted to evaluate technologies that reduce water use in thermoelectric cooling, or use desalinated brackish water for cooling, to release freshwater resources for other functions and to improve the sustainability of the energy and water sectors. (2) Global climate change models and weather data will be combined with a watershed model to create a new modeling system that can be used to assess the resilience and sustainability impacts of electricity generating capacity additions in watersheds with limited water resources. (3) Strategic investment analyses of water conservation and carbon mitigation will be conducted for utilities, in the context of uncertain national climate change policies and regional water regulation and availability. (4) An integrated decision support system will be developed which returns an index of electric power infrastructure resilience enhancement, relative to generating plant location factors and water conservation investment costs, for various thermoelectric cooling alternatives being considered for capacity additions that utilize coal-fired, gas-fired or nuclear-powered generation. (5) Case studies will be conducted using the energy-water infrastructure decision support system for three key watersheds in the U.S. where expansion of energy sector activity is anticipated, and where climate change may impact future water availability for energy infrastructure needs.

The intellectual merit of the proposed research is the development of a novel decision support system, combining plant-scale life cycle assessment of water use, regional-scale evaluation of water resources in watershed basins with electric power infrastructure, and global-scale modeling of climate change as it impacts regional weather phenomena. Quantitative measures of energy-water resilience and sustainability will be developed for utilities in support of their resource planning for sustainable future additions to their generating capacity. This will be of profound intellectual merit, as it will enable coherent and transformative technology implementation and policy design to ease energy-water interdependence. Also, the decision support framework for resiliency developed in this project will be exportable to analyses of other industrial sectors that are dependent upon water supplies. Planning and foresight is needed if energy sustainability is to be achieved without precipitating a water resource crisis. The research will have substantial broader impacts in the international context, as developing nations in China, Africa and elsewhere confront a similar nexus within their energy and water infrastructures. Education and outreach efforts are planned in concert with research objectives.

1. Project Overview: Decoupling the Nexus of Energy-Water Interdependence

Whereas 100 gallons of water are used per person per day for cooking, showering, lawn watering, and other domestic activities that transparently utilize water [1], triple that amount – 300 gallons of water per capita daily – is withdrawn to generate electricity for indoor lighting, refrigeration, and household appliances. Home electricity use is but one manifestation of the interdependence of energy and water. Water is needed to process fuels and generate electricity. Energy, in turn, is required to pump, convey and treat water. Societal use of energy and water is thus highly interwoven. The national energy and water infrastructures are most visibly intertwined at the nexus of thermoelectric power plants and the lakes and rivers that supply massive quantities of water to cool turbine exhaust and scrub emissions from flue gases.

Electricity demand is projected to rise 30% in the next 25 years [2], thus resource pressures on freshwater inventories will escalate (Figure 1). Despite strong linkage of energy production to water availability, energy sector policymaking and investment in water conservation technology are hampered by a tendency to view water as an inexhaustible resource (no price elasticity), because the cost of water does not drive operational expenses of a power plant. Numerous state and local conflicts have arisen over limited water supplies [3]; these disputes are harbingers of a brittle energy infrastructure, vulnerable to disruption by weather variation from drought or from longer-term, global warming-induced redistribution of water resources.

In this project, a team of chemical and environmental engineers will partner with a climate change scientist, resource economist, and policy expert to develop tools and strategies to quantify and enhance the resilience and sustainability of electric power generation in the United States by reducing dependence on freshwater for thermoelectric power plant operations. Life cycle and strategic investment assessments will determine the value of technology integration to reduce water resource impacts in three domains: (i) waterless or hybrid thermoelectric cooling technologies, (ii) substitution of freshwater with nontraditional resources such as brackish groundwater or wastewater, and (iii) carbon capture and storage. The impact of and investment in technologies aimed at compliance with renewable portfolio standard (RPS) policies will be investigated. Sustainability metrics for the electric power sector will be based on reductions in freshwater commitment per kilowatt-hour generated, per unit investment cost in alternative thermoelectric cooling technologies and resources, relative to capacity additions of conventional water-cooled thermoelectric plants. Similarly, a resilience indicator will be defined for electric power infrastructure in terms of reduction in lost kilowatt-hours, per unit investment, achieved by installation of hybrid air-condensed systems that can provide cooling when water scarcity arises. Meteorological data and hydrologic models will be used in conjunction with high-resolution climate models to assess resilience and sustainability improvements resulting from sector-wide implementation of water-conserving technologies in regional markets of the national power grid.

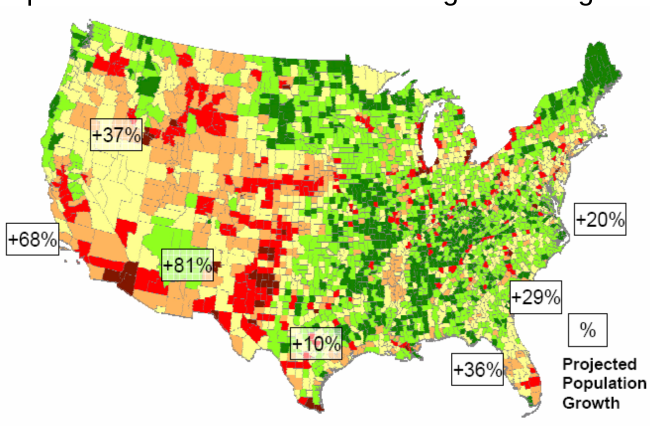


**Figure 1: Thermoelectric plants require abundant water resources. Water shortfalls are projected in much of the U.S. due to population growth and water competition between energy and agriculture. Red and yellow denote counties where water withdrawals exceed precipitation [4-6].**

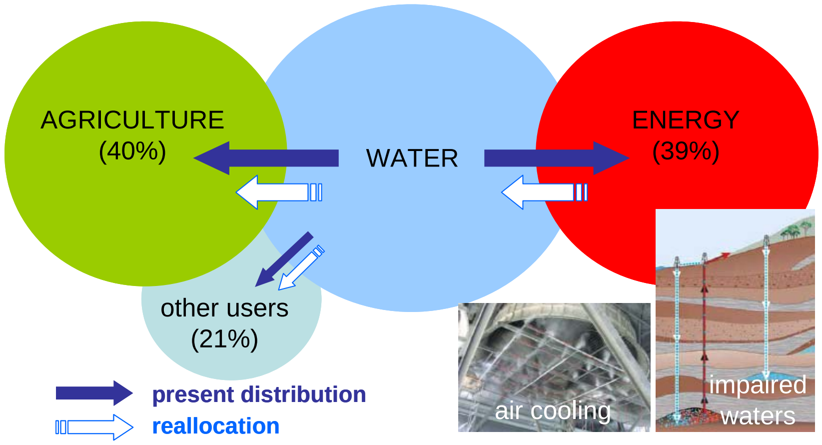


**Figure 2: Project theme and strategy. Electricity production and irrigation each account for two-fifths of all U.S. freshwater withdrawals. Sector-wide use of hybrid air condensers [3] or impaired waters for cooling [7] at thermoelectric plants eases energy-water infrastructure interdependence and frees freshwater for agriculture and other uses. Redundant cooling system technologies enhance energy resilience/sustainability.**

2. Nature of the Challenge Problem and Relation to Strengthening Infrastructures

As shown in Figure 2, the project will focus on decoupling energy-water interdependence at the thermoelectric nexus to achieve sustainable expansion of electric power, while at the same time enhancing sustainability of other sectors that rely upon freshwater, particularly agriculture. Demands on freshwater resources will be unsustainable if conventional cooling methods and water-intensive carbon mitigation technologies are used in new power plants constructed to meet rising electric demand and address emissions policies. Agriculture requires higher-quality water than is needed for the heat exchange carried out with water withdrawals at thermoelectric plants. It is therefore sensible to develop alternative resources to satisfy thermoelectric plant needs. Thermoelectric fleets, moreover, are vulnerable to disruptions caused by weather events and global warming. Cooling redundancy is essential to provide flexibility for uncertainties in future water availability. The project objectives and work plan are based on three observations:

*(1). Energy-water interdependence is a problem of national scope, solved at the regional scale.*

Although renewable resources may ultimately supply a larger fraction of domestic electricity needs, in the near term, rapacious growth in demand will be met by increased thermoelectric generation from coal and natural gas (Figure 3). Water withdrawal and consumption for electric power generation will therefore increase nationwide, exacerbating fierce competition between agriculture and the electric power sector for scarce freshwater. As seen in Figure 1, demand for water in support of new additions to thermoelectric capacity will not be uniform. In southern and western states, robust population growth will impose ever greater burdens upon already overtaxed local water supplies. Competition for water has ignited disputes among several southeastern states due to persistent drought. As an indicator of the severity of the problem, and the conflicts it can generate, Georgia legislators recently moved to redraw their state's northern border with neighboring Tennessee in a bid for access to Tennessee River water [8].

The resolution of interstate disputes over water use for energy, agriculture and other commercial sectors is complicated by the absence of national cohesion in water policy. Whereas the Department of Energy has administers a broad portfolio of energy research, development and policymaking, no single agency within the executive branch of the federal government operates in a comparable manner for water. Rather, oversight of water resources is partitioned among nearly two dozen federal agencies including the Department of the Interior, EPA, U.S. Geological Survey, and other entities. Decisions about water resource allocations are thus generally made at the regional scale by state or local governments rather than by a federal agency. The situation is further complicated by the patchwork quilt of laws that govern water rights at the statehouse level (Figure 4). Eastern states follow a riparian water law that gives landowners adjacent to waterways a right to reasonable use of surface water. By contrast, the prior appropriation system used in western states has its historical basis in allowances made for miners and other settlers to use surface water and groundwater on federal lands they do not own, even in cases when the land is not adjacent to the water resource. Resolution of interstate water conflicts is particularly difficult in regions such as the Missouri River basin, which spans both riparian and appropriation states, as well as states that have a hybrid system of water law.

Given these realities, the objectives and work plan outlined in this project will develop case-appropriate regional-scale solutions to the overarching national challenge of energy-water interdependence. It is at the state and local level where the introduction of technologies and policies to reduce thermoelectric water use will have its most significant impact to enhance the resilience and sustainability of energy and water infrastructures.

*(2). The energy-water nexus represents a crisis today in some regions of the U.S. Climate change further threatens energy and water security by amplifying extreme weather events.*

To meet escalating demand, a new 500 MW power plant must be built in the U.S. *each week* for the next 15 years [1]. Even in the midwestern and northeastern U.S., where population growth is relatively flat, demand for electricity is anticipated will rise due to increases in per capita consumption. For thermoelectric capacity additions using conventional cooling tower systems, a corresponding 21-48% increase in freshwater consumption will occur in 25 years.

The Sunbelt states of the southern and western United States have experienced vigorous population growth and will continue to add new residents. Here, burgeoning energy demand presents a grim water forecast for regions where freshwater supplies are already scarce. Over the next 25 years, freshwater consumption for thermoelectric generation is projected to rise 74% in the Rocky Mountain states; 199% in Florida; and a staggering 352% in California [1]. Even in the southeastern U.S., where freshwater is not ordinarily viewed as a limiting resource, an extended drought in 2007 led to imposition of water use restrictions normally associated with water conservation in western states. Predictably, shortfalls in available freshwater disrupt local economies and engender disputes between energy and agricultural interests over water appropriations. Surprisingly, this occurs even in traditionally water-rich northern states such as Minnesota and Illinois, where permits for new ethanol plants have been rejected over concerns about excessive water use and mining of groundwater resources [3].

Climate change is a wild card that may potentially reallocate freshwater resources, region by region, over the next several decades. The warming of the planet is generally expected to bring more precipitation to the northern part of land masses in the northern hemisphere and amplify desertification in the subtropics [9]. Although regional-scale information on changes in water resources is uncertain, it is generally held that climate change will increase the intensity of droughts, floods and peak summer temperatures. Given that the capital costs for the construction of new thermoelectric plants are typically recouped over a 40-year life cycle, it is prudent to consider whether the water resources presumed to be accessible at a plant location will in fact be available over the full service lifetime of the generating facility.

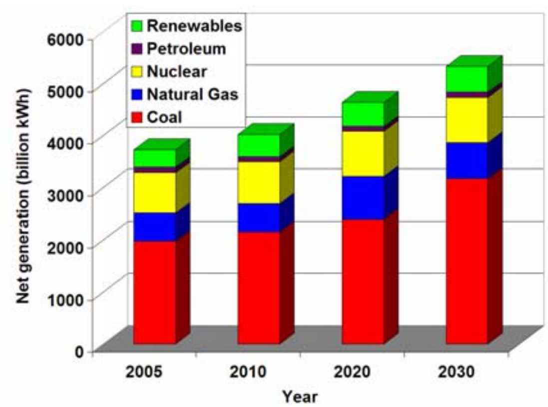


**Figure 3: Projected electric power generation in the U.S. by fuel resource [2].**

**Figure 4: Regional variations in state water laws [3] showing states with riparian (blue), prior appropriation (red) and hybrid water laws (green).**

*(3). Methods to mitigate atmospheric carbon emissions are water-intensive. Strategies to combat global warming must also consider the availability of water to capture and store carbon.*

Because of the ever-rising demand for electricity, business-as-usual approaches to electric power generation through coal and gas combustion will sharply increase greenhouse gas discharges to the atmosphere. Societal recognition of climate change has spurred interest in carbon-neutral electricity. However, the U.S., China, India and other nations possess large coal reserves and will likely use them to generate cheap electricity in the near-term. Hence, carbon mitigation systems will be essential components for coal-fired or gas-fired capacity additions.

Unfortunately, many of the proposed technologies within reach for carbon capture and storage (CCS) are water-intensive. Post-combustion capture of carbon dioxide from the stack gases of coal-burning plants or gas turbines can be presently accomplished most economically by scrubbing using an absorption column with an amine solvent [10]. Large volumes of additional water, beyond that already used in condenser equipment, are required to scrub $CO_2$ from combustion flue gases at the gigaton scales necessary to affect a meaningful change in atmospheric $CO_2$ concentrations. Alternatively, an integrated coal gasification combined cycle (IGCC) approach can be undertaken to generate electricity from coal while exhausting $CO_2$ at elevated pressures and volume fractions suitable for capture by physical absorption or by using membranes or porous adsorbents [10]. While these separation methods reduce the water requirements of CCS, the water savings are undercut by the large amounts of process steam needed to convert coal synthesis gas to $CO_2$ and hydrogen via the water-gas shift reaction. Thus, the continued exploitation of fossil fuels to meet rising electricity needs in a climate-conscious manner will require the appropriation of huge new volumes of freshwater.

Clearly, strategies undertaken to move toward energy sustainability with respect to climate change will be fatally flawed if they precipitate water crises by exacerbating energy-water interdependency at generating plants with CCS. An integrated approach to resource planning is therefore needed to ensure that the nation's water infrastructure is properly maintained even as a significant expansion of generation occurs in the domestic energy sector.

## 3. Project Objectives

(1). Analyze the life cycle costs and resource impacts of alternative technologies or water resources to supply the process water needs of thermoelectric power plants, through material balance models for fossil fuel-fired plants (with and without carbon capture), nuclear plants, and biomass co-fired plants, to guide technology selection.
(2). Interface high-resolution climate-weather models with surface water and groundwater hydrologic models, to project water resource availability within watersheds for a long-term planning horizon under changing climatic conditions.
(3). Conduct strategic investment analyses for utilities in water conservation and reuse technologies, as well as emissions mitigation technologies, in the context of uncertain national climate change policies, regional water regulation, and water availability.
(4). Integrate the tools developed in objectives (1), (2) and (3) into a decision support system, with resilience and sustainability metrics applied at the watershed level, to inform water resource allocations and investments in alternative energy technologies, for the benefit of stakeholders in the energy sector and other industries and communities reliant upon freshwater.
(5). Apply these tools to case studies for three different regions of the U.S. representing a diverse set of geographic features, climatic conditions, water inventories, and trends in regard to population growth, electricity consumption, and energy resource development.

## 4. Research Plan: Background and Technical Approach

A description of the key project personnel, their research expertise, and their synergistic activities on this project can be found in the supporting information.

4.1. Life Cycle Assessment of Sustainable Thermoelectric Water Use (Lastoskie, Schwank)

*Background and State of Art*: Steam-driven plants require heat exchange to condense turbine exhaust. Most coal-fired plants and all nuclear plants in the U.S. use wet cooling systems based on open-loop or closed-loop cooling cycles. In open-loop or once-through systems, cooling water is withdrawn directly from a lake or river and heated water is returned to its source. Because of thermal pollution concerns and entrainment problems on intake screens, open-loop cooling is generally done only with seawater at coastal facilities [11]. Most plants built since enactment of the Federal Water Pollution Control Act in 1972 use closed-loop or recirculating wet cooling systems (Figure 5) to dissipate waste heat to the atmosphere rather than to surface water [3]. These systems use a cooling tower to transfer heat to ambient air by conduction, convection and evaporation. Closed-loop systems withdraw less than 5% of the water required for once-through cooling [3]; however, water *consumption* is larger in recirculating systems because of evaporation and blowdown losses to prevent mineral fouling. Freshwater losses from evaporation in wet cooling amount to 3.3 billion gallons per day in the U.S., nearly 20% of all nonagricultural freshwater consumption [5].

One option to reduce thermoelectric freshwater use is to deploy air-cooled condensers (Figure 2) for "dry cooling" of turbine exhaust by conduction into ambient air blown by fans across the tube surface. Air cooled condensers eliminate water use, but incur higher capital and operating costs and a 2-5% plant efficiency reduction relative to wet cooling [12,13]. Power output at dry-cooled plants decreases by as much as 25% in hot weather [14], so air-cooled condensing is potentially most effective for power plants in states with northern climates.

Alternatives to reduce freshwater use at inland plants are to utilize brackish groundwater or wastewater effluents in wet cooling systems (Figure 2). Shallow saline aquifers (Figure 6) are found in much of the U.S., as are produced waters from mining operations and oil and gas extraction. However, impaired waters from these sources must be treated to be suitable for thermoelectric cooling. Brackish groundwater typically contains 500-30,000 mg/L total dissolved solids [3], including $Ba^{2+}$, $Ca^{2+}$, $SO_4^{2-}$, and $CO_3^{2-}$ solutes that foul condenser equipment from calcite, gypsum and barite precipitation. Wastewater effluents have high dissolved solid content. Scale reduces heat exchange efficiency and damages equipment as minerals concentrate from evaporative losses [15]. Desalination using reverse-osmosis membranes [16-32] or chemical demineralization [33] must therefore precede impaired water use in thermoelectric cooling.

*Technical Approach and Implementation Plan*: In this project, life cycle assessment [34-44] will be conducted to determine the economic costs, environmental emissions, and water resource impacts of electricity production from non-renewable and renewable fuels using different thermoelectric cooling options. Previously, LCA has been used to evaluate various components of energy and water infrastructure, including energy extraction from crops and fuel cells [45-48] and potable water processing by seawater desalination [49-56]. Here, case studies will be carried out for wet, dry, brackish water, and wastewater effluent cooling for a 350 MW coal-fired steam plant; a 1000 MW nuclear reactor; and a 500 MW gas combined-cycle plant in 2x1 configuration (i.e. two 165 MW gas turbines and one 170

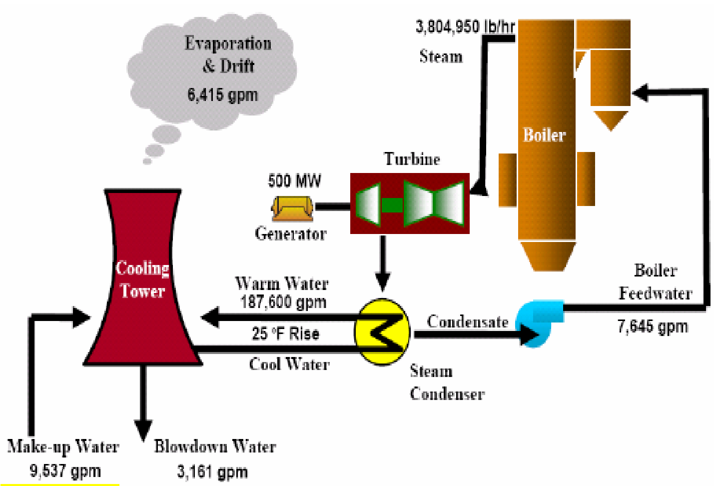


**Figure 5. Representative steam and cooling water flowrates for a 500 MW coal-fired steam power plant with a wet recirculating cooling tower [1].**

MW steam turbine). These configurations represent the coal, gas and nuclear power plants that collectively account for 90% of domestic generation (Figure 3). Plant types differ in substantive ways in regard to their cooling requirements. Nuclear plants, for example, have higher condenser loads than coal-fired plants because they do not reject heat in combustion flue gases. Material flows, air and water emissions, and construction and maintenance components for condensers and impaired water treatment units will be inventoried using data gathered with the assistance of Dr. Bob Goldstein (EPRI), Dr. Tom Feeley (National Energy Technology Laboratory), and Dr. Mary Ann Curran (EPA). Seasonal temperatures and moisture conditions for humid, cold northern states; arid, warm western states; and humid, temperate southern states will be evaluated. Operating penalties (e.g. low efficiencies at high turbine backpressures [13]) and aggregate total costs will be calculated for cooling options at specified power ratings.

A *sustainability index* [57] for water use in electricity production will be calculated as the *reduction in freshwater commitment per kilowatt-hour generated, per unit added capital and operating cost* of the water-conserving technology. This index will be computed relative to a base scenario wherein a conventional closed-loop water-cooled thermoelectric condenser is used for generating capacity additions. Sustainability indices will be determined for water use commitments in new fossil fuel-fired plants utilizing CCS or in the case of coal-fired plants, gasification units for the production of hydrogen or methane combusted in gas turbines. The water sustainability index will augment conventional life-cycle indicators (e.g. fuel depletion, global warming potential) by explicitly measuring the decoupling of energy and water infrastructure using alternative cooling methods. Water consumption in processes that indirectly sequester carbon, e.g. coal co-firing with biomass, will be also investigated.

4.2. Climate Change Projections and Watershed Modeling (Rood, Weintraub)

Freshwater sustainability measures developed from LCA studies in objective 1 are of limited standalone application on the infrastructure scale because they focus exclusively on water withdrawals and consumption at a single thermoelectric plant. Integrated resource planning, by contrast, is conducted by utilities on larger geographical scales as they determine the suitable number, size, type, and location of generating plants needed to meet projected increases in electricity demand in their respective service regions. To quantify impact of thermoelectric capacity additions on water inventories in a utility's service region, a watershed model will be developed. The hydrologic model will be adapted to allow local effects of global climate model predictions to be accounted for in freshwater resource simulations over intervals of decades.

*Background and State of Art (Watershed Models)*: In this project, the WARMF (Watershed Analysis Risk Management Framework) watershed management tool, created by Systech in partnership with EPRI and available for download from the U.S. EPA (58,59), will be developed into a decision support system for assessment of the water resource impacts of planned additions to electricity generation and synfuel production. WARMF is a peer-reviewed, dynamic watershed simulation model that calculates daily surface runoff, groundwater flow, non-point source loads, hydrology, and water quality of river segments and stratified reservoirs [60,61]. It has been applied to over twenty watersheds in the United States and abroad, and was originally designed to support modeling and planning for total maximum daily loads [62].

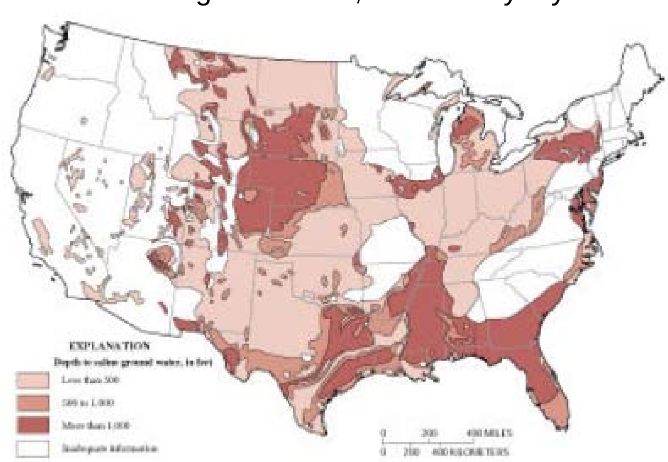


**Figure 6. Saline aquifers in the continental U.S. Brown shading indicates aquifer depth, with the lighter shaded areas denoting shallow and thus more accessible brackish water resources [7].**

A schematic of the WARMF modeling framework is shown in Figure 7. Input topography, land cover, and meteorology data are applied to a network of interconnected catchment basins and surface water segments to simulate snowpack accumulation, snowmelt, groundwater percolation, moisture content of soil layers, groundwater table elevation, and lateral flow to neighboring streams and lakes. Water infiltrates into pervious soils based on the soil moisture content, volume of water available for infiltration, and hydraulic conductivity. Under saturated soil conditions, the model simulates surface runoff and soil erosion. Evapotranspiration is calculated based on latitude, air temperature, and relative humidity. Subsurface lateral flow and overland flow entering the river is then routed from one river segment to the next downstream river segment until it reaches the watershed outlet. The management of water impacts the available streamflow and reservoir volumes, and is defined in the model by specified reservoir releases, diversions, and irrigation applications. Nonpoint source loads are simulated for each sub-watershed and land use category using a build-up/wash-off algorithm. Point and nonpoint loads are routed through the system and transformed via first order reactions. Heat budget and mass balance calculations are performed to calculate the temperatures and concentrations of water quality constituents in each soil layer, river segment, and lake compartment.

Model input coefficients and output visualizations are accessible via a GIS-based watershed map. Model predictions are viewed as a time series output of flows, concentrations, and water shortages/surpluses at various watershed locations. Shortages, available pass-through, and point/nonpoint pollutant loadings, are displayed via color-coded maps and bar graphs.

*Technical Approach and Implementation Plan (Watershed Models)*: The application of WARMF to one or more pilot watersheds will involve several steps. First, the watershed will be delineated into a network of land catchments, river segments and reservoirs using 30 m digital elevation model data and a National Hydrography Dataset stream network. Input data on meteorology, land use, observed stream flows, diversions, and reservoir releases will be obtained from national databases. To capture power generation impacts on the watershed, additional data will be gathered with guidance of utilities on power plant withdrawals and return flow volumes and temperatures. Calibration will be performed by comparing simulated and observed flows at locations with available gauging data. Landscape parameters (soil thickness, field capacity, hydraulic conductivity) will be adjusted within a reasonable range, based on local knowledge, to improve hydrology predictions for the water budget including global, seasonal and event-specific balances. Statistical comparisons will be used to determine quality of fit.

The calibrated WARMF application will be used to test potential management scenarios related to energy-water interdependence and cooling water resource use. Scenario development will require additional power generation input data to characterize expected changes in diversions, reservoir releases or point source returns. For example, a newly sited plant in a basin may withdraw water directly from an adjacent river, or produced waters may be used instead. The quantity of water withdrawn will depend on the proposed condenser technology.

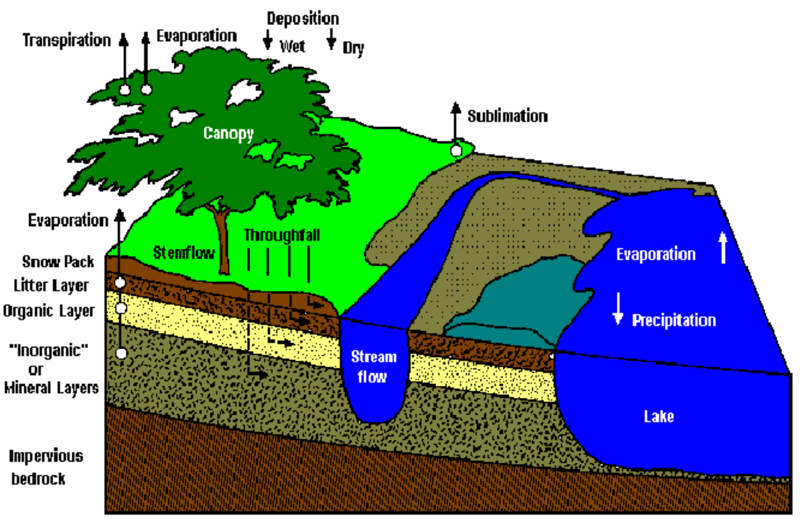


**Figure 7: WARMF watershed process model to simulate freshwater flow.**

To characterize model uncertainty, an iterative stochastic sampling technique developed in the WARMF

ZeroNet module will allow construction of a range of scenarios based on a database of historical climate data. An ensemble of simulations will be run to produce a probabilistic distribution of results characterizing resulting stream flow, shortage, and surplus of water in watersheds faced with potential drought or competing water uses. The watershed tool will provide a record of where violations of minimum stream flow or minimum reservoir elevation occur under such conditions. An adaptive management approach will be used to iterate multiple potential alternatives and evaluate a balance between potential issues and risk.

*Background and State of Art (Climate/Weather Models)*: Human management of water significantly alters the runoff, distribution, and availability of surface water as compared with a natural state. Changes in precipitation, snow pack and evaporation expected with global warming will alter distribution and annual variability of surface water. Loss of stationarity (the assumption that over time, the statistics that describe the variability of a system are unchanging) due to climate change will impact water resource management systems [63].

Climate change models provide input data to a hydrologic model to project the effects of climate change on regional water availability. The most significant variables to consider are precipitation, temperature, and whether or not storage of water in seasonal snow or ice is important to regional resources. Climate change effects are often counterintuitive. In many regions, more precipitation is expected; however, increased temperatures will amplify evaporation such that there is net drying of soil moisture and surface water. Climate change is expected to increase the frequency and severity of droughts and intense storms, and shift flow cycles that water management systems have been designed to accommodate. For example, earlier and more rapid melting of snow from high mountains such as the Sierra Nevada will release water in the spring that historically discharges over the summer. In the Midwest, rather than sustained wintertime snow cover, there will be cycles of snowfall and snowmelt.

The atmospheric dynamics that transport moisture into the continent are affected by topographic features not well resolved at the 100-200 km scale of many climate models. In the summer, for example, moisture is carried into North America in low level jet streams confined to the bottom 1-2 km of the atmosphere and concentrated at the edge of large-scale, quasi-stationary high pressure systems like the Bermuda High [64]. In the western U.S. in particular, these jet streams are often confined by topography. High resolution climate change models, linked to weather phenomena, are therefore needed if these models are to provide input information to the watershed model to be used for energy infrastructure planning.

*Technical Approach and Implementation Plan (Climate/Weather Models)*: Two strategies will be followed to link the projected effects of global warming to the hydrological model of water availability for energy applications. First, downscaling of high resolution statistical information will be performed to infer local features from model results obtained at coarse resolution. Downscaling has been shown to be useful in the western U.S., where the bulk of precipitation is from large-scale atmospheric phenomena and regional variability is associated with topography [65]. A database of downscaled surface air temperature and precipitation projections in the U.S. at 12 km resolution from 1950–2099 is publicly available [66,67].

While downscaled models provide a credible starting point, their predictions often do not convincingly represent the weather-scale phenomena responsible for water transport. Therefore, two higher resolution climate-weather models will also be evaluated to provide input to the hydrological model: the Community Climate System Model (CCSM) [68] from the National Center for Atmospheric Research, and the GEOS-5 model [69] from NASA/Goddard Space Flight Center. Prof. Rood is currently funded to perform experiments with both models. Figure 8 illustrates the benefit of using CCSM at high resolution to increase the realism of how precipitation is represented in the western U.S. [70,71]. The model at higher (½ degree) horizontal spatial resolution better represents the weather-scale dynamics and thus better accounts for surface topography, as shown by comparison to observations from the National Oceanographic and Atmospheric Administration. Topographic features are extremely important to include in watershed models, as they suggest, for example, a much more robust partitioning of water into the river basins of mountainous regions. The simulations now approach the resolution of the downscaled models described above, and to our knowledge, they will be the first simulations that use weather-scale, global climate models for climate adaptation studies.

4.3. Real Options Analysis of Policy and Weather Uncertainty Impacts on Water Technology Investments (Adriaens, Lyon, Wolfe)

*Background and State of Art*: Global climate change is likely to impact the future geographic distribution of water, rework water allocation strategies for energy and agriculture, and drive emissions management policies [72,73]. Uncertainties associated with water availability, policy frameworks and electricity pricing present a challenge to energy utilities for investment decisions in water conservation, alternative cooling, and emissions abatement technologies [74,75]. These uncertainties and their effect on technology investment decisions in the power sector are taken into account as probability weights in computing an expected discounted cash flow (DCF). However, this methodology does not quantitatively take into account investment risks and the value for utilities and decision-makers of keeping their investment options open.

Real options analysis (ROA) enables a nuanced quantitative approach to model the impact of uncertainty and account for the flexibility of strategic investment when faced with uncertain future cash flows [76]. ROA is particularly useful for policy analysis in this project for the following reasons. (1) Individual elements of risk can be modeled separately and in combination, to look at their relative contribution to overall risk. (2) ROA evaluates regulatory risks in financial terms so they can be related to likely effects on investment behavior. (3) ROA is flexible and allows comparison of different policy designs in terms of their effect on investment risk. Real options approaches have been widely applied to model the effects of uncertainty in a variety of energy subject, including emissions trading and $CO_2$ penalties [77-79]; R&D expenditures for renewables [80]; and technology adoption decisions under uncertainty [74,81,82].

*Why adopt this approach to quantify the risk of investment in water and emission abatement technologies?* Getting the right type of investment in infrastructure for water supply and consumption is a requirement to enable the transition toward a sustainable and resilient energy infrastructure. One of the tasks of climate change policymakers is to create incentives to encourage the private sector to undertake the necessary investments. *However, the translation of climate and water allocation policies into clear investment signals is not straightforward, in part because energy and water infrastructure investments occur in a highly dynamic context*. For example, the risk premium associated with policy uncertainty for coal- and gas-fired power plants to invest in CCS technologies was shown to require an increase in the carbon price by 16-37%, relative to the situation of policy certainty [75]. Generally, firms require sufficiently high output price levels, e.g. elasticity of energy pricing, to be induced to invest in environmental technologies, because they optimally would not want to commit to an irreversible investment that could turn out to be unprofitable in the event of a price and/or policy change [83].

*Technical Approach and Implementation Plan*: This objective will develop a ROA framework for evaluation of water-conserving technologies for power generation, as well as for investment

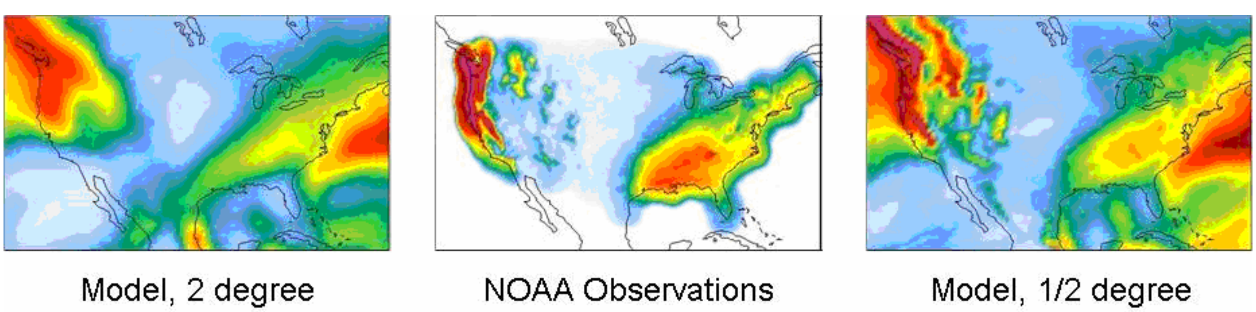


**Figure 8: Twenty-year average of January precipitation from Community Atmosphere Model simulations at 2 degree and ½ degree resolution, and comparison to NOAA observations. The improved realism of the high-resolution spatial model is evident, particularly in the western U.S.**

in alternative and renewable energy sources. The framework will quantify the option value of each technological investment in an uncertain policy environment (e.g. RPS, production tax credits, carbon taxes, power tariffs on water use) as a measure of the contribution of that technology to resiliency of the energy infrastructure, and will identify future circumstances under which adoption of each technology becomes cost-effective. The ROA framework developed under this objective will then be adapted to the circumstances and uncertainties embodied in each of the three case studies (objective 5) to illustrate the likely dependence of technological innovation on regional circumstances. Finally, based on what is learned from the case studies about the essential drivers of investment decisions, a ROA tool that can be applied in any region of the U.S. will be included in the decision support system developed as the project capstone.

The investment analysis will draw on previous objectives, and assumes a multi-step process of (1) investment in an abatement technology (e.g. dry cooling; filtration of impaired water resources; carbon capture and storage); (2) consideration of alternative technologies that reduce water use or $CO_2$ emissions; and (3) a cash flow stream from electricity production [81,84]. The latter depends on the price of electricity at the time it is produced. In classic DCF analysis, the two investments and resulting cash flow stream are aggregated to give a net present value. A manager using real options thinking would view investment in abatement technology as the purchase of a call on an option to continue providing electricity. The strike price (price at which the option can be exercised) is the cost at the time the investment is undertaken. The value of the underlying security is the value of the electricity to be produced less the cost of producing it, for the assumed policy, pricing, and water availability uncertainties.

From objective 1, the effects of investments in water saving technologies and renewable energy on the utility life cycle will be derived, and the effect of fuel prices on power generation costs and carbon emissions will be obtained. Objective 2 will provide predictions of water availability and cost and incorporate inputs of population growth and economic activity. The latter inputs will support development of a time series of electric power demand and water availability under climate change assumptions. The basic ROA approach will be adaptive planning of the technological investments described in objective 1. Power generators will be assumed to plan by maximizing the following objective function, which is the net present value of operations, subject to optimal timing of the investments:

$$W_t = \max T \left[ \int_0^\infty ( P_t Q_t - C_t )\, e^{-rt} - I\, e^{-rT} \right]$$

where $P_t$ and $Q_t$ are the price of and demand for electricity; $C_t$ is the cost of producing electricity; $r$ is the discount rate; $I$ is the investment cost, and $T$ is the time the investment is undertaken. The dependence of $P_t$, $Q_t$, $C_t$ and $I$ on uncertain future trends will be specified based on the findings of objectives 1 and 2, per policies detailed earlier. Objective 1 will provide a connection between alternative investments $I$ and costs $C_t$, including power generation costs and costs associated with carbon emissions. The latter will be represented by a fee or a market value (not shown explicitly as part of $C_t$ above). Regulatory uncertainty will be represented as uncertainty in this fee or market price, which will be assumed to be jointly distributed with uncertain fuel prices, population growth rates, and water availability. Objective 2 will inform expected trends in $Q_t$ and in water availability as a determinant of $C_t$, including the correlation between them.

4.4. Integrated Decision Support System for Resilient Energy-Water Infrastructures (all)

Resilience is a critical performance metric for all infrastructures that have interdependencies [85-93]. In general, the infrastructure to manage water resources is designed to accommodate the mean amount of precipitation (and evaporation) and the variability based on historical observations. Climate change is expected to increase the variability on both ends of the precipitation probability distribution function (pdf), causing more frequent droughts and floods. Climate models allow for the evaluation of the frequency of extreme events for both the past and the future [94,95], and a set of indices has been proposed to extract correlated extremes both for climate change detection and for evaluation of extremes in the future [96]. While it is possible to develop statistical methods to extract extremes, application to real-world problems strongly depends on specifics of the applications. For example, installation of flexible water management systems at thermoelectric power plants might provide energy infrastructures in drought-prone regions with resilience to climate change. The material flow models for atmospheric, surface and thermoelectric plant water developed in objectives 1 and 2, and the real options analysis model developed in objective 3, provide tools for electricity generators to manage extreme weather events or restrictions placed on water use. A decision support system will be developed using these models to transform their respective inputs of climate parameters, freshwater and impaired water resource inventories, technology investment costs, and policy forecasts directly into the information used by resource managers.

*Background and State of Art*: The resilience of an infrastructure is expressed in terms of the extent and rapidity that its services can be restored following a disruption that causes a temporary loss of function [97]. In the context of electric power infrastructure, the resilience $R$ of a fleet of power plants to a shortfall of process water resulting from drought or other event is

$$R = \int_{t_0}^{t_f} [\, 100 - Q(t) \,] \; dt$$

where Q(t) is a quality measure of the combined generation (i.e. the output of the fleet of plants over time, as a percentage of their output at their usual operating capacity factors) following a disruption of water supply that begins at $t_0$ and ends at $t_f$. A quality measure of 100% thus corresponds to no reduction in generation, while 0% corresponds to total loss of output. Energy infrastructures that are resilient to water interruptions return small values of R. The shape of the quality function will depend on the nature of the disruption. For acute catastrophic events (e.g. an earthquake), the infrastructure quality may fall abruptly and then slowly rise, with a recovery time ranging from days to months as damaged plants are repaired and returned to service. For drought episodes, the quality reduction will be less severe, with Q(t) fluctuating at values below 100% as water withdrawals are curtailed at the affected plants over a period of weeks to years. Over even longer timescales (i.e. decades), the gradual effects of global climate change can be embedded in the same resilience measure. For global warming-induced desertification of a region, for example, the quality measure will manifest as a slowly decreasing function over time, as the fleet of plants in an increasingly arid region experiences a cumulative degradation in generating capability due to the withering of local water resources.

Waterless air-cooled or hybrid wet/dry condenser systems can improve the resilience of electric power infrastructures by adding redundant cooling capabilities at thermoelectric plants. Because of the plant efficiency reductions incurred for dry cooling, and the absence of economic disincentives for water use at power plants, less than 1% of domestic thermoelectric plants presently use dry cooling [1]. It is anticipated however that global warming will increase not only mean surface temperatures, but also the magnitude and duration of extreme weather events. Given that climate change will redistribute water resources and amplify weather variability, local water availability for electricity generation will become increasingly unpredictable over the generating lifetimes of new thermoelectric capacity additions. Therefore, hybrid condensers with redundant cooling options, and nontraditional water resources not dependent on recharge by precipitation, will be considered as options to improve the resilience of thermoelectric fleets.

*Technical Approach and Implementation Plan*: While the measure presented above to quantify resilience at the electric power energy-water nexus incorporates life cycle and climate/watershed model results in its calculation, it does not specifically address the economic considerations described in objective 3 which will largely dictate whether the energy sector invests in water management technologies. To this end, a *resilience index* for electric power generation, defined as the *recovery of kilowatt-hours otherwise forfeited* during drought events, per unit additional capital and operating costs for water management systems, will be calculated for thermoelectric plants that are fitted with redundant hybrid cooling systems or impaired water treatment units. Coupled with the freshwater consumption sustainability index noted in objective 1, these indices will be used in the WARMF and LCA models to assess the resilience and sustainability of suggested configurations of generating fleets (i.e. number, type, size and location of power plants) for capacity additions in selected watersheds (objective 5).

Preliminary work by Weintraub *et al*. at Systech and EPRI, in partnership with NETL and Los Alamos, provides a mechanism for integrating critical water supply and demand information [98,99]. An analysis using WARMF was conducted of the effect to the power generation community of climate variability impacts on water resources in the San Juan Basin (NM, CO) and Lewis River Basin (WA) [100]. Temperature variability was evaluated discretely in conjunction with precipitation variability to predict potential risk of reduced available inflows and violation of minimum reservoir elevations or instream flow criteria (Figure 9). In this project, this concept will be expanded using stochastic simulation to include pdfs of temperature and precipitation from climate models, output resulting streamflow and reservoir elevation pdfs from WARMF, and translate these into a composite risk of not meeting in-stream flows or minimum reservoir elevation criteria. Simulations comparing a set of potential water-energy management alternatives will translate the risk into potential for resilience reduction due to inadequate water.

<u>4.5. Case Studies of Regional Energy-Water Infrastructure Interdependence (all)</u>

The tools developed in objectives (1)-(4) will be applied to case studies of three watersheds: (1) the San Juan Basin in New Mexico, Arizona, Utah and Colorado; (2) the Upper and Middle Chattahoochee Basin encompassing Lake Lanier and Lake Harding in Georgia; and (3) the Lake St. Clair-Detroit watershed in southeastern Michigan. These basins present a cross-section of climate conditions, population characteristics, and energy consumption patterns that will demonstrate the robustness and applicability of the decision support system to energy and water community stakeholders. A synopsis of the key features of each region follows.

*<u>4.5.1. San Juan Basin</u>:* This mountainous watershed, spanning the Four Corners region of the U.S. (Figure 10), overlies the nation's largest proven gas reserves. New Mexico also has abundant oil and coal resources and about 90% of in-state electricity is supplied by coal-burning plants [101]. A significant fraction of intrastate power generation is exported to California and western markets. The Public Service Company of New Mexico (PNM) is the principal utility in the region. It withdraws a substantial portion of its water for thermoelectric plant operations from the Navajo Reservoir on Native American land (Figure 9) [102]. PNM has announced environmental performance goals that include using 15% less freshwater per MWh of electricity generation than in 2002 for current plants, and 20% less freshwater for new plants [103].

Although the population density of the San Juan basin is relatively low, population growth in other western states such as Arizona, Nevada and California have led to a sharp rise in regional demand for electricity. The proximity of fossil fuel resources in the San Juan basin makes the

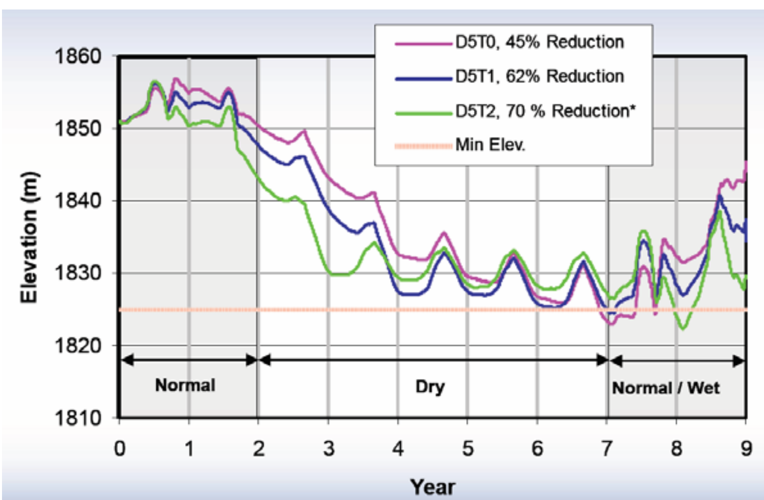


**Figure 9: Simulated Navajo Reservoir elevations under a 5-year drought condition. Scenarios represent a range of expected temperature increases and required reduction of reservoir releases to meet a minimum elevation criterion: D5T0 (0º increase, 45% reduction of outflows), D5T1 (1º increase, 62% reduction), D5T2 (2º increase, 70% reduction).**

region attractive for future capacity additions. However, freshwater supplies in the basin are scarce, and their allocation is handled by the New Mexico Office of the State Engineer and the Interstate Stream Commission [105]. The federal Bureau of Reclamation has convened a Shortage Sharing Team to facilitate collaborative efforts among ten water user entities, including Native American tribes, irrigation districts, and power companies, to conserve San Juan River water resources and negotiate shortage issues [106].

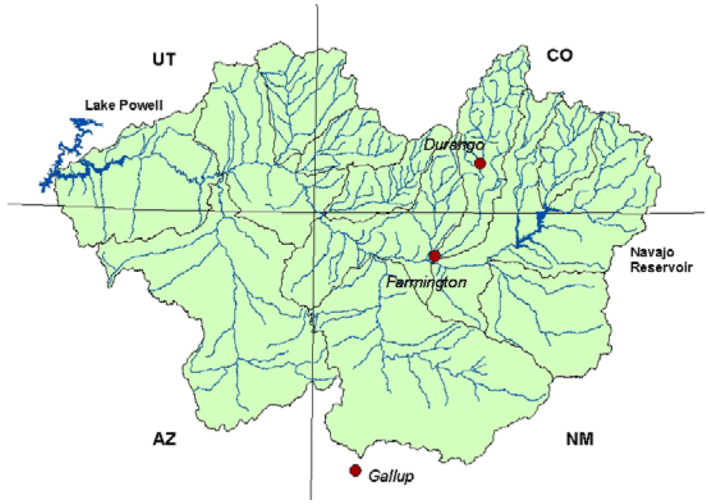


**Figure 10: San Juan basin watershed (24,700 sq. mi.).**

The decision support system developed in this project will be applied in year two to evaluate strategies for resilient and sustainable PNM capacity additions of coal- and gas-fired plants in the San Juan Basin that utilize air condensers, brackish water, or produced waters from oil and gas extraction for thermoelectric cooling. The project team will collaborate with energy-water experts at DOE laboratories in New Mexico, Dr. Michael Hightower of Sandia and Dr. Cathy Wilson of Los Alamos, and their PNM contacts in gathering data and simulating energy infrastructure development scenarios in the San Juan Basin.

*4.5.2. Chattahoochee River Basin:* In year three, the project team will turn its attention to the upper and middle branches of the Chattahoochee River (Figure 11). This basin spans across north-central Georgia and includes Lake Lanier, a water resource that has been the focus of intense controversy over withdrawals during the current period of drought afflicting the southeastern U.S. In 2007, the state of Georgia sued the Army Corps of Engineers, which manages Lake Lanier, to prevent diversion of water to Florida's Apalachicola River [107]. Atlanta's northern suburbs are among the fastest growing regions in the U.S., and Lake Lanier serves as the principal supply for this region's energy and water needs.

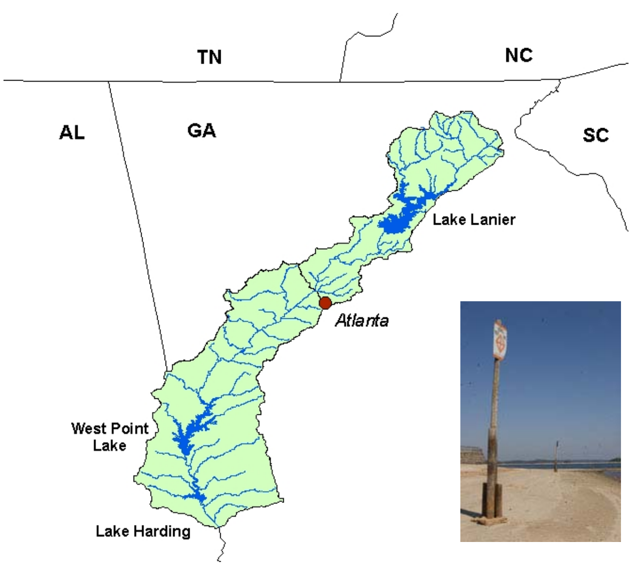


**Figure 11: Upper and Middle Chattahoochee watershed (4620 sq. mi.). Inset shows low water levels at Lake Lanier during 2007 drought [107].**

Georgia imports Appalachian coal and Gulf Coast gas for its fossil fuel resources, and its per capita electricity consumption and generation (which includes substantial hydropower and nuclear) are among the highest in the U.S [108]. Georgia Power, the largest subsidiary of Southern Power, is the major utility in the region. In Georgia, winter precipitation is associated with large-scale weather systems that draw their moisture from the south [104]. In summer, rain is delivered by thunderstorms that form over the heated continental land mass. Lake Lanier receives its water from a small catchment in northern Georgia. Precipitation in both winter and summer is strongly influenced by moisture transport from the Atlantic and Gulf of Mexico. Tropical storms are important parts of the water budget in summer and autumn.

Project modeling tools will be applied to investigate the use of non-traditional water resources, including wastewater, and the water impacts of carbon capture and storage for coal- and gas-fired fleet additions in the Chattahoochee Basin. Additions to nuclear generating capacity will also be considered. The impacts of extended drought on energy infrastructure resilience in northern Georgia will be evaluated, particularly for summer heat wave scenarios when power demand for air conditioning is exceptionally high. Team members will consult with Mr. Frank Stephens of the Gwinnett County Department of Public Utilities and Ms. Pat Stevens of the Atlanta Regional Commission to acquire data for the decision support system.

*4.5.3. St. Clair-Detroit Watershed:* In the final project year, the research team will examine energy-water interdependence in the local environment of the St. Clair-Detroit watershed in southeast Michigan (Figure 12). As a minor great lake, bridging its neighbors, Lakes Huron and Erie, Lake St. Clair is comparatively shallow, with a maximum natural depth of only 21 feet [109]. Like Georgia, winter precipitation in Michigan is associated with large weather systems drawing moisture from the south, and summer rainfall is delivered by organized convection over the heated landmass. There are also large local effects associated with the Great Lakes [104].

The population density of this mostly urban and suburban watershed is decreasing, although demand for electric power is still rising. The watershed chosen for study lies entirely within the service region of Detroit Edison (DTE), which operates a fleet of coal-fired plants and the Fermi 2 nuclear station for baseload power, and gas turbines for peaking power [110]. The fuel mix in this region is heavily coal-based, mostly from imports of Power River Basin coal from Wyoming. Gas is also routed into the region from the Antrim fields in the northern Lower Peninsula [111].

As the Great Lakes state, Michigan would seem an unlikely state to incur a water crisis due to energy production. Expansion of ethanol and biodiesel production in Michigan however has increased in-state energy sector demand for water. Moreover, rising petroleum prices may force a national transition to a coal-based synfuels industry. Given its abundance of water and well-developed coal rail transportation system, Michigan is a logical choice for development of a large-scale infrastructure for coal conversion into liquid fuels and synthesis gas. From a sustainability perspective, it is important to evaluate energy and water impacts of syngas production using coal, steam, and a thermal energy source. Coal gasification produces synthesis gas that can be fired to generate electricity in IGCC processes at thermal efficiencies exceeding 50%, compared to 30% for coal-burning plants [112,113]. But coal gasification is endothermic, so the process must be carried out above 1000 °C. The heat required to maintain high temperature may be generated by coal burning, but this lowers syngas yield and requires removal of $SO_x$, $NO_x$ and mercury emissions.

Alternatively, concentrated solar power can be used to deliver high-temperature heat for coal gasification [114,115] while avoiding the emissions penalties associated with burning coal. Steam is split by solar thermal-assisted photocatalysis into hydrogen and active oxygen and the latter is then used to catalytically convert coal into carbon monoxide [116]. However, the water splitting required for solar thermal gasification temperatures below 600 °C has significant water demands.

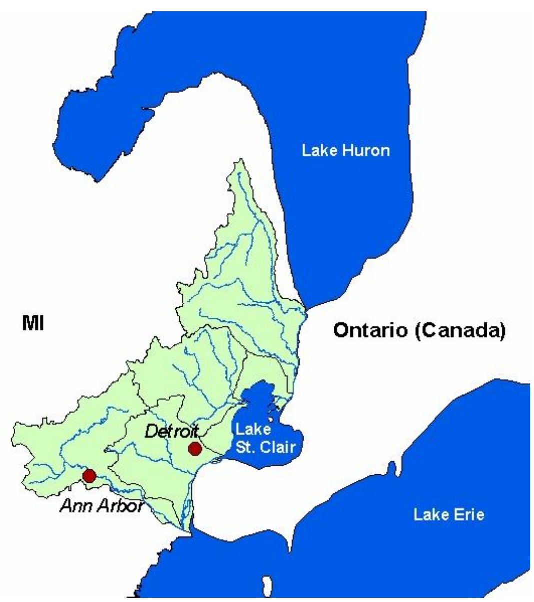


**Figure 12: U.S. portion of St. Clair–Detroit Watershed. The hydrologic units shown encompass a drainage area of 3960 square miles. Northern portions drain to the St. Clair River and Lake St. Clair. Southern portions drain to the Detroit River.**

Water impacts of traditional coal-fired, wood co-fired, solar-thermal gasification and IGCC power plant fleet additions will be analyzed for large-scale conversion of imported coal into electricity and/or synthesis gas for industrial applications [117] using water from the St. Clair-Detroit watershed at facilities in the DTE service region. The project team will collaborate with Mr. Skiles Boyd and Mr. David Harwood of DTE Energy to compile water consumption data at existing DTE plants and resource planning estimates of required fleet additions projected by the Michigan Capacity Needs Forum and 21st Century Energy Plan.

## 5. Education and Outreach Activities

*5.1. Undergraduate Research Assistantships.* Funds are requested to appoint four undergraduate research assistants per year at UM. Students will be recruited through two programs (Marian Sarah Parker Scholars and University Research Opportunity Program) to foster participation in research by underrepresented women and minority groups.

*5.2. Curriculum Development.* New graduate course materials will be developed to utilize research themes and content from the proposed work in the Energy Systems Engineering distance degree program at UM. Lastoskie and Schwank serve on the executive committee of this program. Lastoskie teaches CEE 567: Energy Infrastructure Systems, and Schwank teaches CHE 696: Alternative Energy Sources. Rood teaches AOSS 480: Climate Change – The Move to Action. Climate-watershed modeling studies will be incorporated into this course.

*5.3. Professional Outreach.* Graduate students will travel on-site to the case study regions to work with collaborators during the summer months of the project. These deployments will facilitate bidirectional exchange of information and decision support tools between academia and stakeholders in industry and government. To promote international impact, short courses on energy and water sustainability incorporating research content will be taught by Adriaens at China's Shanghai Jiao Tung University (SJTU) through the UM/SJTU Joint Institute.

Workshops will be organized at UM in years 2 and 3 of the project to address emerging intersections of the energy-water nexus in (1) coal synfuel and syngas production and (2) water quantity and water quality issues associated with biofuel processing in Midwestern states. The escalating water resources needed for alternative coal utilization and ethanol/biodiesel production merit conferences to address development of resilience and sustainability metrics for these fuel infrastructures, and identify technologies that can decouple their interdependencies.

*5.4. K-12 Outreach.* A pilot study of campus workplace energy conservation conducted by the UM Institute for Social Research [118] found that young adults are disproportionately high users of electric power. Given that environmental and resource costs of electricity use are concealed to consumers by historical concentration of generation at massive, remote coal-burning power stations, education is crucial to impart an understanding of energy and water interdependence and the benefits of energy and water conservation. Educational outreach will be conducted for students in grades 5-8 of Ann Arbor schools through the Washtenaw County Science Olympiad and Ann Arbor Mathematics Olympiad Cooperative. Lastoskie, who is a coach and volunteer teacher in both organizations, will coordinate K-12 outreach for this project.

## 6. Impact of the Proposed Research

The importance of achieving domestic energy and water sustainability cannot be overstated. Diversifying condenser technologies and adding redundant resources to thermoelectric cooling will dramatically improve resilience and sustainability in the energy sector and other sectors that depend on freshwater for economic vitality. Other nations, particularly China, confront similar problems in allocating limited water supplies to escalating demand in their energy and agriculture sectors. Tools developed in this project, while immediately applicable to the U.S., will have far reaching impact globally, and be of particular importance in assisting developing nations in Africa, Asia, and other arid regions of the globe to design sustainable energy infrastructures under water resource constraints. New measures of resilience and sustainability developed for the energy-water nexus can be applied to other infrastructures (e.g. impaired water use in agriculture). Finally, the project integrates plant-scale life cycle assessment with infrastructure-scale watershed modeling and weather-scale global climate predictions for first-of-its-kind climate adaptation studies of energy infrastructure resilience and sustainability.

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# SUMMARY PROPOSAL BUDGET
YEAR 1

| | | | | | |
|---|---|---|---|---|---|
| ORGANIZATION<br>**University of Michigan Ann Arbor** | | | FOR NSF USE ONLY<br>PROPOSAL NO. | DURATION (months)<br>Proposed | Granted |
| PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR<br>**Christian M Lastoskie** | | | AWARD NO. | | |

| A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets) | NSF Funded Person-months CAL | ACAD | SUMR | Funds Requested By proposer | Funds granted by NSF (if different) |
|---|---|---|---|---|---|
| 1. Christian M Lastoskie - PI | 0.00 | 0.00 | 1.50 | $ 16,789 | $ |
| 2. Peter Adriaens - Co-I | 0.00 | 0.00 | 1.00 | 15,828 | |
| 3. Thomas P Lyon - Co-I | 0.00 | 0.00 | 0.25 | 4,964 | |
| 4. Richard Rood - Co-I | 0.00 | 0.00 | 0.50 | 9,299 | |
| 5. Johannes Schwank - Co-I | 0.00 | 0.00 | 0.50 | 9,031 | |
| 6. ( 0 ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE) | 0.00 | 0.00 | 0.00 | 0 | |
| 7. ( 5 ) TOTAL SENIOR PERSONNEL (1 - 6) | 0.00 | 0.00 | 3.75 | 55,911 | |
| B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS) | | | | | |
| 1. ( 0 ) POST DOCTORAL SCHOLARS | 0.00 | 0.00 | 0.00 | 0 | |
| 2. ( 0 ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.) | 0.00 | 0.00 | 0.00 | 0 | |
| 3. ( 3 ) GRADUATE STUDENTS | | | | 73,460 | |
| 4. ( 3 ) UNDERGRADUATE STUDENTS | | | | 7,260 | |
| 5. ( 0 ) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY) | | | | 0 | |
| 6. ( 0 ) OTHER | | | | 0 | |
| TOTAL SALARIES AND WAGES (A + B) | | | | 136,631 | |
| C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) | | | | 39,366 | |
| TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C) | | | | 175,997 | |
| D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)<br>Computing cluster $ 51,200 | | | | | |
| TOTAL EQUIPMENT | | | | 51,200 | |
| E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS) | | | | 11,000 | |
| 2. FOREIGN | | | | 10,000 | |
| F. PARTICIPANT SUPPORT COSTS<br>1. STIPENDS $ 2,500<br>2. TRAVEL 5,000<br>3. SUBSISTENCE 0<br>4. OTHER 0 | | | | | |
| TOTAL NUMBER OF PARTICIPANTS ( 25 ) TOTAL PARTICIPANT COSTS | | | | 7,500 | |
| G. OTHER DIRECT COSTS | | | | | |
| 1. MATERIALS AND SUPPLIES | | | | 6,000 | |
| 2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION | | | | 0 | |
| 3. CONSULTANT SERVICES | | | | 0 | |
| 4. COMPUTER SERVICES | | | | 0 | |
| 5. SUBAWARDS | | | | 40,000 | |
| 6. OTHER | | | | 51,899 | |
| TOTAL OTHER DIRECT COSTS | | | | 97,899 | |
| H. TOTAL DIRECT COSTS (A THROUGH G) | | | | 353,596 | |
| I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)<br>MTDC (Rate: 52.0000, Base: 280997) | | | | | |
| TOTAL INDIRECT COSTS (F&A) | | | | 146,118 | |
| J. TOTAL DIRECT AND INDIRECT COSTS (H + I) | | | | 499,714 | |
| K. RESIDUAL FUNDS | | | | 0 | |
| L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K) | | | | $ 499,714 | $ |

M. COST SHARING PROPOSED LEVEL $ 895,270 | AGREED LEVEL IF DIFFERENT $

| | | | |
|---|---|---|---|
| PI/PD NAME<br>**Christian M Lastoskie** | FOR NSF USE ONLY<br>INDIRECT COST RATE VERIFICATION | | |
| ORG. REP. NAME* | Date Checked | Date Of Rate Sheet | Initials - ORG |

 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

# SUMMARY PROPOSAL BUDGET

YEAR 2

| FOR NSF USE ONLY | | |
|---|---|---|
| PROPOSAL NO. | DURATION (months) | |
| | Proposed | Granted |
| AWARD NO. | | |

ORGANIZATION
**University of Michigan Ann Arbor**

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR
**Christian M Lastoskie**

| A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets) | NSF Funded Person-months CAL | ACAD | SUMR | Funds Requested By proposer | Funds granted by NSF (if different) |
|---|---|---|---|---|---|
| 1. Christian M Lastoskie - PI | 0.00 | 0.00 | 1.50 | $ 17,293 | $ |
| 2. Peter Adriaens - Co-I | 0.00 | 0.00 | 1.00 | 16,302 | |
| 3. Thomas P Lyon - Co-I | 0.00 | 0.00 | 0.25 | 5,113 | |
| 4. Richard Rood - Co-I | 0.00 | 0.00 | 0.50 | 9,578 | |
| 5. Johannes Schwank - Co-I | 0.00 | 0.00 | 0.50 | 9,302 | |
| 6. ( 0 ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE) | 0.00 | 0.00 | 0.00 | 0 | |
| 7. ( 5 ) TOTAL SENIOR PERSONNEL (1 - 6) | 0.00 | 0.00 | 3.75 | 57,588 | |
| B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS) | | | | | |
| 1. ( 0 ) POST DOCTORAL SCHOLARS | 0.00 | 0.00 | 0.00 | 0 | |
| 2. ( 0 ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.) | 0.00 | 0.00 | 0.00 | 0 | |
| 3. ( 3 ) GRADUATE STUDENTS | | | | 75,663 | |
| 4. ( 3 ) UNDERGRADUATE STUDENTS | | | | 14,520 | |
| 5. ( 0 ) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY) | | | | 0 | |
| 6. ( 0 ) OTHER | | | | 0 | |
| TOTAL SALARIES AND WAGES (A + B) | | | | 147,771 | |
| C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) | | | | 41,086 | |
| TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C) | | | | 188,857 | |
| D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) | | | | | |
| TOTAL EQUIPMENT | | | | 0 | |
| E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS) | | | | 11,000 | |
| 2. FOREIGN | | | | 11,000 | |
| F. PARTICIPANT SUPPORT COSTS | | | | | |
| 1. STIPENDS $ 7,500 | | | | | |
| 2. TRAVEL 15,000 | | | | | |
| 3. SUBSISTENCE 0 | | | | | |
| 4. OTHER 0 | | | | | |
| TOTAL NUMBER OF PARTICIPANTS ( 25 ) TOTAL PARTICIPANT COSTS | | | | 22,500 | |
| G. OTHER DIRECT COSTS | | | | | |
| 1. MATERIALS AND SUPPLIES | | | | 12,000 | |
| 2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION | | | | 1,000 | |
| 3. CONSULTANT SERVICES | | | | 0 | |
| 4. COMPUTER SERVICES | | | | 2,500 | |
| 5. SUBAWARDS | | | | 40,900 | |
| 6. OTHER | | | | 54,495 | |
| TOTAL OTHER DIRECT COSTS | | | | 110,895 | |
| H. TOTAL DIRECT COSTS (A THROUGH G) | | | | 344,252 | |
| I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) MTDC (Rate: 52.0000, Base: 267256) | | | | | |
| TOTAL INDIRECT COSTS (F&A) | | | | 138,973 | |
| J. TOTAL DIRECT AND INDIRECT COSTS (H + I) | | | | 483,225 | |
| K. RESIDUAL FUNDS | | | | 0 | |
| L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K) | | | | $ 483,225 | $ |

M. COST SHARING PROPOSED LEVEL $ 38,735 | AGREED LEVEL IF DIFFERENT $

PI/PD NAME
**Christian M Lastoskie**

ORG. REP. NAME*

| FOR NSF USE ONLY | | |
|---|---|---|
| INDIRECT COST RATE VERIFICATION | | |
| Date Checked | Date Of Rate Sheet | Initials - ORG |
| | | |

 ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

**SUMMARY PROPOSAL BUDGET** YEAR 3

| | | |
|---|---|---|
| ORGANIZATION<br>**University of Michigan Ann Arbor** | FOR NSF USE ONLY<br>PROPOSAL NO. | DURATION (months)<br>Proposed / Granted |
| PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR<br>**Christian M Lastoskie** | AWARD NO. | |

| A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets) | NSF Funded Person-months CAL | ACAD | SUMR | Funds Requested By proposer | Funds granted by NSF (if different) |
|---|---|---|---|---|---|
| 1. **Christian M Lastoskie - PI** | 0.00 | 0.00 | 1.50 | $ **17,812** | $ |
| 2. **Peter Adriaens - Co-I** | 0.00 | 0.00 | 1.00 | **16,791** | |
| 3. **Thomas P Lyon - Co-I** | 0.00 | 0.00 | 0.25 | **5,266** | |
| 4. **Richard Rood - Co-I** | 0.00 | 0.00 | 0.50 | **9,865** | |
| 5. **Johannes Schwank - Co-I** | 0.00 | 0.00 | 0.50 | **9,581** | |
| 6. ( **0** ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE) | 0.00 | 0.00 | 0.00 | **0** | |
| 7. ( **5** ) TOTAL SENIOR PERSONNEL (1 - 6) | 0.00 | 0.00 | 3.75 | **59,315** | |
| B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS) | | | | | |
| 1. ( **0** ) POST DOCTORAL SCHOLARS | 0.00 | 0.00 | 0.00 | **0** | |
| 2. ( **0** ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.) | 0.00 | 0.00 | 0.00 | **0** | |
| 3. ( **3** ) GRADUATE STUDENTS | | | | **77,934** | |
| 4. ( **3** ) UNDERGRADUATE STUDENTS | | | | **14,520** | |
| 5. ( **0** ) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY) | | | | **0** | |
| 6. ( **0** ) OTHER | | | | **0** | |
| TOTAL SALARIES AND WAGES (A + B) | | | | **151,769** | |
| C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) | | | | **42,286** | |
| TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C) | | | | **194,055** | |
| D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) | | | | | |
| TOTAL EQUIPMENT | | | | **0** | |
| E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS) | | | | **11,000** | |
| 2. FOREIGN | | | | **11,000** | |
| F. PARTICIPANT SUPPORT COSTS<br>1. STIPENDS $ **7,500**<br>2. TRAVEL **15,000**<br>3. SUBSISTENCE **0**<br>4. OTHER **0** | | | | | |
| TOTAL NUMBER OF PARTICIPANTS ( **25** ) TOTAL PARTICIPANT COSTS | | | | **22,500** | |
| G. OTHER DIRECT COSTS | | | | | |
| 1. MATERIALS AND SUPPLIES | | | | **12,000** | |
| 2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION | | | | **1,000** | |
| 3. CONSULTANT SERVICES | | | | **0** | |
| 4. COMPUTER SERVICES | | | | **2,500** | |
| 5. SUBAWARDS | | | | **41,828** | |
| 6. OTHER | | | | **57,219** | |
| TOTAL OTHER DIRECT COSTS | | | | **114,547** | |
| H. TOTAL DIRECT COSTS (A THROUGH G) | | | | **353,102** | |
| I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)<br>**MTDC (Rate: 52.0000, Base: 273383)** | | | | | |
| TOTAL INDIRECT COSTS (F&A) | | | | **142,159** | |
| J. TOTAL DIRECT AND INDIRECT COSTS (H + I) | | | | **495,261** | |
| K. RESIDUAL FUNDS | | | | **0** | |
| L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K) | | | | $ **495,261** | $ |

| | |
|---|---|
| M. COST SHARING PROPOSED LEVEL $ **40,168** | AGREED LEVEL IF DIFFERENT $ |
| PI/PD NAME<br>**Christian M Lastoskie** | FOR NSF USE ONLY<br>INDIRECT COST RATE VERIFICATION |
| ORG. REP. NAME* | Date Checked / Date Of Rate Sheet / Initials - ORG |

 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

# SUMMARY PROPOSAL BUDGET

YEAR 4

| FOR NSF USE ONLY | | |
|---|---|---|
| PROPOSAL NO. | DURATION (months) | |
| | Proposed | Granted |
| AWARD NO. | | |

ORGANIZATION
**University of Michigan Ann Arbor**

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR
**Christian M Lastoskie**

| A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets) | NSF Funded Person-months CAL | ACAD | SUMR | Funds Requested By proposer | Funds granted by NSF (if different) |
|---|---|---|---|---|---|
| 1. Christian M Lastoskie - PI | 0.00 | 0.00 | 1.50 | $ 18,346 | $ |
| 2. Peter Adriaens - Co-I | 0.00 | 0.00 | 1.00 | 17,295 | |
| 3. Thomas P Lyon - Co-I | 0.00 | 0.00 | 0.25 | 5,424 | |
| 4. Richard Rood - Co-I | 0.00 | 0.00 | 0.50 | 10,161 | |
| 5. Johannes Schwank - Co-I | 0.00 | 0.00 | 0.50 | 9,868 | |
| 6. ( 0 ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE) | 0.00 | 0.00 | 0.00 | 0 | |
| 7. ( 5 ) TOTAL SENIOR PERSONNEL (1 - 6) | 0.00 | 0.00 | 3.75 | 61,094 | |
| B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS) | | | | | |
| 1. ( 0 ) POST DOCTORAL SCHOLARS | 0.00 | 0.00 | 0.00 | 0 | |
| 2. ( 0 ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.) | 0.00 | 0.00 | 0.00 | 0 | |
| 3. ( 3 ) GRADUATE STUDENTS | | | | 80,271 | |
| 4. ( 3 ) UNDERGRADUATE STUDENTS | | | | 14,520 | |
| 5. ( 0 ) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY) | | | | 0 | |
| 6. ( 0 ) OTHER | | | | 0 | |
| TOTAL SALARIES AND WAGES (A + B) | | | | 155,885 | |
| C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) | | | | 43,520 | |
| TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C) | | | | 199,405 | |
| D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) | | | | | |
| TOTAL EQUIPMENT | | | | 0 | |
| E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS) | | | | 11,000 | |
| 2. FOREIGN | | | | 11,000 | |
| F. PARTICIPANT SUPPORT COSTS<br>1. STIPENDS $ 2,500<br>2. TRAVEL 5,000<br>3. SUBSISTENCE 0<br>4. OTHER 0 | | | | | |
| TOTAL NUMBER OF PARTICIPANTS ( 25 ) TOTAL PARTICIPANT COSTS | | | | 7,500 | |
| G. OTHER DIRECT COSTS | | | | | |
| 1. MATERIALS AND SUPPLIES | | | | 12,000 | |
| 2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION | | | | 1,000 | |
| 3. CONSULTANT SERVICES | | | | 0 | |
| 4. COMPUTER SERVICES | | | | 2,500 | |
| 5. SUBAWARDS | | | | 42,782 | |
| 6. OTHER | | | | 60,081 | |
| TOTAL OTHER DIRECT COSTS | | | | 118,363 | |
| H. TOTAL DIRECT COSTS (A THROUGH G) | | | | 347,268 | |
| I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)<br>MTDC (Rate: 52.0000, Base: 279687) | | | | | |
| TOTAL INDIRECT COSTS (F&A) | | | | 145,437 | |
| J. TOTAL DIRECT AND INDIRECT COSTS (H + I) | | | | 492,705 | |
| K. RESIDUAL FUNDS | | | | 0 | |
| L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K) | | | | $ 492,705 | $ |

M. COST SHARING PROPOSED LEVEL $ 41,657 AGREED LEVEL IF DIFFERENT $

PI/PD NAME
**Christian M Lastoskie**

ORG. REP. NAME*

| FOR NSF USE ONLY | | |
|---|---|---|
| INDIRECT COST RATE VERIFICATION | | |
| Date Checked | Date Of Rate Sheet | Initials - ORG |
| | | |

 ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

# SUMMARY PROPOSAL BUDGET

Cumulative

| | FOR NSF USE ONLY | | |
|---|---|---|---|
| ORGANIZATION<br>**University of Michigan Ann Arbor** | PROPOSAL NO. | DURATION (months)<br>Proposed | Granted |
| PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR<br>**Christian M Lastoskie** | AWARD NO. | | |

| A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets) | NSF Funded Person-months CAL | ACAD | SUMR | Funds Requested By proposer | Funds granted by NSF (if different) |
|---|---|---|---|---|---|
| 1. Christian M Lastoskie - PI | 0.00 | 0.00 | 6.00 | $ 70,240 | $ |
| 2. Peter Adriaens - Co-I | 0.00 | 0.00 | 4.00 | 66,216 | |
| 3. Thomas P Lyon - Co-I | 0.00 | 0.00 | 1.00 | 20,767 | |
| 4. Richard Rood - Co-I | 0.00 | 0.00 | 2.00 | 38,903 | |
| 5. Johannes Schwank - Co-I | 0.00 | 0.00 | 2.00 | 37,782 | |
| 6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE) | 0.00 | 0.00 | 0.00 | 0 | |
| 7. ( 5 ) TOTAL SENIOR PERSONNEL (1 - 6) | 0.00 | 0.00 | 15.00 | 233,908 | |
| B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS) | | | | | |
| 1. ( 0 ) POST DOCTORAL SCHOLARS | 0.00 | 0.00 | 0.00 | 0 | |
| 2. ( 0 ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.) | 0.00 | 0.00 | 0.00 | 0 | |
| 3. ( 12 ) GRADUATE STUDENTS | | | | 307,328 | |
| 4. ( 12 ) UNDERGRADUATE STUDENTS | | | | 50,820 | |
| 5. ( 0 ) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY) | | | | 0 | |
| 6. ( 0 ) OTHER | | | | 0 | |
| TOTAL SALARIES AND WAGES (A + B) | | | | 592,056 | |
| C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) | | | | 166,258 | |
| TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C) | | | | 758,314 | |
| D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) $ 51,200 | | | | | |
| TOTAL EQUIPMENT | | | | 51,200 | |
| E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS) | | | | 44,000 | |
| 2. FOREIGN | | | | 43,000 | |
| F. PARTICIPANT SUPPORT COSTS<br>1. STIPENDS $ 20,000<br>2. TRAVEL 40,000<br>3. SUBSISTENCE 0<br>4. OTHER 0 | | | | | |
| TOTAL NUMBER OF PARTICIPANTS ( 100 ) TOTAL PARTICIPANT COSTS | | | | 60,000 | |
| G. OTHER DIRECT COSTS | | | | | |
| 1. MATERIALS AND SUPPLIES | | | | 42,000 | |
| 2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION | | | | 3,000 | |
| 3. CONSULTANT SERVICES | | | | 0 | |
| 4. COMPUTER SERVICES | | | | 7,500 | |
| 5. SUBAWARDS | | | | 165,510 | |
| 6. OTHER | | | | 223,694 | |
| TOTAL OTHER DIRECT COSTS | | | | 441,704 | |
| H. TOTAL DIRECT COSTS (A THROUGH G) | | | | 1,398,218 | |
| I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) | | | | | |
| TOTAL INDIRECT COSTS (F&A) | | | | 572,687 | |
| J. TOTAL DIRECT AND INDIRECT COSTS (H + I) | | | | 1,970,905 | |
| K. RESIDUAL FUNDS | | | | 0 | |
| L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K) | | | | $ 1,970,905 | $ |

M. COST SHARING PROPOSED LEVEL $ **1,015,830** AGREED LEVEL IF DIFFERENT $

| PI/PD NAME<br>**Christian M Lastoskie** | FOR NSF USE ONLY<br>INDIRECT COST RATE VERIFICATION | | |
|---|---|---|---|
| ORG. REP. NAME* | Date Checked | Date Of Rate Sheet | Initials - ORG |

C *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

Budget Justification

*Personnel*

1.5 summer months per academic year is requested for the PI and project director, Prof. Christian Lastoskie. One summer month per academic year is requested for the project co-director in Civil and Environmental Engineering (CEE) and Ross School of Business, Prof. Peter Adriaens. One-half summer month per academic year is requested for co-PIs Johannes Schwank (ChE), Richard Rood (AOSS), and one-quarter summer month per academic year for Tom Lyon (SNRE).

Three twelve-month 50% graduate research assistantships are requested in each project year. A fourth GSRA will be supported through a cost-share with the College of Engineering, OVPR and Rackham School.

Two undergraduate research assistants will be appointed for 10 hours per week in the fall and winter terms of each project year (Sept 1 – Apr 30) at a rate of $8.25/hr. Two additional undergraduate RAs will be appointed at the same hours and rate for project years 2, 3 and 4.

*Fringe Benefits*

Fringe benefits for senior research personnel and graduate students are calculated as 30% of personnel costs. Undergraduate fringe benefits are calculated at 7.65%. Graduate student tuition is for Ph.D. pre-candidate status. The GSRA tuition for the cost-shared student is calculated at candidate status for years 2, 3 and 4.

*Capital Equipment*

Funds are requested for the purchase and installation of a 24-node, AMD Opteron computing cluster with two dual-core CPUs, 8GB of RAM, 3 year warranty, and supporting infrastructure (switch ports, software, storage, etc.). The cluster will be housed in CAEN facilities and maintained by personnel in the Center for Advanced Computing (CAC). $51,200 is requested from the project sponsor for this equipment. A cost-share of the remaining $30,000 is requested: 1/3 from the PI's funds in CEE; 1/3 from the College of Engineering; and 1/3 from OVPR.

*Travel*

Funds are requested to support the following activities:

(1) Domestic and foreign travel by the PI, co-investigators, and students to conferences for presentation and dissemination of research results, and to annual meetings hosted by the project sponsor.

(2) Travel of student researchers to the southwest, southeast and midwest U.S. to meet with energy and water utility executives and stakeholders and national laboratory personnel to collect data needed for the project work plan.

*Participant Support Costs*

Funds are requested to support the following activities:

(1) Domestic travel expenses for five external advisory board members to travel to the campuses of the participant universities for annual research reviews and planning meetings.

(2) Travel funds for twenty participants each for two workshops to be organized on the UM campus: the first, in year two of the project, on water use in coal conversion technologies; and the second, in year three, on water resource impacts of large-scale biofuel production and associated technology solutions.

(3) Funds for travel and subsistence of graduate students participating in the research for summer internships at national laboratories.

*Other Direct Costs*

Funds are requested for the following:

(1) Office and computing laboratory supplies, computing support services, and offset of manuscript publication costs.

(2) A subcontract to Limo-Tech for salary support and funds for travel and supplies for John Wolfe and Laura Weintraub, who will serve as consultants and collaborators throughout the duration of this project on development of the decision support system for integrated energy-water resource planning.

*Indirect Costs*

Indirect costs are calculated as 52% of modified total direct costs, which exclude capital equipment, graduate student tuition and participant support costs.

Indirect costs are calculated as 52% of the first $25,000 of modified total direct costs for the subcontract to Limno-Tech.

Project Personnel and Research Synergies

The project will be led by Prof. Christian Lastoskie of the civil and environmental engineering department at the University of Michigan. Prof. Lastoskie is an expert in material flow models for chemical fate and transport processes and in carbon capture and storage methods. He will direct the life cycle assessment studies in this project in collaboration with Prof. Johannes Schwank of chemical engineering, who has expertise in energy technologies and in synthesis routes for coal and biomass conversion to electricity and fuels.

Prof. Richard Rood is a climate change expert in the department of atmospheric, oceanic and space sciences. He will collaborate with Ms. Laura Weintraub, P.E., a senior project engineer at Limno-Tech Inc. (LTI) with expertise in hydrologic modeling, to interface the climate change and watershed models as described in objective two.

Prof. Peter Adriaens holds a joint appointment in engineering and the Ross School of Business and has directed numerous multidisciplinary research initiatives. He will lead the real options analyses of utility investment for water conservation, in collaboration with Prof. Thomas Lyon, a policy expert in the School of Natural Resources and Environment, and Dr. John Wolfe, Vice President of LTI, an economist who has consulted extensively with member utilities of the Electric Power Research Institute (EPRI) on resource planning issues.

The UM and LTI team members will work together on integration of modeling components into the decision support system and case studies detailed in objectives 4 and 5. The project will be advised by consultants in the study regions at national laboratories and at energy and water utilities and their umbrella organizations. As described in the supporting letters, the consultants will provide data on utility resource use and planned capacity additions in the study regions, and facilitate meetings with stakeholders for data gathering and model development.

The project will be staffed by four graduate students, three appointed on requested project funds and a fourth sponsored by UM in a cost-share agreement. One graduate student will work full-time on each of the project objectives (1)-(4), and all four will work on elements of the three case studies planned in objective (5). At least three undergraduate students will also be appointed as research assistants throughout the duration of the project.

*Research Backgrounds and Appointments of Key Personnel:*

Christian Lastoskie (PI) is Associate Professor of Civil and Environmental Engineering. His research is themed on analysis of material flows in industrial processes, chemical fate and transport of environmental discharges, and capture and storage of energy fuels and emissions. His research interests are in carbon capture and storage, hydrogen production and carriers, and thermodynamic simulations and process model development.

Peter Adriaens (co-PI) is Professor of Civil and Environmental Engineering. He is a faculty associate in the Zell-Lurie Institute for Entrepreneurial Studies and the Ross School of Business. His research focuses on the areas of remediation design and sustainable industrial practice. His research interests include fate pathways and forensics of contaminants in environmental systems, and development of innovative technology platforms for cleanup of industrial process streams and natural systems. He is also involved in the integration of market-based strategies for control of energy emissions.

Richard Rood (co-PI) is Professor of Atmospheric, Oceanic and Space Science. He previously served as Chief of the Computational and Information Sciences and Technology Office at the NASA/Goddard Space Flight Center. His research interests are in weather and climate models, stratospheric and tropospheric chemistry and modeling, and data assimilation.

Johannes Schwank (co-PI) is Professor of Chemical Engineering and director of the Transportation Energy Center. His research is directed toward finding novel solutions to the problem of energy production, storage, and utilization in the transportation, distributed generation, and chemical process sectors. His interests include advanced catalytic Fischer-Tropsch to create clean-burning synthetic fuels from coal and biomass, and generating syngas from biomass-derived gas mixtures for solid oxide fuel cells. He has evaluated novel energy harvesting and conversion concepts to improve efficiency of large-scale industrial processes.

Thomas Lyon (co-PI) is the Dow Chair of Sustainable Science, Technology and Commerce at the Stephen M. Ross School of Business. His research interest is the interplay between corporate strategy and public policy, which he has pursued in a number of application areas, including corporate environmentalism, electric utility investment practices, natural gas contracting, innovation in the health care sector, and the introduction of competition in regulated industries.

John R. Wolfe (consultant), Ph.D., P.E., is Vice President of Limno-Tech, an environmental consulting firm in Ann Arbor, Michigan. He is a civil and environmental engineering with expertise is in project management, fate and transport modeling of contaminants, and environmental economics. He has extensive experience in surface water quality modeling, including contaminated sediments, wastewater treatment, and permitting and hazardous waste management, including groundwater protection.

Laura Weintraub (consultant), P.E., is a Senior Project Engineer at Limno-Tech. She is a civil and environmental engineer with experience in hydrologic analysis, water quality modeling, and watershed management. Her work includes managing and executing water resources and water quality analyses for public, private, and research clients involving TMDL development, watershed planning, source water protection, loading analyses, and various stormwater management activities.

Project Management and Timeline of Activities

Prof. Christian Lastoskie will serve as the director of the project, and lead the overall integration of elements into the decision support system (objective 4). Prof. Peter Adriaens will serve as project co-director and lead the real options analysis (objective 3). Prof. Johannes Schwank will lead the thermoelectric plant life cycle assessment research (objective 1), and Prof. Richard Rood will be the lead investigator on the climate change – watershed interface modeling. All key project personnel, including the Limno-Tech subcontractors, work and reside in Ann Arbor, Michigan, so that regular monthly meetings of the entire project team can be scheduled without undue travel constraints.

Communication between group members within the UM College of Engineering, Business School and the School of Natural Resources will occur through the usual phone and email exchanges and biweekly meetings of the graduate student research assistants with their project advisors (student one – Schwank and Lastoskie; student two – Rood and Weintraub; student three – Adriaens and Wolfe; student four – Lastoskie and Adriaens). An undergraduate student will also be assigned to work on the respective project of each graduate student on a part-time basis. Prof. Adriaens also has a staff appointment and office at Limno-Tech, so he is well-positioned to serve as a conduit between the Limno-Tech consultants and the University of Michigan faculty team members.

Project data from the life cycle assessments, climate-watershed models, real options analysis, and data support system integration efforts will be stored on a 24-node, AMD Opteron computing cluster with two dual-core CPUs housed in the College of Engineering's Center for Advanced Computing (CAC). All project team members and student researchers will have accounts on the CAC cluster with computing privileges and full access to project data.

An advisory board of energy-water experts from electric utilities, water management boards, and federal laboratories will be assembled for this project. Advisory board members will be asked to participate in annual research reviews organized by the PI at the end of the each project year. Funds have been requested in the project budget to reimburse travel and lodging expenses for advisory board members.

Ownership of intellectual property resulting from this project will reside with the University of Michigan.

**Project Timeline**

| Task | Year 1 | | | | Year 2 | | | | Year 3 | | | | Year 4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| **1. Thermoelectric Plant LCA (CL, JS)** | | | | | | | | | | | | | | | | |
| 1.1. Air-cooled/hybrid condensers | x | x | x | x | | | | | | | | | | | | |
| 1.2. Produced waters/brackish water | | | | x | x | x | x | x | | | | | | | | |
| 1.3. Carbon capture/wastewater reuse | | | | | | | x | x | x | x | x | x | | | | |
| 1.4. IGCC & CSP coal gasification | | | | | | | | | | | x | x | x | x | x | x |
| **2. Climate/Watershed Model (RR, LW)** | | | | | | | | | | | | | | | | |
| 2.1. Downscale climate models | x | x | x | x | | | | | | | | | | | | |
| 2.2. Evaluate high res. climate models | x | x | x | x | x | | | | | | | | | | | |
| 2.3. Interface climate/hydrologic models | | x | x | x | x | x | | | | | | | | | | |
| 2.4. Interface LCA alts. with hydro model | | | | | x | x | | | x | x | | | x | x | | |
| **3. Real Options Analysis (PA, TL, JW)** | | | | | | | | | | | | | | | | |
| 3.1. Develop basic framework | x | x | x | x | | | | | | | | | | | | |
| 3.2. Incorporate Task 1 & 2 findings | | | x | x | x | x | | | | | | | | | | |
| 3.3. Apply to case studies | | | | | x | x | x | x | x | x | x | x | x | x | x | x |
| 3.4. Develop tool for decision support | | | | | | | | | | | x | x | x | x | x | x |
| **4. Integrated DSS (all)** | | | | | | | | | | | | | | | | |
| 4.1. Resilience/sustainability indicators | x | x | x | x | | | | | | | | | | | | |
| 4.2. LCA/WARMF/ROA interface | | | x | x | x | x | x | x | | | | | | | | |
| 4.3. Knowledge base construction | | | | | | | x | x | x | x | x | x | | | | |
| 4.4. Quick scenario tool development | | | | | | | | | | | x | x | x | x | x | x |
| **5. Case Studies (all)** | | | | | | | | | | | | | | | | |
| 5.1. San Juan River Basin | | | | | x | x | x | x | | | | | | | | |
| 5.2. Chattahoochee River Basin | | | | | | | | | x | x | x | x | | | | |
| 5.3. Lake St. Clair – Detroit River Basin | | | | | | | | | | | | | x | x | x | x |
| **6. Education/Outreach (all)** | | | | | | | | | | | | | | | | |
| 6.1. Undergraduate research | x | x | x | | x | x | x | | x | x | x | | x | x | x | |
| 6.2. Graduate summer field work | | | | x | | | | x | | | | x | | | | x |
| 6.3. Energy-water graduate courses | x | x | x | | x | x | x | | x | x | x | | x | x | x | |
| 6.4. K-12 curriculum development | | x | x | | | x | x | | | x | x | | | x | x | |
| 6.5. Energy-water nexus workshops | | | | | | x | x | x | | | x | x | x | | | |
| **7. Project Administration (CL)** | | | | | | | | | | | | | | | | |
| 7.1. Advisory board meetings | | | x | | | | x | | | | x | | | | x | |
| 7.2. Grantees conference | x | | | | x | | | | x | | | | x | | | |
| 7.3. Annual/final project reports | | | | x | | | | x | | | | x | | | | x |

Project Deliverables

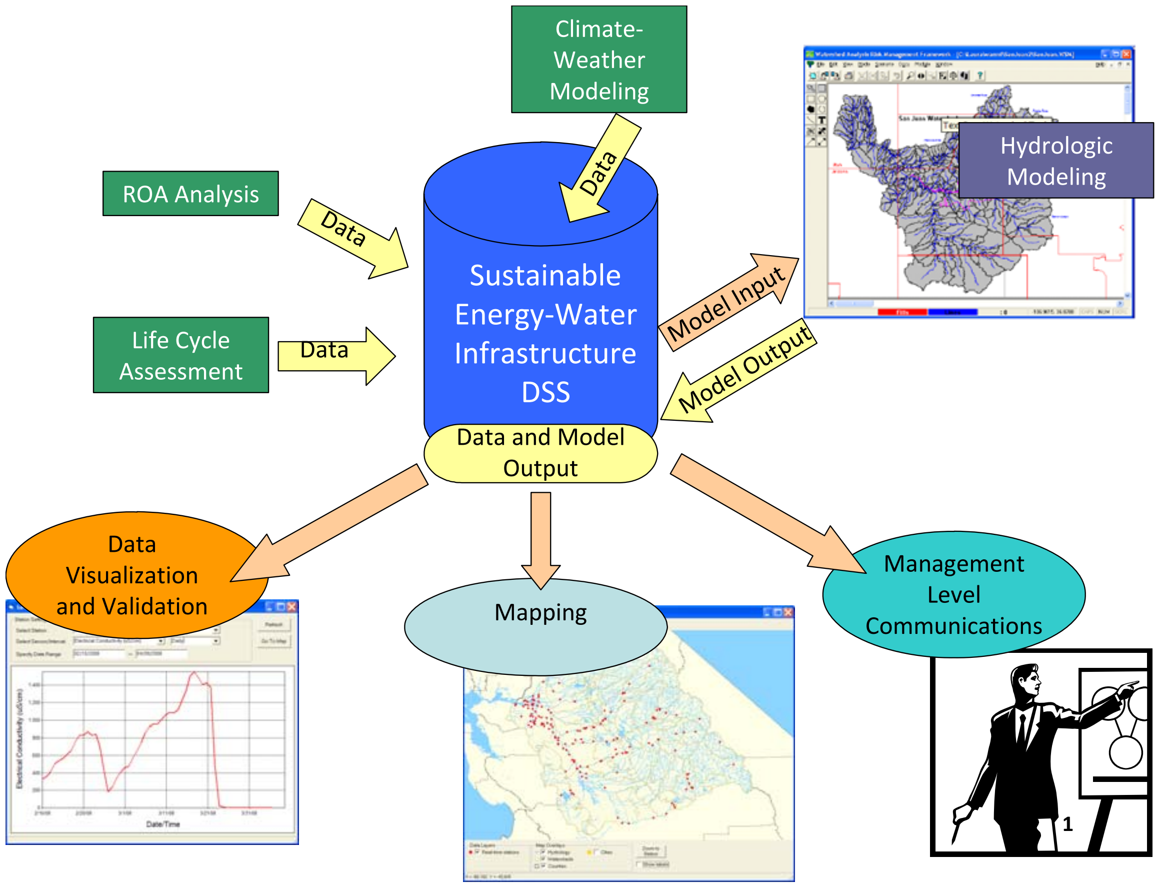
The following mechanisms will be used in this project to share research outcomes with the scientific community:

- A *Research at the Nexus of Energy and Water* (ReNEW) website, maintained by the principal investigator (Lastoskie) at the University of Michigan, which will serve multitasked functions. Included among these are a description of the project and its objectives and the sponsor's EFRI-RESIN initiative; a directory of project personnel; research resources for students working on the project; seminar, workshop and advisory board meeting announcements; and posting of pdfs of peer-reviewed publications.
- Publication of scholarly work in highly regarded peer-reviewed journals and presentation of research findings at professional conferences.
- An archived knowledge base for an integrated decision support system (DSS) that will be crafted for energy and water resource policymakers to use in infrastructure planning.
- A set of modeling algorithms for plant- and infrastructure-scale engineering and economic analysis of energy-water nexus resilience and sustainability issues. These will be made available on the project website for research community use at the conclusion of the project.

The research tools and resources to be developed in this project are as follows:

- A life cycle model for water use impacts of alternative cooling technologies for principal categories of thermoelectric power plants.
- A climate-weather interface for the WARMF watershed model that incorporates the effects of global-scale climate change into hydrologic outcomes for regional watersheds.
- A real options analysis tool for energy sector policymakers to use in evaluating contemplated investments in water conservation and emissions control technologies at thermoelectric plants.
- Archived input data and output results from three case studies to be conducted in this project on the watershed impacts of energy development.

The research products listed above will form the basis of a Sustainable Energy-Water Infrastructure decision support software system that will be separately developed after the conclusion of this project, using WARMF source codes obtained following negotiated agreements with Systech, the original developer of the WARMF model. A schematic of the decision support system envisioned for this project is shown on the next page.


Climate-
Weather
Modeling
ROA Analysis
Data
Data
Life Cycle
Assessment
Data
Sustainable
Energy-Water
Infrastructure
DSS
Data and Model
Output
Model Input
Model Output
Hydrologic
Modeling
Data
Visualization
and Validation
Mapping
Management
Level
Communications

LimnoTech
Water | Environment | Scientists | Engineers

April 25, 2008

Christian M. Lastoskie, Ph.D.
Department of Civil & Environmental Engineering
and Department of Biomedical Engineering
University of Michigan
1351 Beal Avenue, 180 EWRE Building
Ann Arbor, MI 48109-2125

Subject: Project Advisory Board, Water Use in Thermoelectric Power Generation

Dear Chrisitian:

It would be our pleasure to participate in watershed modeling and decision support tool integration activities for the proposed project on Alternative Cooling Water Technologies for Resilient and Sustainable Thermoelectric Power Generation, as you have requested. We are very interested in the subject, having recently completed a draft report and proposed research plan for the Electric Power Research Institute (EPRI) dealing with very similar issues. In our EPRI project, Limno-Tech researchers interviewed power utility decision-makers to identify their most pressing water sustainability concerns and needs for technological solutions, quantified the potential gains from the alternative water conservation technologies, and proposed a 10-year research program to pursue and develop the most promsing approaches. Additionally, Limno-Tech staff have participated in past EPRI projects applying a watershed model to assess the impact of extended drought or climate change-induced surface temperature increases on water availability in water-scarce regions where alternative cooling-water technologies are being explored. Your proposed NSF project complements our EPRI recommendations very nicely.

We wish you luck with the proposal and look forward to participating in the project.

Sincerely,
Limno-Tech, Inc.

John R. Wolfe

John R. Wolfe, Ph.D., P.E., BCEE
Vice President

Laura H. Z. Weintraub

Laura H. Z. Weintraub, P.E.
Senior Project Engineer

501 Avis Drive
Ann Arbor, MI 48108
734-332-1200
fax 734-332-1212
www.limno.com

ELECTRIC POWER
RESEARCH INSTITUTE

April 25, 2008

Christian Lastoskie
The University of Michigan
Department of Civil and Environmental Engineering
1351 Beal Ave, 180 EWRE Bldg
Ann Arbor MI 48109-2125

Dear Christian:

Thank you for sharing your proposal to the NSF RESIN Program with me. At EPRI, we feel that electric power/water sustainability is an important emerging national issue. We have been active in conducting research on this subject since the turn of the century. We have also collaborated closely with the Federal Energy/Water Nexus Program, the California Energy Commission, the National Rural Electric Cooperative Association, the University of California, the Sustainable Water Resources Roundtable, and Electricité de France. Should you be funded by NSF, we would be interested in active collaboration with your program. We would also be happy to facilitate access to EPRI member electric power organizations.

Best wishes,

*Bob*

Robert Goldstein
Technical Executive, Water and Ecosystems
Electric Power Research Institute
rogoldst@epri.com
650-855-2593

April 24, 2008

Christian M. Lastoskie, Ph.D.
Associate Professor
Department of Civil & Environmental Engineering
and Department of Biomedical Engineering
University of Michigan
1351 Beal Avenue, 180 EWRE Building
Ann Arbor, MI 48109-2125

Dear Christian:

Thank you for offering the opportunity for the Department of Energy/National Energy Technology Laboratory (DOE/NETL) to collaborate with the University of Michigan on your proposal to the National Science Foundation's EFRI-RESIN program entitled "Alternative Cooling Water Technologies for Resilient and Sustainable Thermoelectric Power Generation." While DOE/NETL cannot formally partner on this effort, nor can we provide funding at this time, we are excited about your proposed systems-based modeling concept to evaluate life-cycle material flows and economic and environmental implications of using alternative methods to cool and condense turbine exhaust steam.

As you know, the research and development (R&D) of advanced technologies and concepts for reducing the withdrawal and consumption of freshwater in thermoelectric power plants is a key component of DOE/NETL's environmental research activities. Your proposed modeling effort offers the potential to elucidate critical life-cycle benefits and costs associated with replacing freshwater with impaired waters for cooling or using dry/wet-dry hybrid cooling systems in lieu of traditional wet cooling towers. As such, the proposed project would directly benefit DOE/NETL's research program as well as an emerging national program directed at the energy-water nexus.

With that said, should your proposal be selected for funding by NSF, DOE/NETL would be pleased to consider participating in meetings or workshops sponsored by the University of Michigan related to the modeling effort or more broadly to the linkage between energy and water. And of course, the results from our ongoing power plant-water R&D program would be available to you in carrying out your proposed NSF project.

I want to wish you best of luck in your endeavors to receive funding from NSF.

Sincerely,

Thomas J. Feeley, III
Technology Manager, Existing Plants

**UNITED STATES ENVIRONMENTAL PROTECTION AGENCY**
NATIONAL RISK MANAGEMENT RESEARCH LABORATORY
CINCINNATI, OH 45268

OFFICE OF
RESEARCH AND DEVELOPMENT

February 5, 2008

Christian M. Lastoskie, Ph.D.
Associate Professor
Department of Civil & Environmental Engineering
and Department of Biomedical Engineering
University of Michigan
1351 Beal Avenue, 180 EWRE Building
Ann Arbor, MI 48109-2125

Dear Dr. Lastoskie -

Thanks for sharing your proposal to the NSF on the life cycle implications of power generation. The effort looks very interesting. I will be glad to serve in an advisory capacity as much as time allows me.

Hosting a student here, as you suggested, is a possibility as long as all expenses are taken care of. We can provide office space and computer access. Keep in mind that citizenship is an issue regarding hosting students that work with us for an extended period. Preference is given to US citizens. If the student is not a citizen, he or she must have the right kind of visa. We would have to make sure all this in order before the student can work here at the Lab. I will be glad to work with you on these details when the time comes.

Sincerely,

Mary Ann Curran

Mary Ann Curran
LCA Research Program Manager
Office of Research and Development
Cincinnati, Oh 45268
Ph: 513-569-7782
curran.maryann@epa.gov

Sandia National Laboratories
Operated for the U.S. Department of Energy by
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Mike Hightower
Distinguished Member Technical Staff

P.O. Box 5800
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Fax: (505) 844-0968
Internet: mmhight@sandia.gov

February 6, 2008

Christian Lastoskie, Associate Professor
Department of Civil and Environmental Engineering
University of Michigan
EWRE Building, Room 178
1351 Beal Avenue
Ann Arbor, Michigan 48109

Dear Dr. Lastoskie,

Water is indeed an integral part of energy development, production, and generation. Water is used directly in hydroelectric power generation and is used extensively for thermoelectric power plant cooling and air emissions control. Water is also used extensively in energy-resource extraction, refining, and processing, as well as for energy resource transportation. Currently, over 50 percent of daily water withdrawals in the U.S. and about 25 percent of all daily non-agricultural water consumption are for energy demands. As the population and economy of the U.S. continue to grow, the demand for energy will also grow. The expected growth in electric power generation and domestic development of alternative transportation fuels, such as biofuels, oil shale, and hydrogen, could significantly increase water demands for energy development and increase competition with other sectors for finite fresh water resources.

This growth in water demands for energy will come at a time when the nation's fresh water supplies are seeing increased stress from limitations of surface-water storage capacity, depletions of ground water, growing population and pressures to keep fresh water in stream for ecological needs, and uncertainty about the potential impacts of climate variability on future fresh water supplies. Sandia National Laboratories has worked extensively over the past several years with other national laboratories to create an awareness of these emerging energy and water issues. These efforts have included a Report to Congress on the emerging water demands for future energy development, as well as a research and development roadmap that identifies the major science and technology directions needed to reduce fresh water consumption in the energy sector and integrate energy and water management to enhance both energy and water reliability and sustainability.

We have read your proposal and your focus on identifying the costs and benefits of low water use or non-traditional water use approaches for thermoelectric cooling. The ideas are completely in line with recommendations presented in the Energy Water Research and Development Roadmap. As we mover forward with other research organization across the nation and the Department of Energy in implementing the Roadmap research strategies, we would be happy to work with your university and proposal team in supporting undergraduate and graduate students as summer interns to work on projects associated with our energy and water research, demonstration, and modeling efforts.

Thank you for the opportunity to participate in this effort. If you have any questions my contact information is provided above.

**GWINNETT COUNTY**
Department of Water Resources
Office of the Director
678-376-7149

April 29, 2008

Christian M. Lastoskie, Ph.D.
Associate Professor
Department of Civil & Environmental Engineering
and Department of Biomedical Engineering
University of Michigan
1351 Beal Avenue, 180 EWRE Building
Ann Arbor, MI 48109-2125

Dear Professor Lastoskie,

I would be pleased to participate with you on the University of Michigan's proposed National Science Foundation project on electric power generation and water allocation within watersheds. As Program Specialist for the Department of Water Resources for Gwinnet County, it is my responsibility to inform and help resolve water resource allocation questions involving Lake Lanier and its watershed. Understanding the sustainability of regional water resources and the effects of climate change and water-conserving energy technologies is of great interest, and I would be happy to serve on an advisory panel to your research project.

Thank you for the opportunity to provide input to this project.

Sincerely,

Frank Stephens

Frank J. Stephens, P.E.
Program Specialist
Department of Water Resources
Gwinnett County, Georgia

**Skiles W. Boyd**
Vice President
Environmental Management & Resources

DTE Energy Company
2000 2nd Ave., Detroit, MI 48226-1279
Tel: 313.235.7141 Fax: 313.235.5018

**DTE Energy**

April 29, 2008

Dear Professor Lastoskie,

Detroit Edison is pleased to support your National Science Foundation project on water use in electric power generation. Detroit Edison is continually evaluating the long term needs of our customers while looking to maintain and further improve the associated environmental impacts. The effects of electric capacity additions on water resource commitments in southeast Michigan is certainly of interest.

As a participating member in the State of Michigan's Capacity Needs Forum and 21st Century Energy Plan, Detroit Edison can provide estimates of capacity additions in the region targeted for your case study, as well as the mix of energy technologies (coal, nuclear, wind, gas) being contemplated to meet projected demand. Detroit Edison can also provide data on water use for cooling and for process needs at our existing fleet of thermoelectric plants sited along the coastlines of Lake Huron, St. Clair River, Detroit River and Lake Erie.

I have asked Dennis Leonard of my staff to coordinate information sharing and interaction with graduate students on your research team as they develop engineering and policy recommendations for cost-saving and water-conserving electric power generation technologies. Dennis will contact you in the near future.

If you have any questions, please feel free to contact me directly at 313-235-7141. We look forward to working with you and your research team on this project.

Sincerely,

Skiles W. Boyd

Skiles W. Boyd
Vice President - Environmental Management & Resources
The Detroit Edison Company