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Supporting the Nation's Electric Interconnections through Integration of Water into their Long-Term Transmission Planning

5-year Plan (2019-2023)

Vincent Tidwell Sandia National Laboratories

Jordan Macknick National Renewable Energy Laboratory

Nathalie Voisin Pacific Northwest National Laboratory

Jim Kuiper Argonne National Laboratory

Abstract: Water is a critical resource in the production of electric power. The purpose of this plan is to extend support to the nation's three electric interconnections toward integrating water issues into their long-range transmission planning. This continued support is at the request of the interconnections. The proposed program leverages prior support as well as that of other similarly focused efforts funded across the Department of Energy (DOE). The effort will utilize a project team lead by Sandia National Laboratories and supported by Argonne National Laboratory, National Renewable Energy Laboratory, and Pacific Northwest National Laboratory. The activities recorded here are meant to provide a menu of potential projects that could be implemented as available resources permit.

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Contents

Motivation

While consumptive water use associated with thermoelectric power generation in the United States, estimated at 4,836Mm^3 (Diehl and Harris 2014), is small with respect to other water sectors (particularly irrigated agriculture), continued growth is expected for the electric sector (electricity demand to increase by 7-23% by 2032 [Energy Information Administration 2013]) prompting concern over the availability of water to meet future demands (e.g., GAO 2012; DOE 2006). Studies attempting to project future thermoelectric water consumption have yielded results ranging from an increase of 63% to a decrease of 60% depending on the assumed mix of fuel/cooling type and emission controls (Macknick et al. 2012; National Energy Technology Laboratory 2008; Feeley et al. 2008). More important is how these new demands are geographically distributed and their relation to regional water resources (Sovacool and Sovacool 2009; Scott et al. 2011; Tidwell et al. 2012; Averyt et al. 2013; Yates and Flores 2013). Also of concern is the resilience of the existing suite of power plants to intensifying drought conditions where their operations could be forced off-line due to streamflow/reservoir levels dropping below intake structures or water temperatures exceeding permitted operating conditions (e.g., Department of Energy 2013).

Transmission expansion planning (TEP) is a process in which the need for new electric power generation and transmission capacity is assessed for a range of assumed future conditions (e.g., Wu et al. 2006). Beyond identifying the need for new generation, specification of power plant type (fuel and prime mover), cooling type, and location are generally made. These choices ultimately dictate changes in the thermoelectric water withdrawal and consumption profile of the TEP region. As such, consideration of available water supply (both fresh and non-fresh sources) in TEP represents an important opportunity for managing the evolving impact of thermoelectric power on water resources. While water has traditionally been an important consideration for the individual power plant (Hamilton 1979), little coordinated planning has been practiced at the utility or interconnection level. Also lacking has been engagement with local, state and federal water managers, at least until the point of permitting (Hightower and Pierce, 2008). This has led to the siting of several new thermoelectric facilities being contested on the basis of water supply (e.g., Tucson Citizen 2002; Reno-Gazette Journal, 2006; U.S. Water News Online, 2003; Curlee and Sale, 2003). Other evidences include Idaho's moratorium on construction of coal-fired power plants (Reuters 2006) because of potential impacts to the state's water resources, and California's policy against use of freshwater for new thermoelectric development (California Water Code, Section 13552).

Central to TEP is consideration of the resilience of the evolving electric grid; that is, how reliable are the planned transmission systems and generation portfolios. While many factors impact grid resilience, an often-overlooked element is the vulnerability of operations to extremes in water supply. Drought could limit operations both due to limited cooling water for thermoelectric power generation as well as hydropower production. At the other end of the spectrum is the threat of damage caused by flood, hurricane, or wildfire.

Background

In 2010 the U.S. Department of Energy initiated an effort to support the nation's three electric interconnections in their long-range TEP. One element of this support focused on the integration of water into transmission planning (see "Technical Support for Interconnection-Level Electric Infrastructure Planning, RC-BM-2010" Area of Interest 3: Water/Energy Nexus). At that time the Western Electricity Coordinating Council (WECC) and the Electric Reliability Council of Texas (ERCOT) requested support on water related issues. A National Laboratory team led by Sandia National Laboratories and supported by Argonne National Laboratory, the National Renewable Energy

Laboratory, Pacific Northwest National Laboratory, Idaho National Laboratory, the University of Texas and the Electric Power Research Institute, responded.

There were several dimensions to this support including: calculating water withdrawals and consumption for current and projected thermoelectric power generation; estimation of future water demands for competing water use sectors (municipal, industrial, agriculture, mining and livestock); mapping water availability, considering both the physical and institutional limits on water for new development, for surface water, groundwater, and non-potable resources; risks posed by environmental policy were mapped; a climate change calculator was developed for estimating potential changes in water availability; the potential cost of water for new development was calculated; and, an energy for water calculator was developed to calculate electricity demand to pump, convey, treat (both primary and waste water), and distribute water. These tools enabled planners in the Western and Texas Interconnections to analyze the potential implications of water stress for transmission and resource planning. Working with WECC and ERCOT a wide range of transmission planning scenarios were simulated and evaluated. By the end of 2014, most of these studies had been completed.

There was a recognized need to provide similar support to the Eastern Interconnection; specifically, the Eastern Interconnection Planning Cooperative (EPIC). Studies began in 2014 and stretched into 2018. These studies largely adopted a similar range of activities as that for the West as laid out in the 2014 Multi-year Work Plan.

Objective

The purpose of this plan is to extend support to the nation's three electric interconnections for integrating water issues into their long-range transmission planning. This continued support is at the request of the interconnections. The proposed program leverages prior effort and expertise gained from the aforementioned projects as well as that of other similarly focused efforts funded across the Department of Energy (DOE). The effort will utilize a project team lead by Sandia National Laboratories and supported by Argonne National Laboratory, National Renewable Energy Laboratory, and Pacific Northwest National Laboratory.

The activities described here are meant to provide a menu of potential projects that could be implemented as available resources permit. These activities are organized according to eight tasks. This organization was adopted to allow flexible scheduling of work packages; specifically, discrete tasks can be funded individually or grouped in a variety of ways. Alternatively, work can be further segmented by major river basin or region to allow targeted analyses on assets of highest concern.

Expertise Offered

Below, a brief overview is given of the expertise and tools offered by the National Laboratory team to support WECC, ERCOT and EIPC in their integrated energy-water planning. These capabilities represent a significant investment by DOE which are now being made available to our nation's interconnections. Descriptions are organized by laboratory.

Argonne National Laboratory

Internet-accessible mapping, modeling, and reporting: The Energy Zones Mapping Tool (EZMT) was first developed by Argonne, National Renewable Energy Laboratory, and Oak Ridge National Laboratory in support of the Eastern Interconnection States' Planning Collaborative, and the Eastern Interconnection (Figure 1). Since then, the DOE Office of Electricity Delivery has funded Argonne to continue hosting the EZMT, extend it to a full U.S. extent, and make several other additions and enhancements. Argonne and Sandia have also partnered to add energy-water data content and reporting to the EZMT, and to use EZMT models and data in a study analyzing water-related influences on future power plant siting in the Eastern Interconnection. The EZMT is a unique and extensive system with a large data repository, a scope of nine energy resource categories, a variety of dynamically-generated, location-specific reports, and user-configurable suitability models for power plant locations and corridor routes. Because of its broad scope in content and capabilities, it can serve a wide range of uses, and it has attracted a diverse user community. In addition to the EZMT, Argonne has developed and hosts many other Internet-accessible mapping, reporting, and modeling tools, including the Section 368 Energy Corridor Mapping Tool, Solar Energy Environmental Mapper, Wind Energy Environmental Mapper, Hurricane Electrical Assessment Damage Outage Tool Portal, and an under-development portal for accessing and analyzing past and projected extreme weather intensity, duration, and frequency.

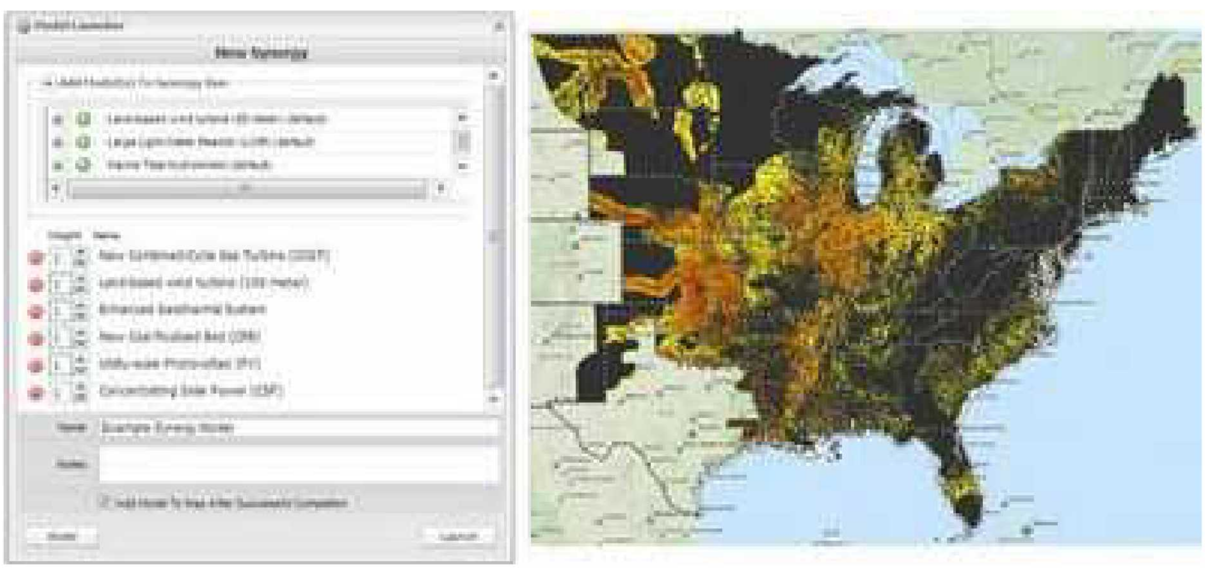


Figure 1. Example of analysis interface and geospatial display for the Energy Zones Mapping Tool.

National Renewable Energy Laboratory

Capacity expansion modeling (ReEDS and RPM): The Regional Energy Deployment System (ReEDS) is a long-term capacity-expansion model for the deployment of electric power generation technologies and transmission infrastructure throughout the contiguous United States (Short et al., 2011). ReEDS addresses issues related to renewable energy technologies, including accessibility and cost of transmission, regional quality of renewable resources, seasonal and diurnal load and generation profiles, variability and uncertainty of wind and solar power, and the influence of variability on the reliability of electric power provision. NREL has modified the structure of the ReEDS model to incorporate water availability as a constraint. Recent efforts have used ReEDS to demonstrate the importance that water constraints can have on regional deployment of electricity technologies (Macknick et al., 2015) as well as the environmental and public health benefits of achieving high penetrations of renewable energy penetration in the United States (Wiser et al., 2016).

The Resource Planning Model (RPM) is a capacity expansion model designed for a regional power system. RPM can be used to understand how increased renewable deployment might impact regional planning decisions. RPM includes an optimization model that finds the least-cost investment and dispatch solution over a 20-year planning horizon. The model investment decisions are made for multiple conventional and renewable generation technologies, storage technologies, and transmission. The model has high spatial resolution to represent the grid network (down to the individual unit and line for a "focus region" of interest) and multiple solar and wind spatial resource regions. Dispatch modeling within RPM is conducted using hourly time-steps sampled throughout a year. RPM can be utilized for specific target regions to provide high levels of spatial and temporal resolution to better understand grid dynamics (Hale et al., 2016; Barrows et al., 2016).

Production cost modeling (PLEXOS): PLEXOS Integrated Energy Model optimizes unit commitment and dispatch of generators in the U.S. electric power system at various time steps, including at a sub-hourly level. NREL has built the capability in PLEXOS to incorporate hydrologic model and climate model outputs (Macknick et al., 2016). PLEXOS can be utilized to see what the reliability/cost/dispatch impacts on the local and regional grid is due to additional generation, storage, and demand response technologies that would be implemented on agricultural operations and/or water utilities. PLEXOS was utilized by these project team members in a recent study evaluating the feasibility of achieving a 50% reduction in GHG emissions in California in 2030 under multiple energy pathways, including high penetrations of solar energy technologies (Brinkman et al., 2016). PLEXOS electricity databases are publicly available through the California Independent Systems Operator (CAISO).

Pacific Northwest National Laboratory

Integrated water resources scenarios: Droughts reduce both hydropower generation and the generation capacity of thermoelectric power plants. When droughts coincide with high summer temperatures, which is when energy demand is typically highest, the electric grid becomes stressed and grid operations must deviate from normal to avoid unserved energy (i.e., blackouts and brownouts). However, assessments of electric infrastructure vulnerability are typically performed for a baseline water year or a specific period of drought. A more holistic approach has been developed to estimate the distribution of stress on the grid by simulating electricity grid operations over the Western United States during 56 years of water availability conditions. Using a combination of regional climate, hydrology, water management models and power system models, PNNL quantified the impact of simulated historical droughts on grid operations (Voisin et al. 2016, 2018). The analytics allow the identification of regional drought patterns that are associated with higher grid vulnerability and the associated return period (Figure 2). This expertise is available to develop a range of critical hydro-climate scenarios with specific probability of occurrence to guide capacity expansion planning. This expertise is also available to complement regional long-term planning considering extra-regional boundary condition information.

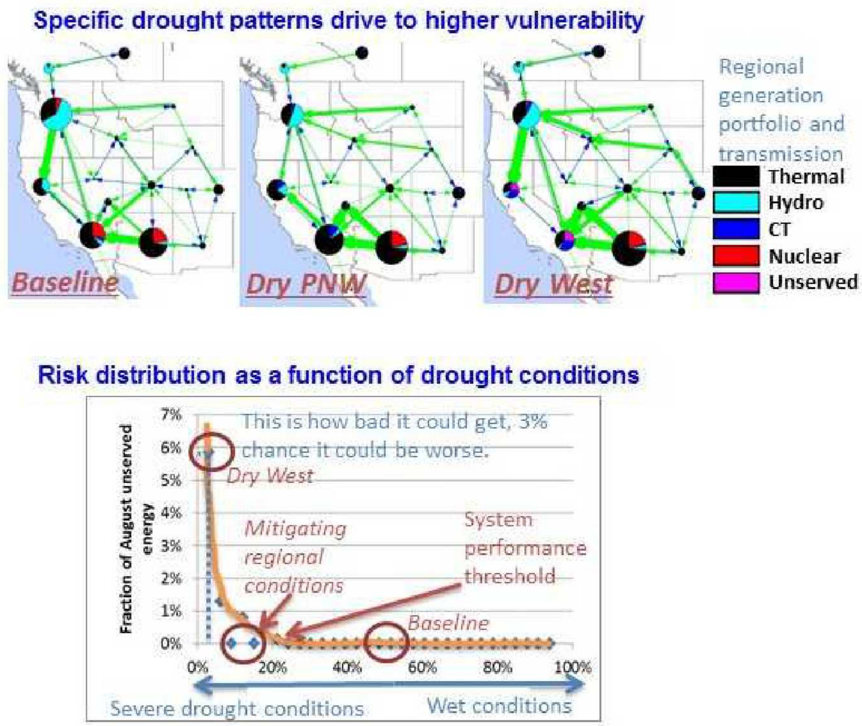


Figure 2: Identification of historical drought patterns leading to power system operations stress (Voisin et al. 2016,8)

Hydropower modeling: PNNL developed an enhanced process-based hydropower model to predict future hydropower generation and that also addresses the commonly under-represented constraints, including 1) the ecological spills, 2) penstock constraints to provide flexibility in electricity operations, and 3) biases in hydro-meteorological simulations (Zhou et al. 2018). PNNL evaluated the new process based hydropower model over the western United States under two emission scenarios (RCP4.5 and RCP8.5) and ten downscaled Global Circulation Models which define future water availability scenarios (Figure 3). The projections of mean annual and regional hydropower are comparable to other regression-based relationships. However, the representation of more complex operations and constraints tend to reduce the uncertainties inherent to climate projections at seasonal scale. The model can also capture the seasonal non-stationarity in hydrologic changes where regression-based relationships are limited. The spatial and temporal scales of the model increased accuracy and quantification of uncertainty thus allowing their use to inform power system models toward supporting energy sector planning activities and water-energy trade-offs. The direct link to hydrological models represents a communication platform with analyses supporting a range of other water uses.

CERF: The CERF model is an open-source community model that was built to determine the on-the-ground feasibility of achieving energy system expansion plans by combining multi sectoral high spatial resolution information with deducted interconnection and operational costs (Vernon et al. 2018). CERF is unique in that it further determines feasible siting locations using a combination of on-the-ground suitability constraints (e.g., protected lands) with simulated economic competition between energy technologies using an algorithm that minimizes net locational cost (NLC) to choose specific siting locations within suitable areas. More specifically, regional infrastructure projections developed by grid expansion models are first evaluated for their suitability using a geospatial approach which identifies

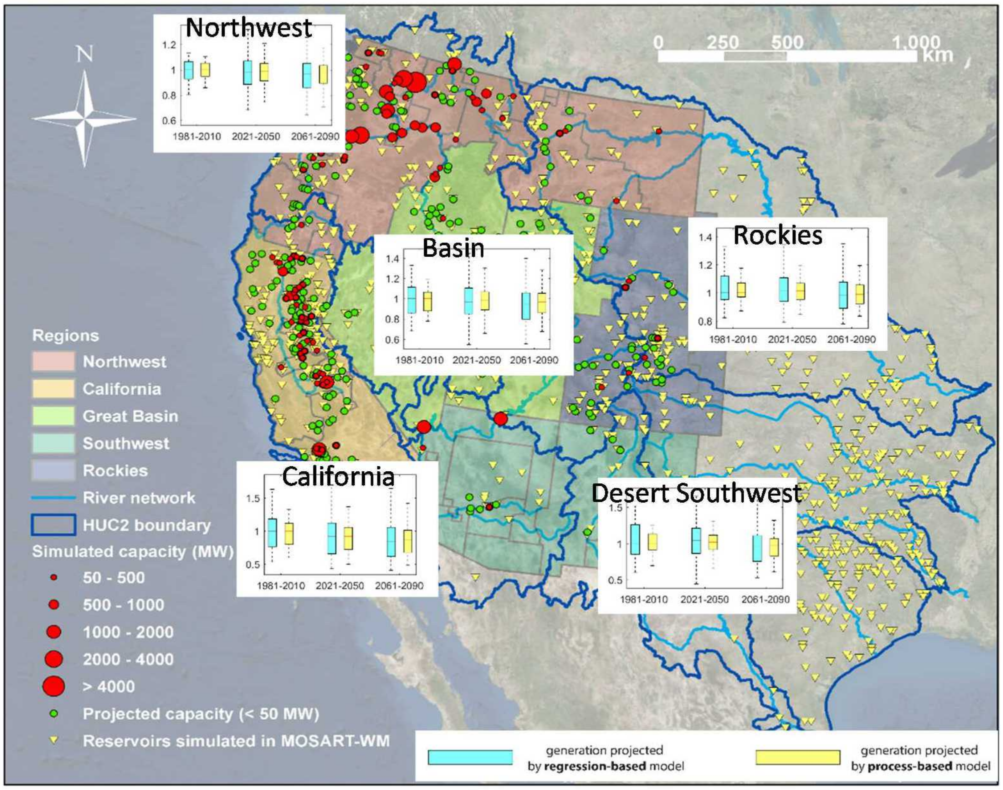


Figure 3: projection of hydropower potential over the Western U.S. (Zhou et al. 2018) which leverages a process based hydropower module with current environmental and power system regulations.

technology specific sites based on land characteristics, water availability, institutional status (protected, etc.) as well as proximity to fuel and electricity demand. CERF also evaluates a plan's interconnection and operational costs and determines the least expensive option for power plant siting per subregion per technology. Water availability constraints can be static or based on the output from a hydrology model using a specific scenario of future climate conditions and corresponding time-evolving water availability. The NLCs are calculated for each technology and are influenced by the distance to existing transmission infrastructure, technology-specific marginal operating costs, and technology- and location-specific marginal energy values. In effect, the algorithm posits the existence of a regional planner who determines the costs and benefits of having new generation in different locations and sites power plants in order from lowest to highest NLC.

Electricity demand modeling and power system responses under heat waves: Heat waves are characterized by locally extremely high temperatures, and the peaking building energy demand is not necessarily linearly related to the increase in temperature due to HVAC cooling system performance, as represented by typical regression-based load forecast models. PNNL developed an approach that reconciles scales between the heat wave and the energy demand response and that represents the non-linearity of the response. The approach consists of imposing historical heat wave scenarios to the building stock and simulating load anomalies using a building energy demand model. The approach isolates the specific heat wave signal from the potential aggregation of other events in the historical sequence (such as warm or mild summer as underlying conditions, timing of heat wave during weekends, number of heat waves, etc.). This enables characterization of the heat wave event with stress metrics (spatial extent, duration, intensity) to quantify its implications to the electric grid (Voisin 2016). A catalog of historical and synthetic heat waves with associated return periods can be derived and applied to the regional building stock with a range of efficiency technologies to support long term energy planning.

Link with NREL models: All water and energy demand scenarios are presently developed in order to be consistent with power system models including NREL's PLEXOS and ReEDS models. In addition, PNNL developed meteorological datasets consistent with dry cooling thermoelectric models toward understanding how future climate and heat wave conditions impact power system operation in conjunction with the impact of droughts and energy demand.

Sandia National Laboratories

Spatial analysis of energy-water resources: The siting of future power plants needs to be made with a clear understanding of available water resources and projected future competing demands for the available resource. Sandia has developed interconnection-wide coverages of current and projected water availabilities for fresh surface water, fresh groundwater, appropriated water, municipal wastewater and brackish groundwater sources. These estimates were developed in direct consultation with state water managers that consider both the physical availability of water as well as institutional controls that may limit access to fresh surface and groundwater supplies (e.g., water rights, environmental regulation). Estimates were made at the watershed level (8-digit Hydrologic Unit Code level or approximately 2500 watersheds across the continuous United States). To fully understand the tradeoffs across alternative water sources, associated costs to capture, convey, and treat the water have also been calculated. The primary result of this work is a set of detailed maps of water availability (e.g., Figure 4) and cost that help guide future siting of power plants so as to avoid permitting issues related

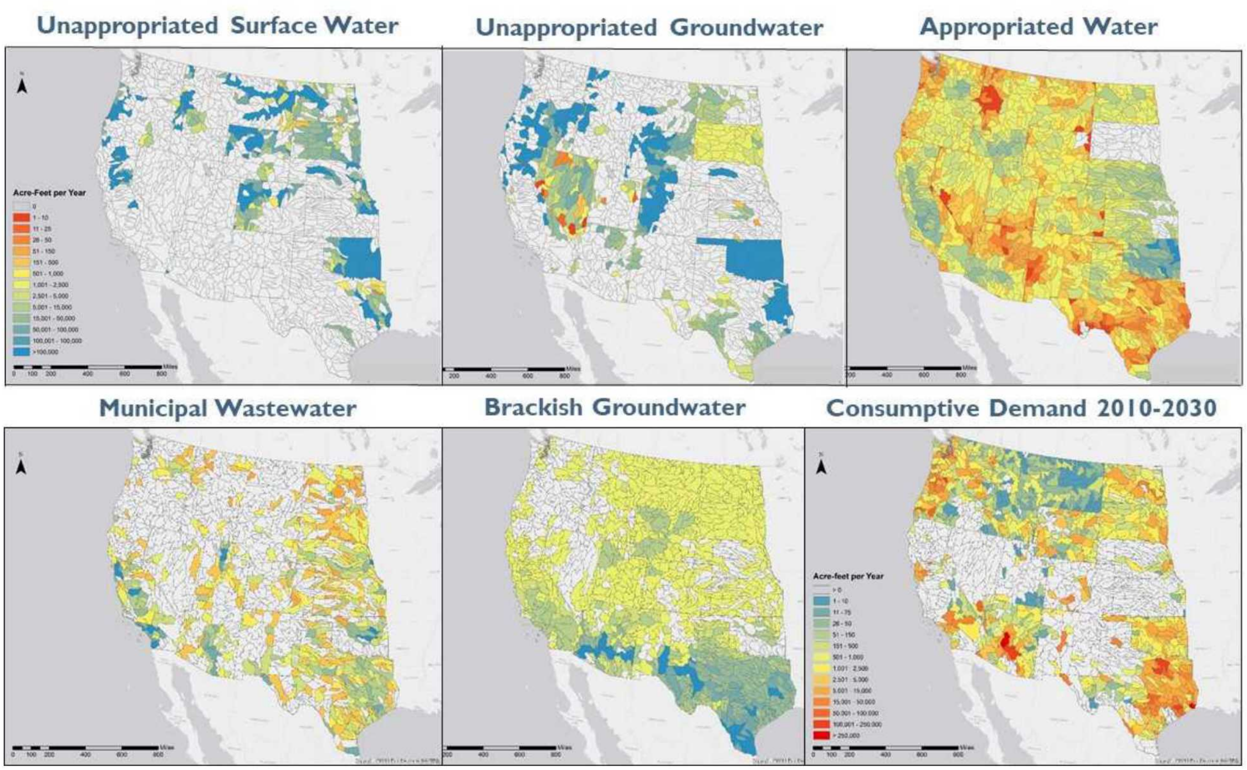
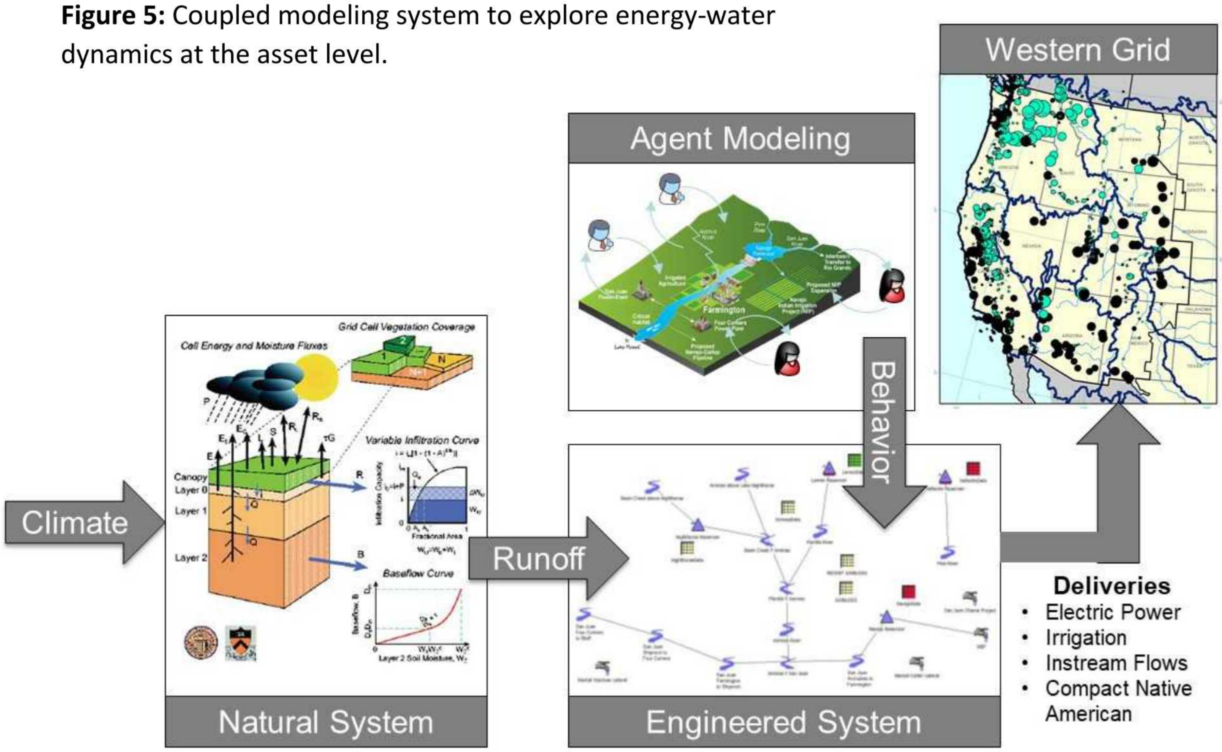


Figure 4. Water availability mapped at a HUC-8 level for the western U.S.

to regions with limited water availability. Results of this work are documented in two peer reviewed papers (Tidwell et al. 2018; Tidwell et al. 2014) while the data and maps are also available at https://energy.sandia.gov/climate-earth-systems/energy-water-nexus/data-modeling-analysis/#water-availability. Under a separately funded project, efforts are currently under way to add Alaska and Hawaii to the database.

Asset level analyses: Evaluation of the vulnerability of a particular asset or group of assets (e.g., power plant, utility, reservoir) often requires detailed assessment. Similar arguments can be made for the suitability of siting a particular asset in a particular location. There are a variety of Agency/commercial models for simulating key aspects of interacting energy-water infrastructure systems. Sandia has developed capabilities to configure, use and couple a range of these models (e.g., Figure 5). Specifically, the Variable Infiltration Capacity (VIC) model which simulates surface hydrology dynamics, partitioning precipitation between evaporation, evapotranspiration, infiltration and runoff. RiverWare is another key tool that is often used to route tributary flows (as modeled by VIC) through reservoirs to make deliveries to water users. These models have been linked to the tools described by NREL (e.g., PLEXOS and ReEDS) to evaluate impacts of water supply on electricity generation. These tools have also been linked to Agent Based Models to simulate the impacts of human behavior on water use as well as economic models to assess impacts on the economy. A recent example explored vulnerabilities of two large coal plants in the San Juan Basin in the Four Corners region of the Southwest to changing climate and increasing utilization of Native American water rights in the basin (Bennett et al. 2018 in review). This expertise is available to assist the interconnections in assessing the impact of watershed scale dynamics (e.g., climate change, rapidly changing energy demands, population growth) on critical existing assets or siting of key future assets.

Figure 5: Coupled modeling system to explore energy-water dynamics at the asset level.



Program Plan

Below we outline a range of tasks that utilize the expertise and tools described above to assist WECC, ERCOT and EIPC in the integration of water issues into their long-range transmission planning. This list of tasks has been prepared in consultation with the three interconnections. Specifically, over the past six months a series of webinars and face-to-face meetings have been held with the three interconnections. During this time the project team has provided briefings on our capabilities, while the interconnections have outlined their needs. There is no implied order or priority to the tasks; rather, this is simply a list of needs. The idea is that as needs evolve, DOE, the interconnections and the Laboratory team will consult and determine the appropriate course of action, selecting from the tasks identified below.

Task 1: Project Management

Appropriate attention to project management is key to project success. Project management as defined here serves several critical roles. First is project direction and coordination; specifically, defining the evolving course of the project. This will require consistent consultation between the Laboratory technical team, interconnection planning staff, and the DOE. Periodic conference calls and as needed face-to-face meetings will be utilized to plan evolving work scope. Here the goal is to maximize the level of support with the resources that are made available both from DOE and the interconnections.

The second activity is work control. This largely involves the preparation of the documents that control and track project work. On at least an annual basis work control documents will be established between Sandia and DOE that will define the work scope and available resources for the coming year. In turn, contracts will be developed between cooperating Laboratories to manage work subcontracted to these entities. Similarly, project financial controls will be established, tracked and reported.

Project communication is the third element of this task. This includes both internal and external communications. Monthly written reports will be submitted to DOE detailing project progress. Modeling and analysis updates will be provided to the interconnections as the need dictates. External communication will be managed in large part through the project’s website which will serve project data, published documents, presentations and summary project information. There are also likely to be invited presentations to interested stakeholder groups, trade organizations, universities and others concerning the purpose, approach and results of this project.

Deliverables: Primary products of this task include maintenance of the project’s external website and delivery of monthly updates to DOE documenting financial and technical project status.

Task 2: Data Support

Integral to any modeling exercise is acquisition of the supporting data. This is certainly the case here as a wide range of models are proposed in support the transmission planning of our nation’s three electric interconnections. Efforts fall conveniently into three subtasks.

Subtask 2.1: Update water availability and cost data

It has been roughly five years since the western water availability and cost data were updated. Since this time new information has been published, particularly a new report by the U.S. Geological Survey mapping brackish water reserves in the U.S. Additionally, water use estimates for 2015 have recently been published by the U.S. Geological survey, updating data from 2010 used previously to estimate competing water demands (municipal, industrial, agricultural water sectors). Growing use of recycled wastewater and brackish groundwater also need to be captured.

As the project evolves it may also become necessary to project potential impacts of climate change on streamflow and groundwater recharge and thus determine impacts on water availability and demand. This was not previously attempted so as to remain consistent with state projections (which do not consider climate change effects). Rather than change the state's availability estimates a vulnerability metric will be developed. The metric will be based on projected changes to precipitation and evaporation over a wide range of climate models and scenarios. This will help identify basins where climate change has a strong potential to reduce current water supplies.

Deliverable: Review new publications, update prior estimates of water availability, water cost and future water demand as well as develop metrics addressing vulnerability to climate change. These data will serve as the primary water constraint for future transmission planning.

Subtask 2.2: Extend boundaries of analysis to include Canada and Mexico

The WECC and EIPC planning regions extend into Canada and Mexico. Prior energy-water planning support did not address dynamics outside the United States. This task will collect data necessary to extend modeling into WECC and EIPC regions in Canada and Mexico. The interconnections will supply grid related data while the project team will be responsible for all other required data (primarily water sector information).

Deliverable: Collect non-energy sector data for energy-water planning in the WECC and EIPC planning regions outside the U.S.

Subtask 2.3: Other supporting data

This subtask is added to simply capture all additional data collection exercises that are not covered by the prior subtasks. Collected data would simply be that necessary to accomplishes the modeling and analysis exercises described in the following tasks.

Deliverable: Collect non-energy sector data including model parameterization for energy-water planning in the WECC and EIPC planning regions outside the U.S.

Benefit to the Interconnections

Collection of the required data has little immediate benefit to the interconnection. However, collection and updating of data is necessary for the proposed modeling and analysis exercises. So in this way, this task is integral to delivering benefit across all the other tasks.

Capacity Development Opportunity

In most cases, data are very particular to a specific modeling exercise. We know the details of what we need and thus are best suited to collect the data. For this reason, it is expedient for the modelers, e.g., National Laboratories, to lead the effort to acquire the needed data. However, the modeling team will lean heavily on the interconnections to supply data specific to their electric grid. This might include information on the topology of the grid, portfolio of power plants, energy demands among others.

Task 3: Reliability of water and climate dependent electricity generation

Many large hydropower projects are located in Canada and provide a range of ancillary services to the grid including long term storage, flexible high capacity and a generation that exceeds local load. Their location in remote areas also decreases the level of regulation and which allows the project to be more flexible than projects in the U.S. We propose to extend the hydrological modeling capabilities to the regions outside of US and which contributes to US inter-connections.

The hydrological modeling includes a spatially distributed hydrology model coupled to a river routing reservoir model further coupled to a stream temperature model which includes reservoir stratification. Constraints on thermoelectric plants can therefore be derived. The water management model includes dynamic withdrawal capabilities from surface water and groundwater systems which allows evaluation of stress scenarios where river operations could be partially restricted, with respect to static management, in times of multi-year or severe droughts. Similarly, the hydropower model will complement the analysis and can be run under a range of regulation scenarios, i.e. different spinning reserve and/or environmental flow requirements. Finally, a catalog of historical heat waves will be developed toward constraining a dry-cooling thermoelectric plant model and to inform load forecast models. Those individual stress scenarios, and in particular the combination of those scenarios, have been proven to be critical in long term resources planning. The design of compounded stress scenarios will be discussed with the interconnections.

Deliverable: i) scenarios of constrained hydropower generation and thermo-electric capacity which represent regional and extra regional risk and opportunities to the interconnection long term planning; and, ii) scenarios of heat wave driven load anomalies and dry cooling thermo-electric plants. Each scenario will be associated with spatially distributed integrated hydro-meteorological simulations (regulated flow, withdrawals from surface water and ground water systems, etc.) that can be shared, if not already used, by water resources managers to understand resilience and opportunities. The hydrology scenarios will also be shared with the siting models to develop consistent water availability constraints.

Benefit to the Interconnections

The interconnections often develop "what if" scenarios of compounded conditions which could lead to a range of different expansion plans. This task provides the tools and expertise to understand critical water and climate scenarios, and their impact on regional and extra regional assets, which could influence the expansion plans.

Capacity Development Opportunity

A multi-model coupled system will be necessary to address the task which require high performance computing. The capacity transfer from the Lab team to the individual interconnections would not be time or resource efficient. In conjunction with the Lab team, interconnections will define the range of combinations of events that influence long term planning and which can be communicated with other water users for understanding resilience and mitigation strategies.

Task 4: Capacity expansion modeling constrained by water

This task will produce multiple future electricity sector infrastructure configurations that incorporate variations in technology cost and performance characteristics, fuel price uncertainty, and changes in water availability. Each of these driving factors can influence long-term investments in electricity-generating technologies and transmission infrastructure, and each will be considered in isolation as well as in combination. Specific technology cost and performance characteristics can include changes in the efficiencies, capital and O&M costs, and technology lifetimes of wind, solar, geothermal, natural gas, nuclear, and coal technologies. Fuel price uncertainty can affect coal, natural gas, and uranium resources. Water availability changes can affect water resources required for thermal generators as well as hydropower facilities, and can face total annual as well as seasonal variations. Exact scenarios to be analyzed will be discussed and defined by the broader project team according to specific needs and research questions.

Capacity expansion modeling efforts will be conducted utilizing the ReEDS and RPM models, which provide high resolution analytical capabilities that can incorporate water resources as a constraint (e.g., Macknick et al., 2015). Capacity expansion results from these models will project out to the year 2050, with interim analyses and capacity results every two years from present day. If desired, the ReEDS model can project out as far as they year 2100. Specific outputs from the model for analysis and comparison include total generator capacity, generation, emissions, water withdrawal and consumption, total system costs, regional electricity costs, and transmission infrastructure investments, all at high spatial resolution. These metrics, and others to be defined by the project team, will serve as the basis of comparison across future portfolio scenarios. Policy measures may also be included, as necessary, such as those addressing the types of water that can be used in the power sector, cooling system limitations for thermal generators, renewable portfolio standards, or other relevant policies that can affect capacity development and operations.

Deliverable: Comprehensive library and comparison of future capacity expansion scenarios under multiple technology cost and performance, fuel price, and water availability conditions.

Benefit to the Interconnections

The Interconnections would benefit from a broad array of future market and water scenarios at high spatial resolution that could influence regional investment decisions. Using best-in-class water-constrained capacity expansion models, these future portfolio results could also be built upon for additional analyses of operations and resilience.

Capacity Development Opportunity

The ReEDS model is currently being transformed into an open-source model, which would offer ample opportunities to train Interconnection staff on best practices for water-constrained capacity expansion modeling, scenario design, and sensitivity analyses using a high-resolution model.

Task 5: Reliability/Resilience analysis of existing and future system to water shocks

This task will build off the results of Task 3’s future capacity results to analyze operational impacts of water resource variability on technology dispatch, electricity system costs, and overall system reliability. Variations in water availability as well as water temperatures throughout the year can affect individual generating unit capacities, their ability to dispatch at certain times, and broader system responses. Some generating units and future portfolios could have lower operating costs during times of abundant water, but could be more vulnerable to water-related disruptions in summer months. Other generating units and future portfolios could have lower water requirements throughout the entire year, but would face other variable integration challenges. The results of this task will provide the Interconnection with quantitative assessments of the tradeoffs of different future portfolios in terms of their operational reliability and costs under various scenarios of water availability.

Future electricity mixes in designated years (e.g., 2030, 2050) will be modeled with the PLEXOS software linked with a water resource model to capture how water resources affect system operations at high temporal resolution (e.g., five-minute to one-hour timesteps). Water resource availability modeling will be consistent with water availability data driving the capacity expansion of each future portfolio scenario. Specific methods of linking PLEXOS with water resource models will be based on Macknick et al, 2016. Metrics analyzed include technology dispatch differences, total system costs, and reliability metrics such as reserve margins. These metrics will be compared across scenarios to provide a more complete assessment of system-level reliability of different future portfolios subject to water-related shocks.

Deliverable: System-level assessment and comparison of operational reliability and vulnerability of different electricity sector capacity configurations under multiple water availability scenarios

Benefit to the Interconnections

The Interconnections would benefit from a more comprehensive assessment of cost and reliability tradeoffs of different future portfolios subject to water constraints. High-resolution linked energy and water models can provide important insights into long-term impacts of investment decisions.

Capacity Development Opportunity

Interconnection staff would have the opportunity to participate in analyzing data, understanding best practices of model linkages, and metrics definitions.

Task 6: Asset level reliability/resilience analyses

This task will evaluate, as needed, the vulnerability and resilience of key grid assets; specifically, a targeted set of power plants or hydropower facilities. Such analyses may be required where details of nexus dynamics, geography, institutional operations, resource access or other are essential to transmission planning decisions. These watershed scale simulations will generally consider operations of existing and/or new assets in response to changing climate conditions—with an emphasis on future heat waves and droughts. Scenarios are also likely to consider other geophysical and socioeconomic stressors. The concern is that without deliberate attention, climate change and development will generally have a significant negative impact on water availability and energy production, and on the performance and reliability of the grid, although these impacts will vary substantially under different scenarios. We do not fully prescribe the scenarios that will be explored as these will be dictated by the evolving and specific needs of the individual interconnections. General categories of scenarios that could be considered include:

- Different climate models and RCPs (representative concentration pathways), which drive different global and regional climate outcomes as well as technological and socioeconomic changes.
- Different SSPs (O'Neill et al. 2014), which describe different "storylines" for population, economic development, energy use, and other factors. Many of the RCPs can be achieved through a variety of SSPs, and exploring different socioeconomic conditions will yield insights into the relative influence of climate and human system changes on vulnerability and resilience outcomes.
- The inclusion or omission of specific technologies or policies (e.g., LNG exports, relaxation of nuclear moratoria, CCS availability, dramatic expansion of biofuels, etc.) that are not directly tied to adaptation.

Evaluation of system resilience will largely follow from comparison of carefully selected metric across the target scenarios. For water systems, a key measure is the delivery of water to users, which depends on the detailed operations of the river system as well as projected runoff from the watersheds. These deliveries ultimately define system performance, as they dictate power plant operations, agricultural production, city function and environmental quality. Metrics of resilience and vulnerability thus include changes in discharges, ability to meet water demand, and frequency of failure (see Christensen et al. 2007; Vano et al. 2010; Van Rheenen et al. 2004; Christensen et al. 2004). We will further define metrics for the joint vulnerability and resilience of integrated energy and water systems. These could include, for example, metrics related to changes in annual hydropower generation (see Kao et al. 2015), deratings of thermoelectric plants (Van Vliet et al. 2016), or quantification of saved water uses when switching to different energy generation technology (Macknick et al. 2015).

These asset level analyses can also be used to explore opportunities to reduce the vulnerability or enhance the resilience of energy and water systems. What is less well understood, in general, is the value of investing in these adaptations—that is, the expected return on investment in terms of operational impacts avoided. In this way we focus on how different adaptation options could be used to reduce or offset some of the negative impacts of climate change/development on energy and water systems--the primary goal being to understand how vulnerability and resilience (quantified through the comparative metrics) might be modified by how future electricity and water systems are configured and operated.

Local adaptive measures that could be considered in the energy sector include alternative water sourcing, fuel alternatives, and cooling system technology choices. In the water sector, some potential strategies include changes in agricultural practices or technologies, changes in reservoir operations, and the use of produced water. One example of an adaptation approach is modifying power plant siting—that is, changing the specific location of certain types of generators in order to improve the overall resilience of the system. Selection of appropriate adaptive technologies will be driven by input from the individual interconnections.

Deliverable: Targeted assessments of specific energy assets (thermoelectric/hydroelectric power plants) particularly considering their vulnerability and the adaptive measures that can be taken to improve their resilience.

Benefit to the Interconnections

The interconnections are each aware of troubled assets that defy simple analysis due to their locations, complexities of their operational role, and uncertainties pertaining to their water supply. These assets require special attention. This task provides the tools and expertise to address the interconnections nagging concerns.

Capacity Development Opportunity

In the majority of cases, a multi-model coupled system will be necessary to address the particulars of these troubled assets. Given the complexity and the tedium of operating such tools, capacity transfer from the Lab team to the individual interconnections would not be time or resource efficient.

Task 7: Short-Term Water Risk Modeling

This is the only task that is unique to a particular interconnection. This task is designed to support extension of ERCOT's Drought Risk Model. This model was originally developed for ERCOT by a contractor, Black & Veatch. The purpose of the model is to project potential risk to thermoelectric power generation due to low reservoir storage (i.e., limited cooling water supply). The model projects risk out 18 months. Each month water levels for each reservoir in Texas are loaded into the model. Simulations then project potential inflows, losses and abstractions to estimate reservoir levels over the coming months. This is then compared to specific power plant cooling water demands to assess risk.

ERCOT has expressed interest in extending the capabilities of this model to better project risks. Upgrades to the current model could include improving the modeled dynamics for key processes such as lake evaporation, reservoir operations and power plant water demands. Opportunities also exist to improve the projections of water demands both by the electric sector as well as other competing water uses. In similar fashion, there is need to improve the hydrology to better represent variability in climate and intensifying drought.

Interest has also been expressed in expanding the capability of the model to consider potential water temperature impacts. Specifically, they would like the model to project risks to cases where power plant effluent temperatures could cause lake temperatures to exceed environmental limits. This would require development of a completely new lake temperature model that would need to be coupled to the existing hydrology model.

Deliverable: Upgraded Drought Risk Model.

Benefit to the Interconnections

Upgrades to the Drought Risk Model would allow ERCOT to better forecast potential issues with thermoelectric water supply. Earlier and more accurate forecasts can then be used to initiate remedial actions and to develop contingency plans toward more reliable and resilient grid operations.

Capacity Development Opportunity

Model upgrades would be performed by the Laboratory team, while utilization and operations of the Drought Risk Model would be the sole responsibility of ERCOT.

Task 8: Energy Zones Mapping Tool

The Energy Zones Mapping Tool (EZMT) hosted by Argonne was used to share the Sandia water availability, cost, and use data. It also includes many other data sets for water and energy-water, including:

- 100-year flood zones – Federal Emergency Management Agency
- Aqueduct Water Risk – Water Resources Institute
- Aquifer Area – U.S. Geological Survey
- Geothermal Well Database – Southern Methodist University
- Hydrokinetic Projects – Federal Energy Regulatory Commission
- National Hydrologic Dataset-Plus – Horizon Systems Corporation, et al.
- Navigable Waterway Network – Research and Innovative Technology
- Pumped storage sites, and permit locations – Sandia National Laboratories
- River Gauging Stations – U.S. Geological Survey
- Run of River Monthly Generation – Argonne
- River Temperature Model – City University of New York
- Thermoelectric Power Plant Water Use – U.S. Geological Survey
- Tidal Power Density – Georgia Institute of Technology
- Trends in Flood Magnitude – Peterson, et al.
- Watersheds (HUC levels 2 and 8) – U.S. Geological Survey
- Wave Energy – National Renewable Energy Laboratory

This task centers on continuing to update the EZMT with energy-water data, to identify and implement enhancements to its analysis and modeling capabilities, and to inform and engage the stakeholder community about this resource.

Deliverable(s): Sharing data and analysis capabilities from the other tasks in an assessable and versatile Internet-based tool.

Benefit to the Interconnections

Each interconnection would leverage the considerable investments already in the EZMT to identify, gather, maintain, analyze, model, and share data. The EZMT can also be used to host data or new tools of interest to one or more interconnections, or as a resource for new studies.

Capacity Development Opportunity

Upgrades and extension of the EZMT would remain the responsibility of the developer (Argonne). The EZMT is designed for easy use by water and energy managers/stakeholders. Specifically, various analyses could be conducted by Interconnection staff with little or no involvement of the Lab team. The tool could be used to scope new transmission corridors, siting alternatives for new generation, or for situational awareness of critical features and habitat important to planning decisions.

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