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Integrated Energy-Water Planning in the Western and Texas Interconnections

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ABSTRACT

While long-term regional electricity transmission planning has traditionally focused on cost, infrastructure utilization, environmental impact, and reliability, the availability of water is an emerging issue. Toward this growing need, thermoelectric expansion should consider competing demands from other water use sectors balanced with fresh and non-traditional water supplies subject to climate variability. To address this need the Department of Energy's Office of Electricity Delivery and Energy Reliability supported an integrated planning project with funding through the American Reinvestment and Recovery Act (2009). Specifically, an integrated energy-water analysis was performed to support transmission system planners in the Western and Texas Interconnections to explore the potential implications of water availability and cost for long-term transmission planning. The project brought together electric transmission planners (e.g., Western Electricity Coordinating Council (WECC) and the Electric Reliability Council of Texas (ERCOT)) with western water planners[1] (e.g., Western Governors' Association and the Western States Water Council). Efforts were organized into ten specific tasks: (1) project coordination and outreach; (2) thermoelectric water use; (3) non-thermoelectric water use; (4) water availability; (5) water cost; (6) environmental risk; (7) climate variability; (8) energy for water; (9) decision support system interface; and, (10) transmission planning support.

Major accomplishments associated with this effort include:

- For the first time water availability was used to inform generation expansion planning by WECC and ERCOT (Section 11.2 and 11.3).
- For the first time, projections of intensifying drought and its effect on reservoir levels, and thermal effluent discharge permitting were used to inform operational and expansion planning by ERCOT (Section 11.3).
- Water withdrawal and consumption were characterized for each power plant in the WECC and ERCOT service areas/regions (Section 3.2). Water use factors were also developed for a range of unit processes that allowed projection of future water demands related to electric generation expansion planning (Section 3.1).
- Working with state water managers current and future water use (withdrawal and consumption) were projected throughout the Western United States at an 8-digit Hydraulic Unit Code (HUC-8) level (over 1200 watersheds) (Section 4).
- In a similar fashion water availability and cost were mapped across the Western United States. Considered were five different sources of water: unappropriated surface water, unappropriated groundwater, appropriated water, municipal wastewater and brackish groundwater (Sections 5 and 6).
- Water basins (at the HUC-8 level) were mapped across the Western United States with regard to their potential for conflicts between aquatic and riparian species and habitats listed under the Endangered Species Act and water availability for future energy development (Section 7).

[1] Water planners were engaged through the Western States Water Council and thus reflects their membership of the 17 contiguous western states (i.e., Texas up through the Dakotas and West).

- Power plants at greatest risk to the impacts of drought were identified. The analysis considered the hazards of low flows, insufficient reservoir storage, and elevated water temperatures under intensifying drought conditions projected for the future (Section 8).
- The electricity used to provide water-related services was mapped at a county level throughout the Western U.S. Considered was the electricity required for interbasin conveyance, agricultural pumping, drinking water and wastewater services (Section 9.1).

To communicate our results the project has produced 6 journal articles, 1 book chapter, 11 reports, and 47 presentations at related conferences.

The data, modeling and reports generated by this project have been made publicly available through the project website: http://energy.sandia.gov/climate-earth-systems/water-security-program/water-energy-and-natural-resource-systems/energy-and-water-in-the-western-and-texas-interconnects/.

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Challenge

In 2010, thermoelectric power withdrew more water than any other sector in the United States (Maupin et al. 2014). With the demand for electricity projected to increase by 24% by 2035 water supply could present a limiting factor for siting of new electric generation. In fact, the lack of integrated electric power and water planning has already impacted electricity production in many basins and regions across the United States. In three of the fastest growing regions, the Southeast, Southwest, and Northwest, new power plants have been opposed because of potential negative impacts on water supplies (Tucson Citizen 2002; Reno-Gazette Journal 2005; U.S. Water News Online 2002 and 2003; Curlee and Sale 2003). For similar reasons, Idaho placed a 2-year moratorium on construction of coal-fired power plants (Reuters 2006). Concerns over falling water levels in Lake Norman, Lake Mead, and reservoirs all along the Apalachicola River had water managers and utility operators perplexed over how to supply water to cool thermoelectric power plants and/or generating hydroelectric power while maintaining adequate flows for environmental and human needs (Webber 2008).

There have been a number of studies exploring the nexus between thermoelectric power and water. Numerous DOE laboratories collaborated to prepare a Report to Congress (DOE 2006) that looked broadly at the energy-water nexus, describing the various ways in which water is used in energy production and providing high-level estimates of the intensity of water use. To provide supporting data, the National Energy Technology Laboratory (NETL) prepared a series of reports estimating water withdrawals and consumption associated with thermoelectric power generation (Feeley et al, 2007; NETL, 2008; 2007). Their analyses extended to the year 2030 and considered a variety of cases that differ according to the mix of fuel and cooling type employed in the future thermoelectric power plant fleet. These analyses were performed for the 13 North American Electric Reliability Corporation (NERC) regions spanning the entire continental United States.

Using county-level data on rates of population growth, utility estimates of future planned electricity capacity additions in the contiguous United States, and scientific estimates of anticipated water shortages, 22 counties were identify as the most likely locations of severe shortages brought about by thermoelectric capacity additions (Sovacool 2009a; Sovacool and Sovacool 2009a; 2009b). The Union of Concerned Scientists provided the first systematic assessment of both the effects of power plant cooling on water resources across the United States and the quality of information available to help public- and private-sector decision makers make water-smart energy choices (Averyt et al, 2011).

Through interviews with subject matter experts, the Government Accountability Office (GAO) (2003) published a report on the energy-water nexus. From these interviews they made three overarching conclusions. First, advanced cooling technologies that rely on air to cool part or all of the steam used in generating electricity and alternative water sources such as treated effluent can reduce freshwater use by thermoelectric power plants. Second, oversight of water use by thermoelectric facilities varies by state and is influenced by state water laws, related state regulatory policies, and additional layers of state regulatory review. Third, improvements to Federal water use data would increase understanding of the trends in power plant water use.

Beyond these nation-wide efforts to explore the thermoelectric-water nexus, several regional analyses have been conducted. The Environmental Defense Fund and Western Resource Advocates conducted an overview of the Energy-Water Nexus in the West. Their study relied on existing data and analyses to promote seven water/energy/planning policies (developed from the core principles of these organizations) aimed at mitigating future problems (Environmental Defense Fund 2010). Texas (Stillwell et al, 2009) and California (California Energy Commission 2002) each have conducted state-specific analyses of the implications of expanding water needs for thermoelectric cooling and its potential to lead to water stress within each state. Similarly, the Great Lakes Commission, supported by Sandia, EPRI, and Argonne, sponsored a study to investigate alternative futures for electric power generation in this region and their implications on water supply and environmental quality (Tidwell and Pebbles 2015).

Several models have likewise been developed to analyze the interplay of thermoelectric power production and water resources at the regional scale. EPRI has developed a framework to evaluate water demands and availability for electrical power production on a watershed basis (EPRI 2005). This framework to date has been applied to a handful of basins across the United States. Other studies include the investigation of wind-driven groundwater pumping to utilize excess electrical power production by local wind farms (Wigmasta and Skaggs 2010). Similarly, detailed modeling of water-energy tradeoffs on the American River in California (Dale 2010), a small, closed watershed, and irrigation-thermoelectric power tradeoffs in watersheds in Texas have likewise been conducted (Stillwell et al. 2010; King et al. 2008; Clayton et al. 2010).

From this brief review it is apparent that numerous energy and water studies have been conducted to date; however, these studies are limited by either their level of spatial detail (e.g., studies are at national or a multi-state regional basis) or their narrow focus on a single aspect of the problem (e.g., thermoelectric water use). The project documented in this report strives to fill this gap, supporting long-range transmission planning at the interconnection scale.

Project Background

Pursuant to Title IV of the American Reinvestment and Recovery Act (2009), the Department of Energy's (DOE) Office of Electricity Delivery and Energy Reliability has endeavored to strengthen long-term analysis and planning in the three interconnections serving the lower 48 United States. Technical teams drawing support from DOE's National Laboratories and leading universities identified transmission requirements under a broad range of alternative electricity futures, and developed long-term interconnection-wide transmission expansion plans. Under the Recovery Act's Funding Opportunity Announcement (DE-FOA0000068), DOE issued awards to five organizations to perform related work in the Western, Eastern and Texas Interconnections.

One aspect of this interconnection-wide planning exercise was the integration of water-related issues into generation and transmission system expansion. Based on the unique needs and priorities of our Nation's three interconnections, the Western and Texas Interconnections requested that water be integrated into the planning process. In response, DOE prepared the

Funding Opportunity Announcement "Technical Support for Interconnection-Level Electric Infrastructure Planning, RC-BM-2010" Area of Interest 3: Water/Energy Nexus. The award was made to a consortium of National Laboratories, a university, and an industrial research entity. The lead for this effort was Sandia National Laboratories (Sandia) supported by Argonne National Laboratory (Argonne), Idaho National Laboratory (INL), the National Renewable Energy Laboratory (NREL), Pacific Northwest National Laboratory (PNNL), the University of Texas (UT), and the Electric Power Research Institute (EPRI). The resulting project was named "Integrated Energy-Water Planning in the Western and Texas Interconnections" and will be referenced by the term Integrated Energy-Water Planning (IEWP) in this report.

Project Objectives

According to the stated needs of the Research Call, three overarching objectives were identified:

1. Develop an integrated energy-water information set that will enable transmission system planners in the Western and Texas Interconnections to analyze the potential implications of water stress for transmission and resource planning.
2. Pursue the formulation and development of the energy-water information set through a strongly collaborative process between members of this proposal team and the Western Electricity Coordinating Council (WECC), Electric Reliability Council of Texas (ERCOT), Western Governors' Association (WGA), the Western States Water Council (WSWC) and their associated stakeholder teams.
3. Utilize the acquired information to investigate water stress implications of the transmission planning scenarios put forward by WECC, ERCOT, WGA, and WSWC.

To support these three objectives, ten broad tasks were identified by which to organize the work. *Task 1: Project Management*, involved basic project management and coordination across the various participants. Key to success was conducting project work in close collaboration with WECC, WGA, ERCOT and their stakeholder teams. To enhance transparency and consensus, a Collaborative Modeling Team (CMT) was assembled to oversee implementation of the project. Team membership included a subgroup of our interconnection partners. The CMT met on a periodic basis to define: 1) key metrics and decision variables; 2) vet process models; 3) vet data; 4) jointly review the models and conduct calibration analyses; and 5) conduct desired scenario analyses.

Under *Task 2: Water Withdrawal and Consumption for Current and Future Thermoelectric Power Generation*, current water demands were calculated according to power plant capacity, power generation, type of plant, type of cooling, and type of emissions control. Accompanying parasitic energy loads imposed by emission controls and water-conserving cooling technologies were also calculated. Average plant level water use characteristics were then used to project future thermoelectric water demands based on generation expansion scenarios produced by WECC and ERCOT.

In efforts to direct future thermoelectric generation expansion, regional measures of projected future water use in the non-thermoelectric sector, as well as for extraction and processing of energy fuel (*Task 3: Non-Thermoelectric Water Demand*), were estimated. These water uses are important as they are potential future competitors with thermoelectricity (and other sectors) for limited water resources. *Task 4: Water Availability*, combined information on water supply with water use and institutional controls (i.e., water rights, policies) to construct maps of water availability. These data were developed in close collaboration with the 17 western state water management agencies. Beyond the availability of water, information concerning the potential cost of water for a new withdrawal[2] was calculated including water rights purchase, cost to convey and/or lift the water, and cost of treating non-potable water (*Task 5: Water Cost*).

The water demand and availability analyses are accompanied by additional process models to further resolve water availability. The first of these was an environmental controls model for identification and assessment of potential environmental risks associated with growing water use (*Task 6: Environmental Risk*). A climate variability calculator (*Task 7: Climate Variability Analysis*) was included for estimating potential changes in water availability. This included two components – a climate downscaling model to provide future climate forcing data for the watershed model and a dynamic large-scale watershed model to project related changes to water availability. *Task 8: Energy for Water*, explored energy for water, mapping the electricity demand to pump, convey, treat (both primary and waste water), and distribute water.

The final two tasks were aimed at making use of the developed models and data sets. *Task 9: Decision Support System Interface*, created an accessible data base and interface dashboard to visualize and interact with the energy-water data. The acquired data and associated mapping were made publically available at the following website: http://energy.sandia.gov/climate-earth-systems/water-security-program/water-energy-and-natural-resource-systems/energy-and-water-in-the-western-and-texas-interconnects/. *Task 10: Transmission Planning Support*, involved coordination with WECC and ERCOT to integrate the developed models and data into their long-term transmission planning.

Project Area

The project area for the IEWP was defined as the 17 contiguous states that lie along and/or west of the 100th meridian (Texas to the Dakotas and west). These states were selected as they encompass all the states serviced by our key cooperating partners, WECC, ERCOT, WGA and WSWC. The WGA and WSWC have the largest geographic footprint and thus their service region is adopted as the project area for the IEWP. It should be noted that all are parts of eight states (North Dakota, South Dakota, Montana, Nebraska, Kansas, Oklahoma, New Mexico and Texas) lie outside the WECC and ERCOT service areas.

Project Benefits and Outcomes

A key deliverable of the IEWP was an integrated energy-water dataset and model suit that enabled planners in the Western and Texas Interconnections to analyze the potential implications of water stress for transmission and resource planning. Working with WECC, WGA, and

[2] New withdrawals, water supply accompanying development such as required to operate a new thermoelectric power plant, are problematic as many basins in the West are fully appropriated; that is, all water rights that the basin can normally fulfill are already in use. This means existing water users with senior rights receive the water they need while new development could be denied due to a lack of water.

ERCOT, and utilizing this energy-water information set, a wide range of transmission planning scenarios were simulated and evaluated.

Additionally, the IEWP represents the first comprehensive, regional analysis of the energy-water nexus undertaken by federal and state agencies, the power industry, NGOs and other interested stakeholders. In this way, the data, models, scenario analyses, and insights derived from the IEWP provide a significantly improved body of evidence for policy-making at local, state and federal levels.

TASK 1: PROJECT MANAGEMENT

Appropriate attention to project management is paramount to project success. This task established necessary project coordination, communication, contracting, and resource tracking practices among members of the project team, DOE, and our Interconnection partners.

1.1. Scope of Work and Management Plan

The first activity included the preparation of a project Scope of Work and Project Management Plan[3]. The Project Management Plan addressed issues of intellectual property, quality assurance, configuration management, along with defining an approach to communication and coordination throughout the duration of the project. Another element on the plan was a clear process of review and acceptance for the products developed throughout the IEWP.

1.2. Project Coordination

Vincent Tidwell of Sandia National Laboratories served as overall Principal Investigator/Project Coordinator for research under this proposal; however, multiple principal investigators (PIs) collaborated to plan and conduct the research. This collaboration included Argonne PI John Gasper, EPRI PI Robert Goldstein, NREL PI Jordan Macknick, INL PI Gerald Sehlke, PNNL PI Mark Wigmosta and UT PI Michael Webber. Project Coordinator and PI responsibilities included directing, coordinating and conducting research for specific projects under this proposal, jointly reporting to the DOE program manager, and assuring administrative requirements were met. Project coordination across this team was pursued through monthly web conferences among all project participants augmented by periodic face-to-face meetings.

To enhance project coordination with entities outside the direct project team, a Collaborative Modeling Team (CMT) was assembled. Team membership involved a self-selection process of participants from the WECC, WGA, and ERCOT planning teams. The CMT also included willing experts from other organizations as appropriate. The CMT met on a monthly basis to define: 1) key metrics and decision variables; 2) vet process models; 3) vet data; 4) jointly review the models and conduct calibration analyses; and 5) conduct desired scenario analyses. Meetings were largely handled through web conferencing with occasional face-to-face meetings coordinated with other project events. Figure 1 provides the basic structure of the collaborative modeling team and its relationship with the interconnections and state water management agencies.

[3] following the basic principles set forth in the Project Managements Institute's "A Guide to the Project Management Book of Knowledge

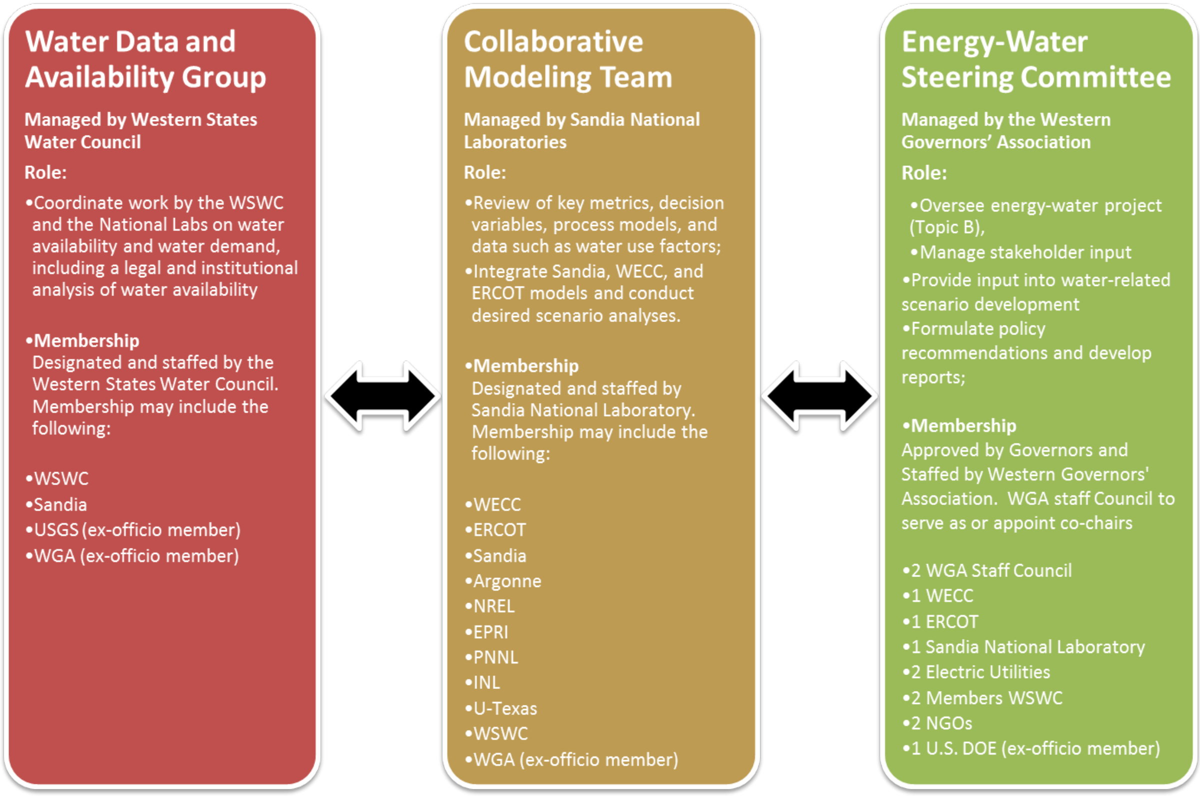

Figure 1. Structure and role of the Collaborative Modeling Team and its relation to the Interconnections and state water management agencies (through the Western States Water Council).

1.3. Project Website

A project website was developed and maintained throughout the duration of the project. The website served as an internal file share and configuration management for project partners as well as a port for external communication. The internal file share was password protected providing a place where participants could share documents and models subject to configuration managed protocols. The external public website (Figure 2) includes a description of the effort, contact personnel, approved scopes of work, project status, presentations, and documents completed under the project. The project's website is linked to DOE Office of Electricity's interconnection –wide planning website as well as the interconnection partners' websites. Efforts continue to maintain this site so the data are available beyond the project's end. The site is located at: http://energy.sandia.gov/climate-earth-systems/water-security-program/water-energy-and-natural-resource-systems/energy-and-water-in-the-western-and-texas-interconnects/ .

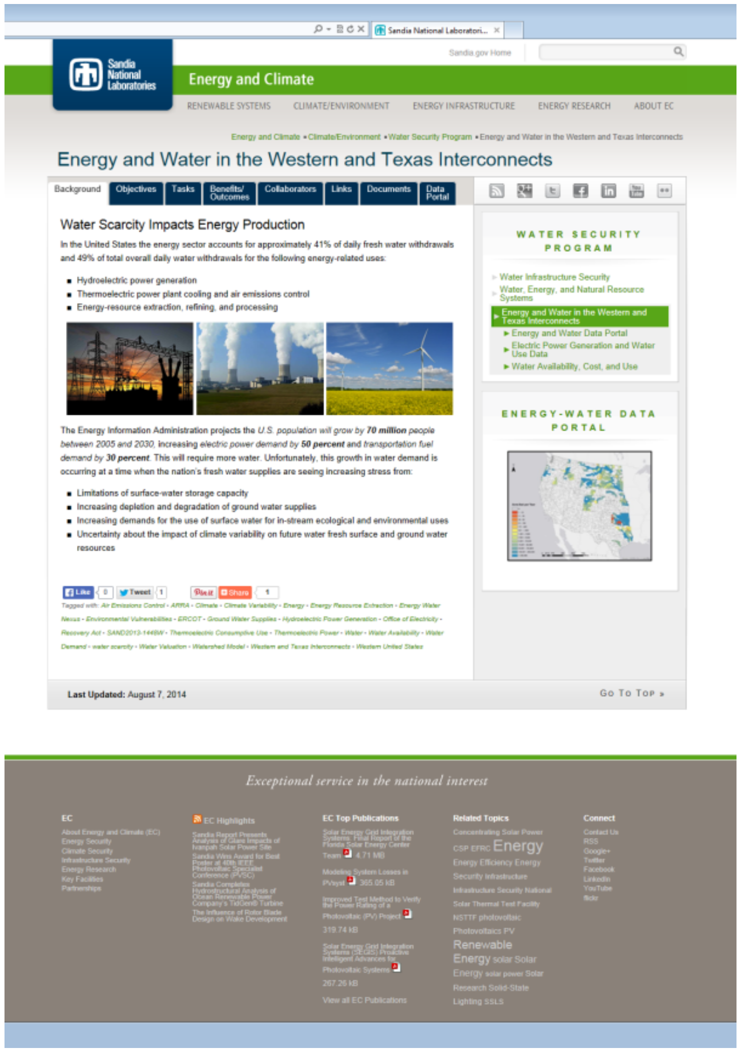

Figure 2. Project website splash page. The website provides information on the project, project contacts and access to produced documents. Importantly the site also provides direct access to project related data and an interactive mapping tool to interact with the data.

TASK 2: WATER WITHDRAWAL AND COMSUMPTION FOR CURRENT AND FUTURE THERMOELECTRIC POWER GENERATION

A model was developed to estimate water withdrawal and consumption at the power plant level across the Western and Texas Interconnections for the existing fleet as well as potential new capacity builds. Water use factors were developed based on unique power plant characteristics including capacity, production, type of plant, type of cooling, and type of emissions controls. In addition, regional climatic conditions, which can affect power plant efficiencies and water use, were also considered. Analyses considered both potential impacts of carbon capture and sequestration (CCS) and use of alternative power plant cooling strategies which can lead to parasitic energy losses. Average water use factors across this broad suite of power plant operations and cooling characteristics form the basis for projecting future thermoelectric water demands utilizing WECC and ERCOT generation expansion planning results that represent a range of potential energy scenarios.

2.1. Water Withdrawal, Consumption and Parasitic Energy Factors

Prior to the IEWP, there were a number of efforts to estimate and consolidate water withdrawal and water consumption factors based on boiler type and cooling technology for both renewable and conventional technologies (DOE 2008; DOE 2006; Fthenakis and Kim 2006). Some efforts based reported numbers on estimated national averages, others used data from specific utilities, and others used a combination of these two approaches. None of these efforts, however, provided data comprehensive enough to fully account for all the potential technologies to be deployed in the project area. Various studies had utilized these factors to estimate water withdrawals and consumption at a regional level across the United States assuming various future power generation scenarios (King et al. 2008). The modeling frameworks in these studies, however, were highly aggregated (10-13 NERC regions on a national scale), and were not directly applicable to specific transmission system planning processes and analyses. Transmission system planning activities require technology- and climate-specific water use factors, which before the IEWP had not been developed for the project area. Power plant-specific data are required to adequately assess regional water impacts, which are very localized by nature. To date, no comprehensive power-plant specific data are available for the project area.

The results of this analysis are captured in a number of technical reports and journal articles. Efforts characterizing water withdrawal and consumption rates of multiple power plant and cooling system configurations are summarized in a 2011 NREL technical report, "*A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies*" and a peer-reviewed journal article, "*Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature*," published in Environmental Research Letters in 2012 (see Appendix A to access paper).

This effort contributed to further refinement of water use factors to address the variation in power plant efficiencies associated with differences in microclimates (e.g., elevation, temperature, humidity). This analysis provides important insights regarding annual and seasonal water demands for various types of power plants (e.g., all else being equal, annual power plant water usage can be approximately 20% higher in hot, arid parts of WECC than in cooler parts).

Results are summarized in an NREL Technical Report entitled "Quantitative model to determine Water Withdrawal and Consumption Factors of Thermal Power Plants Utilizing Multiple Climate Variables" that is currently in review.

Cooling system types can also affect power plant efficiencies, which in turn can affect power plant water usage. Dry cooling and hybrid cooling systems can be used to mitigate water requirements, but can impose additional energy requirements (Clayton et al. 2010; Stillwell et al. 2010). The focus of this particular activity was to identify and evaluate these parasitic energy requirements and associated reduced efficiencies related to choice of cooling technology. This effort leveraged existing work on renewables being conducted by NREL, the National Energy Technology Laboratory (NETL) and other institutions to develop parasitic requirements for conventional technologies (NETL 2007). Results are summarized in an NREL Technical Report entitled "Cost and Performance Characteristics of Cooling System Options at Thermoelectric Power Plants" that is currently in review.

Task 2 Key Products: Water withdrawal and consumption were characterized for each power plant in the WECC and ERCOT service areas (Figure 3). Water use factors were also developed for a range of unit processes that allowed projection of future water demands related to electric generation expansion planning (Figure 4).

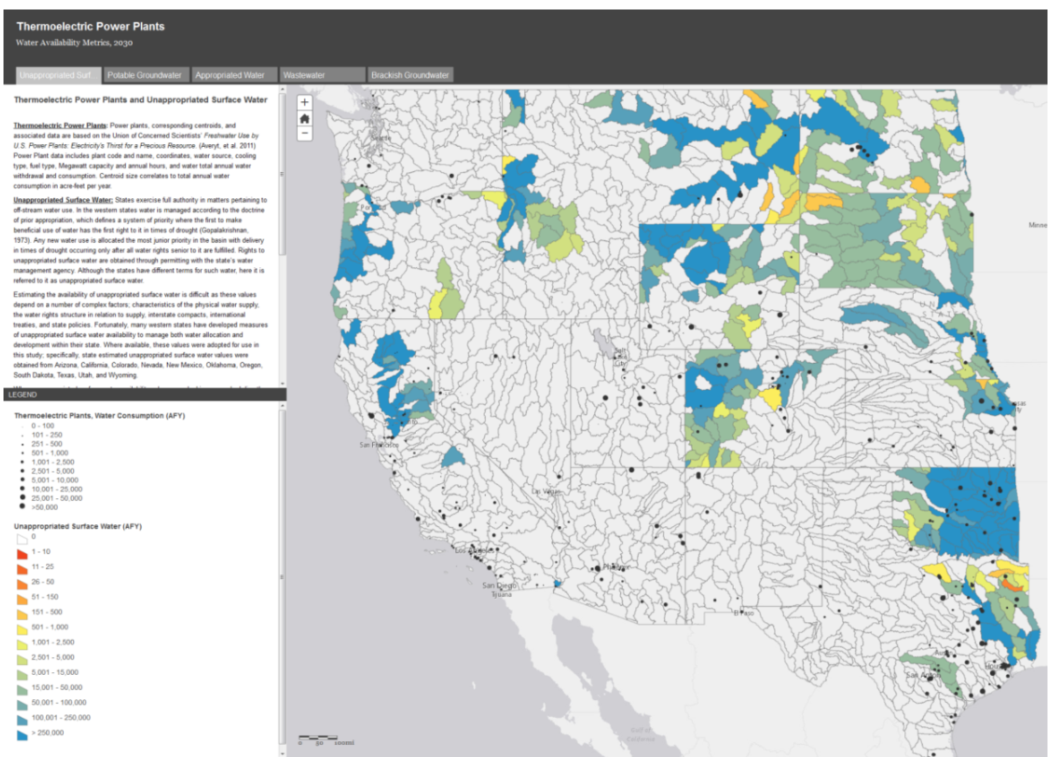

Figure 3. Map showing estimated water consumption for power plants in the project area. The map is reproduced from the project website. This data and other power plant water use information can be accessed on the project website.

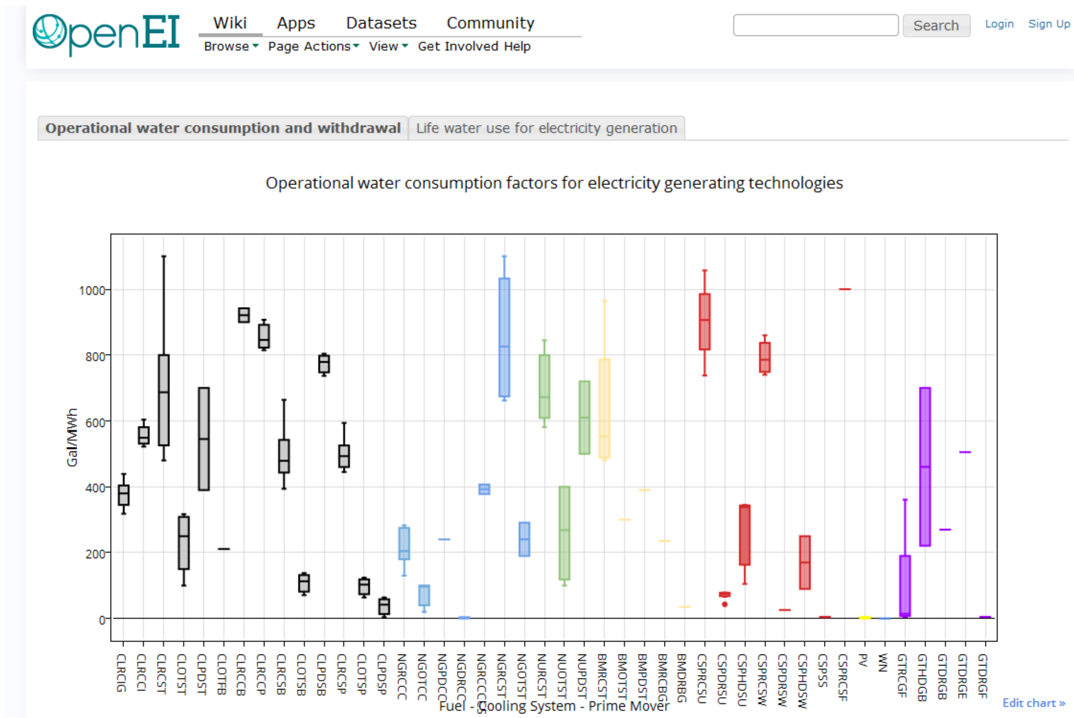

Figure 4. Ranges for water consumption factors for different electricity generating technologies. The graphic is reproduced from the project website. Additional data and related graphics are available on the project website.

TASK 3: NON-THERMOELECTRIC WATER DEMAND

Non-thermoelectric water demand projections were also estimated as these sectors compete with thermoelectric power generation for limited water resources in the West. These estimates were calculated at the interconnection, state, county and watershed levels. Through interactions with the WSWC, which is comprised of water managers from each western state, access was gained to each western state's water data and reports. This information was used to update and develop alternative growth scenarios of future water demand. Also considered was the potential growth in the withdrawal and consumption of water for energy resource extraction and processing throughout the Western United States. This included conventional oil, gas and coal extraction as well as other potentially important energy sources such as gas shales, tar sands and others.

3.1. Non-Energy Related Water Demand

Every five years since 1950, the nation's water-use data have been compiled and published by the U.S. Geological Survey (USGS)[4]; however, the level of detail at which these data are reported varies from year to year. Data are published according to type of use, domestic, public, industrial, mining, thermoelectric, irrigation and livestock, although the type categories have varied to some degree between surveys. The data are also distinguished by source at the national, state and county level. The most recent survey for 2010 (Maupin et al. 2014) only included water withdrawals, while the last survey to include water consumption was in 1995 (Solley et al. 1995). Although the state water management agencies work closely with the USGS, the water use data do differ on occasion largely due to differences in accounting procedures. Also, the USGS does not attempt to project water demand into the future, an interest of this work.

For these reasons, our analysis of current and future non-thermoelectric water use focused on state generated data. State water managers were engaged to characterize projected water use across the Western United States. Acquired data largely came from the states' individual water plans and other online sources. Consumptive water use was distinguished according to current versus projected future use; withdrawal versus consumptive use; and, the source water (e.g., surface water, groundwater, wastewater, saline/brackish water). Uses were also distinguished by sector; specifically, municipal/industrial, thermoelectric, and agricultural.

Water use projections varied by state in terms of spatial resolution, target dates, and scenarios of population growth. All projected future uses were mapped to an 8-digit HUC level. Projections were also uniformly adjusted to the year 2030. This was achieved through simple linear extrapolation between current use estimates and those projected at target dates beyond 2030. Where multiple growth scenarios (e.g., high, medium and low) were estimated in the individual state water plans, all data were collected; however, the "medium" growth projections were used as the basis of analysis.

The primary result of this analysis included a west-wide map of projected change in the consumptive use of water between 2010 and 2030. Surprisingly, large regions were noted to have zero or decreasing projected consumptive use corresponding to areas where the states estimate

[4] See http://water.usgs.gov/watuse/

some level of abandonment of water permits/rights associated with agricultural irrigation combined with slower rural population growth. While the states projected little growth in the number of acres of irrigated agriculture, increased water use in the municipal and industrial sectors was consistent across the West. As such, the largest increases projected for consumptive use were clustered around metropolitan areas.

A full accounting of the methods for projecting future non-thermoelectric water use can be found in the paper titled, "*Mapping water availability, projected use and cost in the Western United States,"* published in Environmental Research Letters in 2014 (see Appendix A to access paper). The map showing the estimated future water use is likewise available in the paper and at the project's website: [http://energy.sandia.gov/climate-earth-systems/water-security-program/water-energy-and-natural-resource-systems/energy-and-water-in-the-western-and-texas-interconnects/.](http://energy.sandia.gov/climate-earth-systems/water-security-program/water-energy-and-natural-resource-systems/energy-and-water-in-the-western-and-texas-interconnects/)

Task 3 Key Product: Projected non-thermoelectric withdrawal and consumption were estimated at a HUC-8 level for the Western United State for the period 2012-2032 (Figure 5). These data help understand where competition for limited water supplies are likely to be greatest, which in turn informs siting decisions for new thermoelectric generation.

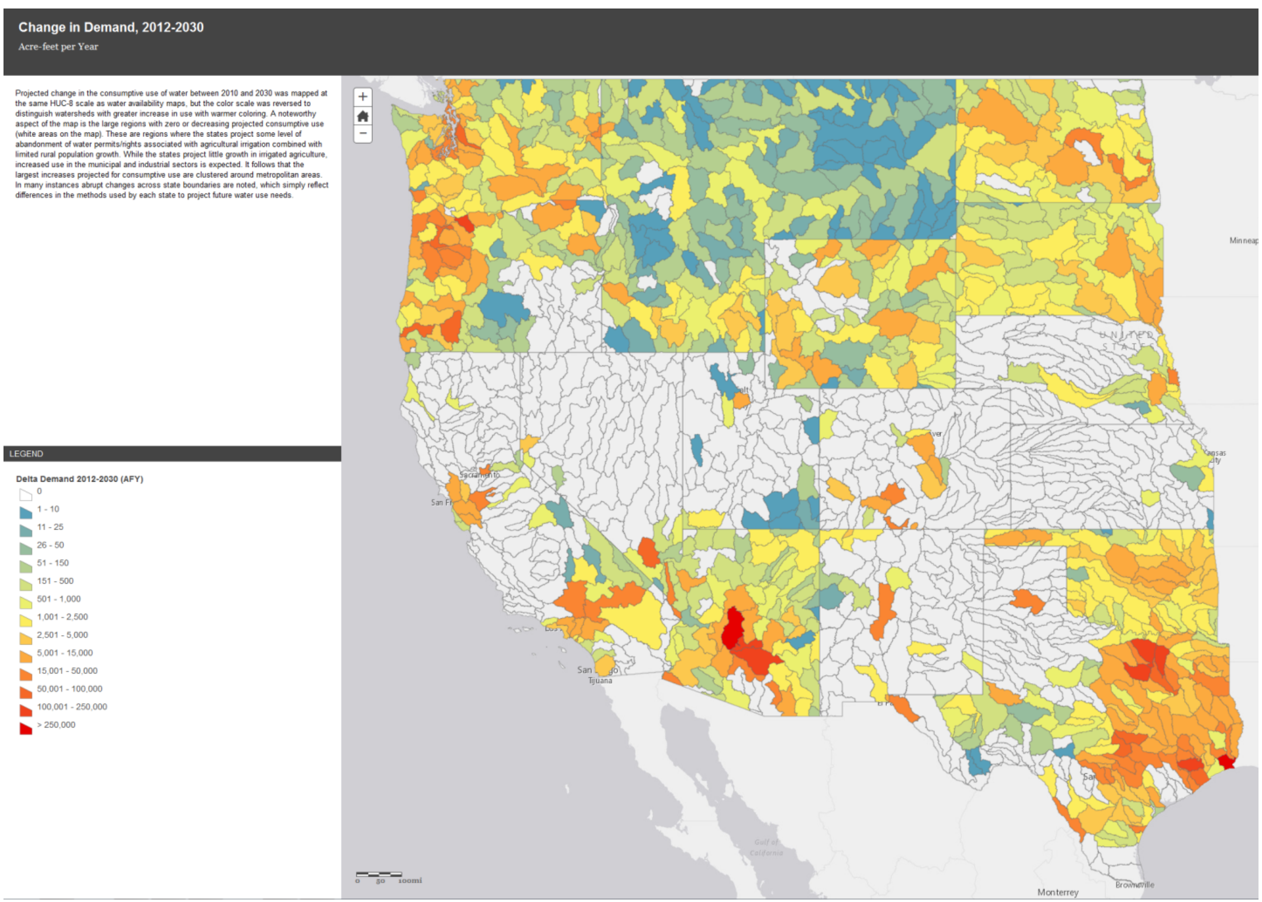

Figure 5. Map of projected non-thermoelectric water consumption for new development for the period 2012-2032. This map is reproduced from the project website. This and additional projected water use data is available at the project website.

3.2. Water Use for Energy Extraction

Like water withdrawal and consumption for other sectors, associated data for fossil fuel production is currently only estimated every five years and in a highly aggregated way (combined with all other mining activities) by the USGS. The IEWP sought to improve upon those data by estimating and mapping the water consumption for fossil fuel extraction (coal, oil, and natural gas) by county and by fuel type for the 17 western-most states in the United States. Water consumption was estimated by using current county-level fossil fuel production rates reported by state energy agencies, and literature estimates of water consumption for different fossil fuel production methods. Texas and Wyoming, respectively, were found to have the highest and second-highest total water consumption for fuel extraction processes. Although no individual counties were identified as having high water consumption for fuel extraction relative to other uses, areas such as West Texas, Western North Dakota, and parts of the Rocky Mountains were identified as having greater than average water consumption for fuel extraction. Typical water consumption in major fossil fuel producing counties was estimated to be in the range of 2,500-15,000 ac-ft./yr. In general, although fossil fuel extraction does not appear to be the major water consumer in most areas, it may still contribute to conflicts in areas that are already water stressed, especially in times of drought.

Additional detail concerning this analysis is available in a paper titled "*Estimating Annual Water Consumption for Fossil Fuel Production in the Western United States*" submitted to Environmental Science and Technology Letters (see Appendix A to access paper).

TASK 4: WATER AVAILABILITY

New demands for water can be satisfied through a variety of source options. Traditionally, new demands are first met with unappropriated surface or groundwater sources, as these waters are usually least expensive to develop. Unappropriated water refers to those resources whose allocation is managed by a system of water rights and which are in excess of current appropriations (Gopalakrishnan, 1973). Allocation of unappropriated water to a new use simply requires authorization from the state in the form of a water right. Where unappropriated sources are limited, the transfer (sale) of an existing water right might be considered as a means of satisfying new water demands. The transferred water may be made available for the new use through abandonment of the old use or through water savings achieved with improved efficiency. There is also the possibility of using a non-traditional source of water (e.g., municipal wastewater or brackish groundwater), which may require additional treatment.

With the help of western water managers, water availability was mapped for over 1,200 watersheds throughout the Western United States. Five water sources[5] were individually examined, including unappropriated surface water, unappropriated groundwater, appropriated water, municipal wastewater and brackish groundwater. This mapping followed a three step process including raw data collection, translation of the data to a consistent reference system, and metric formulation. Raw data were acquired from a variety of sources; where available, data were collected directly from the western states. In collecting the data, the project team engaged directly with state water data experts to identify and at times gain access to the data. Efforts were made to vet the collected water data with the state experts to verify the fidelity of data collected and any data conversion/translation made to render the data in a consistent and comparable format. The Western States Water Council was instrumental in coordinating the various interactions with state water managers, hosting workshops, assisting with project communications, and addressing state concerns as they emerged.

This analysis made use of multiple data sets from multiple sources reported at differing geographic resolutions (e.g., site, county, watershed, state). For purposes of this analysis, a consistent reference system was required. The 8-digit Hydrologic Unit Code (HUC) watershed classification (e.g., Seaber et al., 1987) was adopted, which resolved the 17 western states into1208 unique hydrologic units. The 8-digit HUC was selected as it provided a physically meaningful unit relative to water supply/use and provided the highest level of detail that can be justified with the data consistently available across all 17 western states. Where a watershed was divided by a state boundary individual water availability/cost metrics were developed for each state's portion of the watershed, reflecting differences in use/policy among the states. For raw data reported in point-format, translation to the 8-digit HUC was achieved by simple aggregation/averaging. For raw data reported in polygonal-format, translation followed a simple population or areal weighting. In the case of water use data, the 1995 USGS water use reported at the 8-digit level (Solley et al., 1995) provided the needed spatial weighting function.

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[5] The five sources selected for analysis represent the most likely alternatives for new thermoelectric development. Two other alternatives, not selected here, include sea water and produced water. Sea water was not treated as its availability is limited to coastal regions and in these areas its availability is not in question—it is also considerably more expensive than the other five sources. Produced water was not estimated here because of the lack of key data and the fact that its long-term availability is suspect.

There are no broadly accepted measures of water availability and cost that span the entire 17-state project area. Rather, metrics needed to be developed from the raw data collected from the states and federal agencies. The challenge was to formulate water availability and cost metrics that appropriately balance the underlying complexity of the system (e.g., physical hydrology, climate, use characteristics, technology and water management institutions) with the data that was consistently available across the entire Western United States. To assist in striking such a balance, water availability/cost metrics were formulated with the help of subject experts. Specifically, representatives from the WGA, WSWC, USGS, and individual state water management agencies assisted in defining appropriate and informative water metrics (in total the team included 11 participants plus the author team). These metrics were developed and vetted over a two month period during 6 webinars.

A unique aspect of the developed metrics is their consideration of institutional controls on access and use of the five physical water sources. Specifically, efforts were made to consider such factors as water rights, administrative control areas, interstate compacts, treaties, and state/federal policies. Where tribal water rights have been established, they are reflected in the water availability estimates, otherwise the estimates reflect the state's current administration of water appropriations.

A full accounting of the analysis of water availability in the Western United States can be found in the paper titled, "*Mapping water availability, projected use and cost in the Western United States"*, published in Environmental Research Letters in 2014 (see Appendix A to access paper). Maps showing the estimated water availabilities for the five sources of water are likewise available in the paper and at the project's website: http://energy.sandia.gov/climate-earth-systems/water-security-program/water-energy-and-natural-resource-systems/energy-and-water-in-the-western-and-texas-interconnects/ .

4.1. Unappropriated Surface Water

Unappropriated water refers to those resources whose allocation is managed by a system of water rights and which are in excess of current appropriations. Estimating the availability of unappropriated surface water is difficult as it depend on a number of complex factors: characteristics of the physical water supply, the water rights structure in relation to supply, interstate compacts, international treaties, and state policies. Fortunately, many western states have developed estimates of unappropriated surface water availability to manage both water allocation and development within their state. Where available, these values were adopted for use in the IEWP; specifically, state estimated unappropriated surface water availabilities were obtained from Arizona, California, Colorado, Nevada, New Mexico, Oklahoma, Oregon, South Dakota, Texas, Utah, and Wyoming. Where unappropriated surface water availabilities were lacking the project team worked directly with state water managers to develop rough estimates.

As expected the availability of unappropriated surface water is very limited. No unappropriated surface water is available in Arizona, New Mexico, Nevada, Utah or Washington. Some availability was registered for California, Colorado, Idaho, Kansas, Montana, Nebraska, Oregon, Texas and Wyoming; however, the scope in each is geographically limited. In contrast, the majority of watersheds in the Dakotas and Oklahoma register some unappropriated surface water availability.

4.2. Unappropriated Groundwater

States exercise full authority over the allocation of groundwater resources. Determining the availability of groundwater for future development is as complex as surface water. However, only a few states have published data on the availability of unappropriated groundwater; specifically, Arizona, Oklahoma, Nevada, and South Dakota. Where available, this data was incorporated into the project. For all other states a simple water balance approach was adopted. Unappropriated groundwater was set equal to the difference between annual average recharge and annual groundwater pumping. Recharge rates were taken from the USGS (2003), which are derived from stream baseflow statistics, while pumping rates were taken from state data where available or from USGS (Kenny et al. 2009) otherwise.

The availability of unappropriated groundwater is likewise very limited. Unlike surface water, all states (except Washington) record some availability of unappropriated groundwater. The geographic footprint of available unappropriated surface water and groundwater are largely different except in the cases of Oklahoma and Western Colorado. The effect of state level institutional controls on groundwater availability is also evident, particularly for Nevada, Oklahoma and South Dakota (e.g., some availability of groundwater is available in every watershed owing to the states' allowances for some degree of aquifer depletion).

4.3. Appropriated Water

This source was defined by the quantity of water (both surface and groundwater) that could be made available by abandonment and transfer of the water right from its prior use to a new use. The appropriated water availability metric was constructed based on the irrigated acreage in a given watershed that is devoted to low-value agricultural production; specifically, irrigated hay and alfalfa. Data (irrigated acreage and water volume applied) were taken from the USDA's Agricultural Census (USDA, 2007). Appropriated water availability was further limited to 5% of the total irrigated acreage in the watershed based on projections from western states water managers. For watersheds experiencing significant groundwater depletions (see unappropriated groundwater metric above) the available appropriated water was reduced by 50%. This is to account for a portion of future water rights abandonment that is likely to be used to offset the groundwater depletion (Brown 1999).

Availability of appropriated water, both surface and groundwater, is consistently distributed throughout the West. Quantities likely to be transferred are relatively small, generally less than 2,500 Acre-foot/yr. The greatest availability corresponds to regions with heavy irrigated agriculture, including Eastern Oklahoma, Southern Arizona, Central California, Eastern Colorado, Texas Panhandle, Central Washington, and the Snake River Basin in Idaho. South Dakota registers no appropriated water availability due to policies that limit transfers out of the irrigated agriculture beneficial use category.

4.4. Municipal Wastewater

Municipal wastewater is rapidly being considered as an alternative source of water, particularly in arid regions, for growing cities, energy development and even irrigated agriculture. Municipal wastewater discharge data is consistently available throughout the United States from a pair of EPA published databases (Permit Compliance System [EPA, 2011], and Clean Watershed Needs Survey [EPA, 2008]) that provide information on the location, discharge, and level of treatment for most wastewater treatment plants in the United States. Not all wastewater discharge is available for future use, as a considerable fraction is currently re-used by industry, agriculture, and thermoelectric generation. Re-use estimates were determined both from the USGS (Kenny et al., 2009) data as well as the EPA databases. Where applicable, the availability of municipal wastewater also considered return flow credits that offset the availability of this source of water.

Availability of municipal wastewater is sporadically distributed across the West. Availability is most uniform in the far eastern portion of the project area where the density of communities is the greatest. The availability of municipal wastewater is highly correlated to metropolitan areas.

4.5. Shallow Brackish Groundwater

For purposes of this analysis, brackish groundwater was defined by salinities between 1,000 and 10,000 ppm total dissolved solids (TDS), restricted to resources no deeper than 2,500 feet, but deeper than 100 feet to account for some locations where groundwater contributes to surface water flows. Only three states have published brackish groundwater studies: Texas (LBG-Guyton Associates, 2003), New Mexico (Huff, 2004), and Arizona (McGavock, 2009). In the absence of a report, the use of brackish groundwater (Kenny et al., 2009) was used as a guide to resource availability.

Finally, if a watershed had no brackish water volume estimate or brackish water use inventoried by USGS, then the presence of brackish groundwater at monitoring wells was used to establish some potential availability (USGS, 2011).

Brackish groundwater is available throughout much of the West except in the Northwest. The availability of brackish groundwater resources are highest in Arizona, New Mexico and Texas, where detailed brackish groundwater studies have been conducted. Thus, mapped availability is more an indication of what is known and currently used rather than an indication of the actual resource in the ground.

Task 4 Key Product: Water availability was estimated at an HUC-8 level across the Western United States (over 1200 watersheds). Considered were five different sources of water: unappropriated surface water, unappropriated groundwater, appropriated water, municipal wastewater and brackish groundwater (Figure 6). These data were subsequently used to inform future siting of new thermoelectric generation.

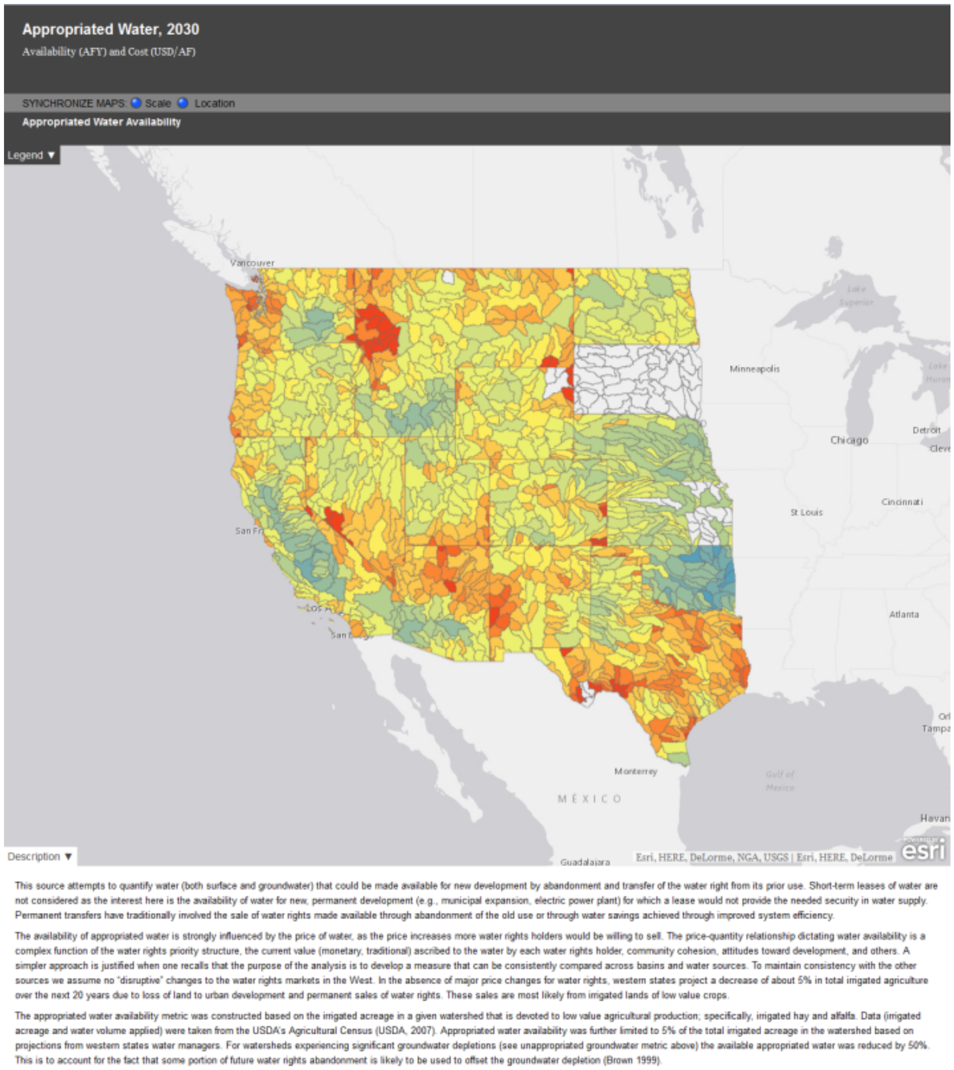


Figure 6. Map of appropriated water availability in the Western United States. This map is reproduced from the project website. This data as well as data/maps for the other four sources of water are available at the project website.

TASK 5: WATER COST

Each of the five sources of water, unappropriated surface water, unappropriated groundwater, appropriated water, municipal wastewater and brackish groundwater, carry a very different cost associated with utilization. The interest was to establish a consistent and comparable measure of the cost to deliver water of potable quality to the point of use. As with water availability, costs were resolved at the 8-digit HUC level. Considered were both capital and operating and maintenance (O&M) costs. Capital costs capture the purchase of water rights as well as the construction of groundwater wells, conveyance pipelines, and water treatment facilities, as necessary. All capital costs were amortized over a 30-yr horizon and assumed a discount rate of 6%. O&M costs included expendables (e.g., chemicals, membranes), labor, waste disposal as well as the energy to lift, move and treat the water.

A full accounting of the methods used to estimate water costs in the Western United States can be found in the paper titled, "*Mapping water availability, projected use and cost in the Western United States*", published in Environmental Research Letters in 2014 (see Appendix A to access paper). Maps showing the estimated costs for the five sources of water are likewise available in the paper and at the project's website: http://energy.sandia.gov/climate-earth-systems/water-security-program/water-energy-and-natural-resource-systems/energy-and-water-in-the-western-and-texas-interconnects/.

5.1. Unappropriated Surface Water Cost

No costs are assigned to unappropriated surface water. It is recognized that there are associated costs, in particular for permitting; however, because of the difficulty and uncertainty in estimating the most important determinant, time and the fact that these and similar costs were consistent with all sources of water, no efforts were made to estimate these cost.

5.2. Unappropriated Groundwater Cost

Assumed capital costs are largely associated with the construction of groundwater wells. Drilling and construction costs were estimated following the approach outlined in Watson and others (2003). The depth to groundwater was taken from USGS well log data (USGS, 2011) averaged at the 8-digit HUC level. Variability in cost for unappropriated groundwater was found to largely correspond to the average depth of groundwater. The average costs for unappropriated groundwater was estimated to be $111/Acre-foot (entire project area).

5.3. Appropriated Water Cost

Costs associated with this source of water result from the purchase and permanent transfer of a water right from a prior use to some new use. Water rights transfer costs utilized by this analysis were based on historic data collected by the *Water Strategist* and its predecessor the *Water Intelligence Monthly* (Water Strategist, 2012). Costs were estimated by state because of the limited availability of data. Only transactions involving permanent transfers from agriculture to urban/industrial use were considered. Recorded transfers were averaged by year and by state and the average of the last five years was used for purposes of the IEWP. Unfortunately the *Water*

Strategist did not track water transfer data for North and South Dakota, Nebraska, Kansas and Oklahoma. Costs for these states were simply calculated as the average of the surrounding states.

Ultimately, appropriated water transfers were seen to be more costly to the south where water supplies are most limited. Average costs for appropriated water was estimated to be $123/Acre-foot (entire project area).

5.4. Municipal Wastewater Cost

Estimated costs considered expenses to lease wastewater from a municipality, convey the water to the new point of use, and to treat the wastewater. Fees charged to lease treated wastewater from the municipality were estimated based on the initial work of the Electric Power Research Institute (EPRI, 2008). Also considered was the cost to transport the treated wastewater from the treatment plant to the point of use, including both capital construction costs for a pipeline and O&M costs principally related to the electricity for pumping. Associated cost calculations were consistent with Watson and others (2003). It was assumed that all wastewater must be treated to advanced standards before it can be re-used. Plants operating at primary or secondary treatment levels (EPA, 2008; 2011) were assumed to be upgraded to advanced standards. Capital construction costs were based on the analysis of Woods et al. (2012), which scale according to treatment plant throughput and original level of treatment.

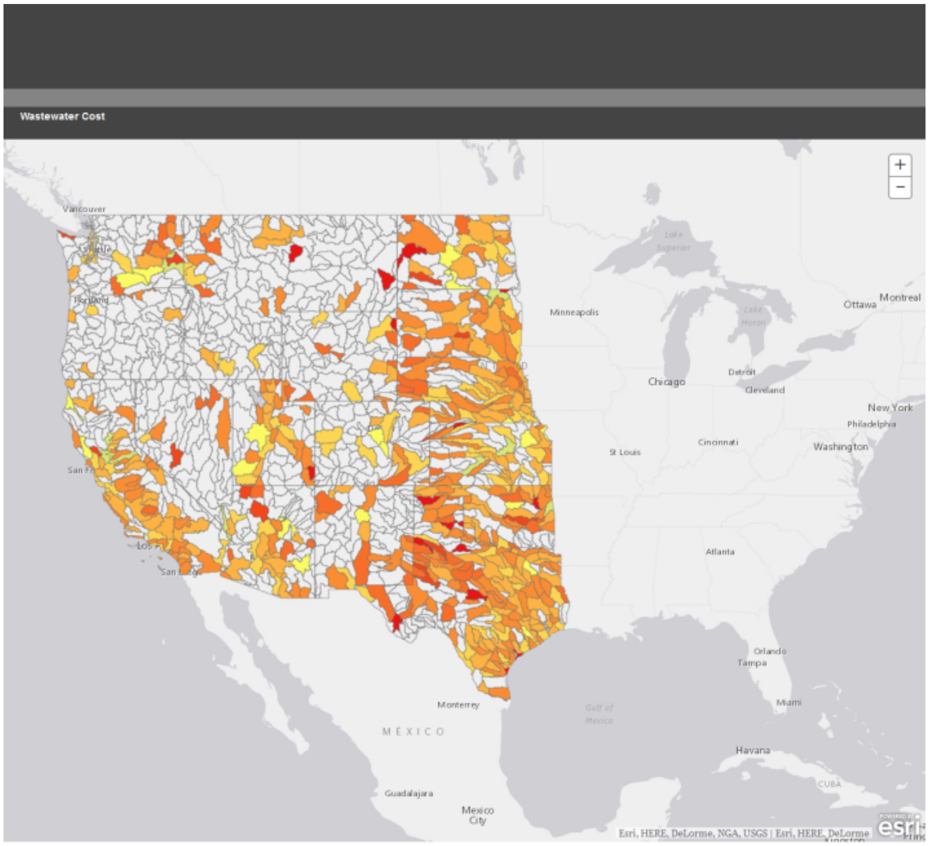
Municipal wastewater costs tended to increase as the size of the wastewater treatment plant decreased and the level of treatment increased. The average cost for municipal wastewater was more expensive than freshwater sources, estimated to be $505/Acre-foot.

5.5. Shallow Brackish Groundwater Cost

Estimated costs considered both capital and O&M costs to capture and treat brackish groundwater. Cost calculations followed standards outlined in the Desalting Handbook for Planners (Watson et al., 2003). Capital costs included expenses to drill and complete the necessary groundwater wells and construct a treatment plant utilizing reverse osmosis. The number of wells needed and treatment plant capital costs were based on the treated volume of water. Other key design parameters included the depth of the brackish water and TDS. These data, averaged at the 8-digit HUC level, were estimated from the USGS brackish groundwater well logs (USGS, 2011).

Brackish groundwater costs were found to increase as depth and TDS increase. The average cost for brackish groundwater was the most expensive, estimated to be $715/Acre-foot.

Task 5 Key Product: Water cost was estimated at an HUC-8 level across the Western United States (over 1200 watersheds). Sources of water considered include: unappropriated groundwater, appropriated water, municipal wastewater and brackish groundwater (Figure 7). Costs were estimated relative to cost of unappropriated water so not estimated here. These data were subsequently used to inform future siting of new thermoelectric generation.



Estimated costs considered expenses to lease the wastewater from the municipality, convey the water to the new point of use, and to treat the wastewater. Fees charged to lease treated wastewater from the municipality were estimated based on the initial work of the Electric Power Research Institute (EPRI, 2008). Values reported in the EPRI report were verified and updated as necessary based on a review of fees published on-line. As no geospatial or plant related trends were noted in the pricing an average of the reported fees was adopted for this study, which was calculated at $395/Acre-foot.

Also considered was the cost to transport the treated wastewater from the treatment plant to the point of use. Considered were both capital construction costs for a pipeline and O&M costs principally related to the electricity for pumping. Associated costs calculations were consistent with Watson and others (2003). Water conveyance costs were dictated by the distance between the treatment plant and point of use. As the distance values are currently unknown (associated with a new point of use) estimates were made as a function of land use density, defined as the ratio of developed land area to total land area in the buffer zone. Land use densities were calculated using a circular buffer area with a radius of 5 mi. around all existing treatment plants. Where more open land is available around a treatment plant (low land use density) a new water user can locate in close proximity to minimize conveyance distance. Thus, conveyance distances were estimated according to a simple rank order of land density around each treatment plant with low values given a conveyance distance of 1 mi. and to the highest land use density given a distance of 5 mi.

It was assumed that all wastewater must be treated to advanced standards before it can be re-used. This conservative assumption was adopted considering both realized improvements in downstream operations (e.g., increased cycles of use, reduced scaling, improved feed quality) and the current trend of regulation toward requiring advanced treatment (EPRI, 2008). Plants operating at primary or secondary treatment levels (EPA, 2008, 2011) were assumed to be upgraded to advanced standards. Capital construction costs were based on the analysis of Woods et al. (2012), which scale according to treatment plant throughput and original level of treatment. Associated O&M costs considered expenses for electricity, chemicals and labor.

Figure 7. Map of the cost to utilize municipal wastewater in the Western United States. This map is reproduced from the project website. This data as well as data/maps for the other sources of water are available at the project website.

TASK 6: ENVIRONMENTAL RISK

Future demand for water may come into conflict with the protection of a variety of ecological resources, especially aquatic and riparian species (and their habitats) that are protected under the Endangered Species Act (ESA). In this task, a set of tools, collectively termed the Environmental Risk Calculator (ERC), were developed for the identification of watersheds where future energy development may encounter additional regulatory constraints and/or mitigation requirements due to the presence of federally protected aquatic and riparian biota and habitats. The ERC tool, which is GIS-based, can be found at: http://energy.sandia.gov/climate-earth-systems/water-security-program/water-energy-and-natural-resource-systems/energy-and-water-in-the-western-and-texas-interconnects/.

To identify watersheds where conflicts with listed ecological resources could occur, the tool considers the spatial distribution of individual species and habitats, the sensitivity of each species or habitat to water depletions during a proposed time-period, and the projected drought potential of hydrologic basins. A database was developed with information pertaining to aquatic and riparian species listed as endangered, threatened, or candidates for listing under the ESA, as well as aquatic and riparian habitats designated 'critical habitat' under the ESA, in the Western United States. This database included geospatial information on the location of these species and habitats at the county, HUC-8 and HUC-12 watershed levels, together with species-specific life history information. Next, a model was developed that characterizes the sensitivity of each species to future water withdrawals (regardless of the need for the withdrawal). Based on the species and habitats present in a watershed, as well as their sensitivities to water withdrawals, the model then calculates, for each HUC-8 watershed, an overall risk level of possible ESA-driven project development requirements (including mitigation) for future energy development in that watershed. These overall risk levels can be viewed graphically, and provide energy planners with early indications of the relative level of potential ESA considerations for any HUC-8 watershed of interest in the West.

6.1. Distribution of ESA-Listed Aquatic and Riparian Species

Working with the U.S. Fish and Wildlife Service (USFWS) and NatureServe, species-specific occurrence data were obtained for and mapped at the HUC-8 level for the Western United States. A total of 310 listed aquatic and riparian species were identified for the Western United States The occurrence of these species in the 1,204 HUC-8 watersheds in the West is shown in Figure 8a. Note that the greatest number of ESA-listed aquatic and riparian species occur in the desert Southwest and the coastal states.

6.2. Watersheds with Potential ESA-WATER Withdrawal Concerns

Species-specific life history information, such as preferred or required water depth, stream flow, water temperature, dissolved oxygen, and turbidity, as well as information on important habitat areas such as spawning areas, nursery habitats, feeding habitats, and migration routes were next used to provide input to a series of algorithms that calculate a relative 'risk' level for each species related to the vulnerability of the species and its habitats to water withdrawals. For all

ESA-listed species occurring in a specific HUC-8 watershed, the individual species-specific risk levels were combined to provide an overall risk level for that watershed. The risk level calculation for each HUC-8 also considered the potential sensitivity of ESA-listed species in adjacent downstream watersheds, since use of water for energy development could also affect downstream watersheds. Figure 8b shows the relative risk of HUC-8 watersheds in the Western United States, based on the number and nature of ESA-listed species present in each HUC, to water withdrawals. Note that while the HUC-8's with the greatest numbers of ESA-listed species occur in California (Figure 8a), HUC-8 watersheds with the highest relative risk ranking related to surface water withdrawals occur not only in California, but throughout the Pacific Coast states as well as other southwestern states.

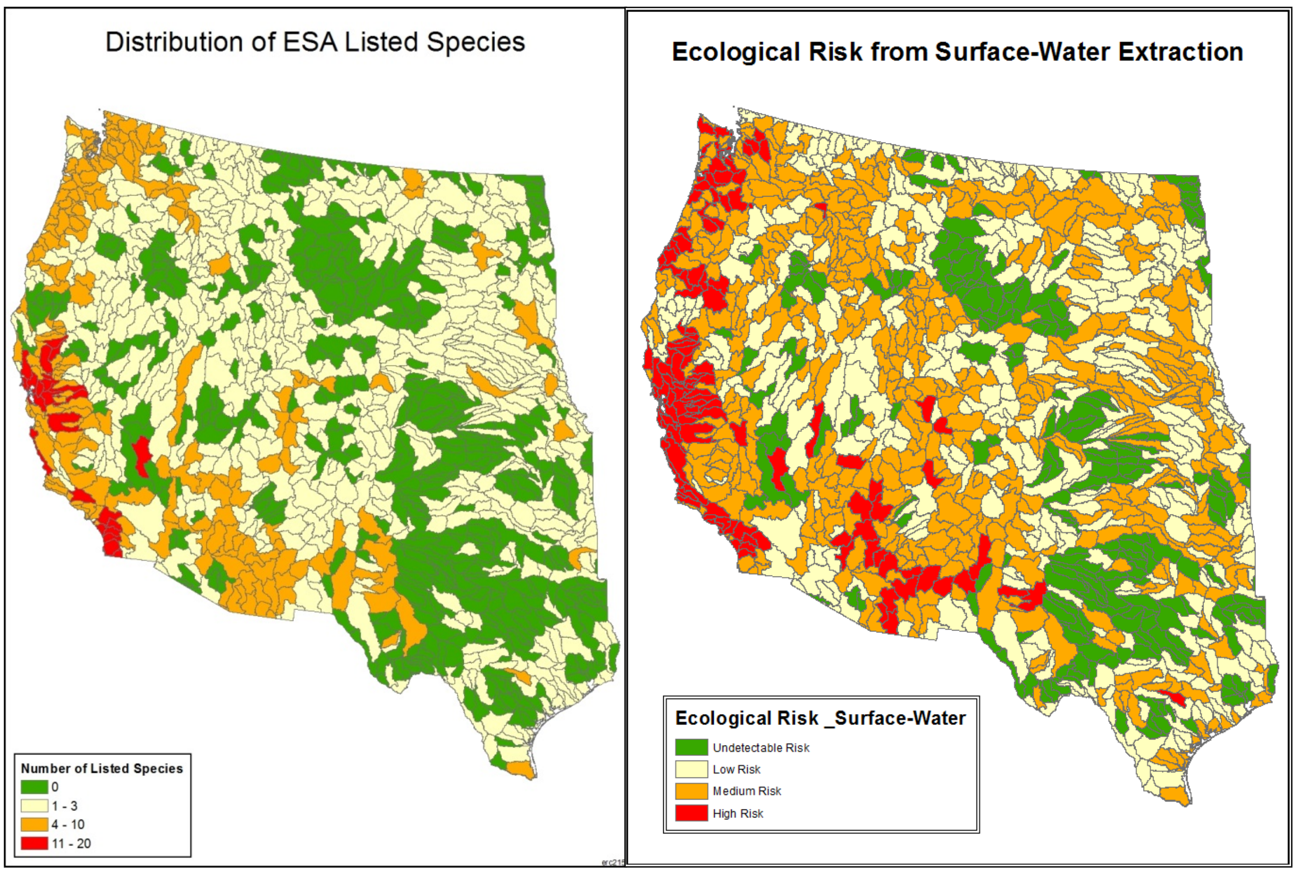


Figure 8. a) Number of aquatic and riparian species (listed as threatened and endangered species under the Endangered Species Act) in HUC-8 watersheds in the Western United States. b) Relative risk of HUC-9 watersheds, on the basis of the number and nature of ESA-listed species and habitats, to water withdrawals.

6.3. Effects of Water Stress on ESA-based Watershed Relative Risks

The HUC-8 level relative risks depicted in Figure 8b reflect risk-level estimates based solely on the known life history requirements of the ESA-listed species of each watershed. The HUC-8 risk-levels were further characterized by also taking into account the current level of water stress of each watershed, with water stress being defined as the volume of water being used (withdrawn for consumptive and non-consumptive use) divided by the availability of water in the watershed. The greater the water use (current or future) within a basin, the less water is potentially available to maintain aquatic and riparian listed species in the watershed. The ERC calculates an overall environmental risk score for each HUC-8 watershed as a function of the known or predicted water use in each HUC-8 basin (see Section 4) and the relative risk of the HUC-8 watersheds to water withdrawals. Combining current (2012) water use estimates (Figure 9a) with the relative HUC-8 risk levels, the ERC tool calculates an overall environmental risk score for each HUC-8 watershed, as shown in Figure 9b. In this figure, watersheds shown in red (high risk) are those where, because of the number and nature of ESA-listed species present, the sensitivity of those species to water withdrawals, and the current level of water use, future energy developments may require more extensive consultation and mitigation requirements. In contrast, watersheds shown in pale yellow are watersheds where consultation and mitigation requirements may be less due to fewer listed species, less sensitive species, and/or greater water availability.

Using predicted water usage estimates (see Section 4), the ERC tool can be used to identify which HUC-8 watersheds could have greater ESA-related regulatory requirements or restrictions for future energy developments requiring surface water or groundwater withdrawals. It is important to note that the ERC toll does not identify specific impacts or effects of future energy developments, nor does it identify watersheds where water withdrawals for energy production would be prohibited. Rather, it identifies watersheds where energy planners may be subject to more extensive regulatory interactions and requirements regarding future energy development. In addition, environmental risk estimates provided by the ERC are based on occurrence information of currently listed aquatic and riparian species and habitats. It does not consider terrestrial or upland ESA-listed species and biota, the presence of which may add additional regulatory requirements.

Task 6 Key Products: Water basins (at the HUC-8 level) were mapped across the Western United States with regard to their potential for conflicts between aquatic and riparian species and habitats listed under the Endangered Species Act and water availability for future energy development (Figure 9b). These data help identify watersheds where the siting of new thermoelectric generation may be problematic due to environmental sensitivities.

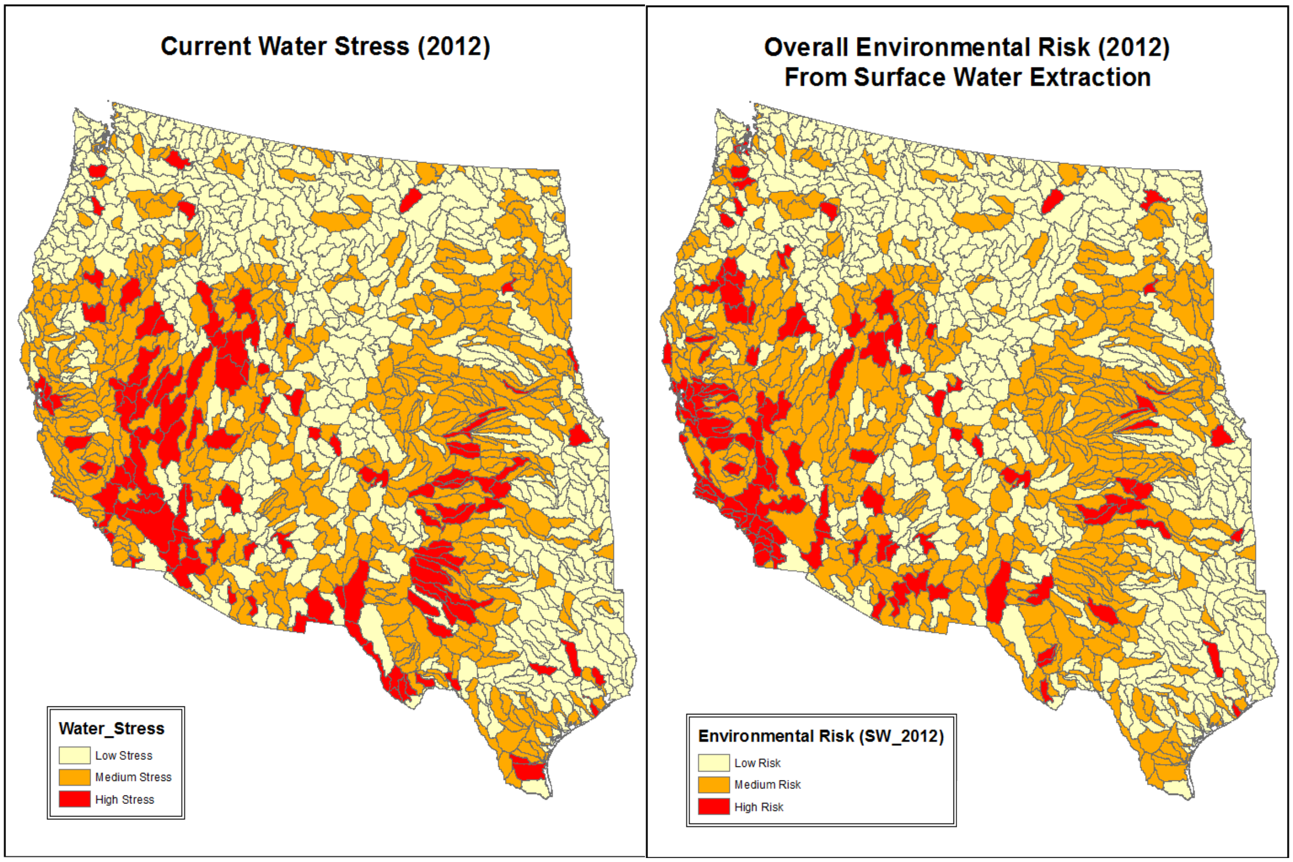


Figure 9. a) Estimated 2012 water stress for HUC-8 basin in the Western United States. b) Overall 2012 relative HUC-8 environmental risk level.

TASK 7: CLIMATE VARIABILITY ANALYSIS

The purpose of this task was to examine the potential impacts of climate variability on electricity generation in the Western and Texas Interconnections. Specifically, the task assessed the vulnerability of United States thermoelectric and hydroelectric power plants in three water resource regions (or major river basins), Pacific Northwest, Texas-Gulf, and California, due to future adverse climate conditions. These three regions were selected based on results of our first-year drought impact study, which showed that these basins (1) have the highest potential losses of electricity generation under drought scenarios and (2) own 72% of generation capacity among all power plants in eight regions using surface water that was more sensitive to intensifying climate variability (Harto et al. 2011).

7.1. Extreme West-Wide Drought Impacts on Electricity Generation

The first exercise in this effort was to conduct a screening analysis that applied a consensus-based designed drought to the project area, to evaluate the impact of a severe design drought to electric generation availability. The analysis leveraged existing regional drought analyses (Mearns et al. 2009). Depending on the outcome of this screening analysis, the need for additional, higher fidelity studies was determined.

The conducted work included contacting the ten utilities with the largest amount of hydroelectric capacity in WECC and ERCOT and obtaining their most recently published drought contingency plans. Also, obtained were the most recent drought contingency plans from Bureau of Reclamation, Bonneville Power Authority, Corps of Engineers, and British Columbia Hydro. A survey and synthesis of ongoing federal, regional, state, or local drought analyses, as well as national labs and academic activities, was performed. Consensus was then obtained on drought study design parameters: 1) geographic footprint, 2) duration, 3) yearly severity, 4) any deviation from average temperatures during drought, and 5) any anticipated drought-induced load changes during duration of the drought. The impacts of the design drought on electric generation were then assessed according to impacts on hydro generation profiles and de-rating of existing thermal generation facilities.

Results showed that even with conservative risk estimates, the majority of basins evaluated showed a limited amount of risk under most scenarios. The level of risk in these basins was likely to be amenable to mitigation by known strategies, combined with existing reserve generation and transmission capacity. At least in some of the more arid basins, such as the Lower Colorado and Rio Grande, this is the result of proactive planning that has minimized the number of generators that depend upon fresh surface water sources. The risks to the Pacific Northwest and Texas Basins, however, do appear to be significant and require more detailed study. The Pacific Northwest is vulnerable because of its heavy reliance on hydroelectric generation. Texas, conversely, is vulnerable because of its heavy dependence on thermoelectric generation, which relies on surface water for cooling, along with the fact that this basin seems to experience more severe drought events on average. Further increasing the risk to Texas is the fact that its electric grid is largely independent of the rest of the country, so it has limited capacity for importing power in times of shortage.

From the perspective of individual power producers or generating units, the most important strategy to minimize risk appears to be to have proactive monitoring, modeling, and planning processes in place in order to anticipate risks well in advance, in order to provide adequate time to implement mitigation strategies. Many operators in arid states have developed sophisticated internal systems to manage water and water related risks. However, it is unclear if operators in other states where drought is not as common have done so. It is possible that generators in states that experience drought infrequently may in fact be more vulnerable than those that deal with drought on a regular basis.

A much more detailed accounting of this work is available in the Argonne Report ANL/EVS/R-11/14, titled "*Analysis of Drought Impacts on Electricity Production in the Western and Texas Interconnections of the United States*" (see Appendix A to access paper).

7.2. Assessment of Climate Impacts on ERCOT Thermal Generation

A study was conducted to determine the medium-term (through the year 2030) impacts of future climate and drought scenarios on electricity generation in the ERCOT service area. Because water in reservoirs is used to cool many of the steam cycle-based power plants, significantly low water levels can reduce their ability to cool power plants processes. This reduced cooling ability can come from physical supply limitations or environmental constraints (power plant effluent temperatures exceeding permitted limits).

The objective of this study was to inform ERCOT as to the potential water-related risks for power plant operations. The approach used a method that projected future climate and water demands to determine stream flows, water storage in reservoirs, and power plant effluent temperatures. The results of the water availability, demands, storage, and stream flows were reported based upon the USGS 8-digit HUC water basins. The water and climate data were compared to power plant characteristics and past performance data to infer the likelihood that future summer power generation could be curtailed at a power plant. Beyond impacts on the existing fleet of power plants, this study also considered siting of future power plants so as to avoid regions of limited water availability.

The main findings from the study relate to four categories as follows:

Water Availability

- Water was projected to be available for ERCOT thermoelectric power plant operations out to 2030. However, water for new development would likely need to come from sources other than unappropriated surface water. This conclusion largely means that future water supplies for thermoelectric power will be more expensive than historical supplies.
- There was generally very little unappropriated surface water available for any uses, including thermoelectric power.
- Water availability from appropriated surface water supplies, assumed as 'low value' agriculture, was limited. This appropriated water was present in quantities > 5,000 ac-ft./yr. in only a few study basins.

- Several study basins have wastewater, potable groundwater, and brackish groundwater availability at greater than 10,000 ac-ft./yr. (enough for a large power plant).
- A number of basins (14) with severely limited water supplies are currently being considered by ERCOT for siting of new electric power production facilities.

Water Supply Costs

- The cheapest water supply (at $18/ac-ft.) that has enough water (~ > 5,000 ac-ft./yr.) to supply wet cooling at a medium to large-sized thermal power plant was through transfers from low-value agriculture.
- Estimated costs for brackish water availability per basin varied widely from $10/ac-ft. to > $1,000/ac-ft., with most in the range of 500-900 $/ac-ft. (or ~ 1.7-2.7 $/1000 gallons). This price for water was close to, but below some estimates for the cost of water needed to incentivize the use of dry cooling systems at > $3/1000 gallons.

Potential Derating of Thermoelectric Cooling During Drought due to Lack of Water Supply[6]

The project team constructed a model of the Texas Gulf-Coast water basin using the Soil and Water Assessment Tool (SWAT). This hydrologic model used input meteorological data (e.g., temperature, precipitation) together with water demands (e.g., municipal, agriculture, power plant operation) to estimate evapotranspiration, streamflow, and water storage in soil and reservoirs. The team used the reservoir storage information and two matrices based on water use vs. water availability to assess the risk that power plants would not be able to withdraw water into their cooling systems.

- The projected drought scenario in 2022 and the historical droughts during 2011 and 1954-1956 represent two different precipitation patterns in the Texas-Gulf basin. The simulated 2022 drought is characterized by low precipitation (<25 inches) in the eastern basin and moderate precipitation (25-30 inches) in the western basin while the historical droughts show extremely low precipitation (<20 inches) in the western basin and high precipitation (>30 inches) limited in the southeastern basin.
- Hydrologic modeling results indicate significant impact on water availability (water yield, streamflow, and reservoir storage) in single-year drought (2011 and 2022) and multiple-year drought (1950-1957) scenarios.
- The model predictions for average and minimum monthly reservoirs storages during the 2011 drought year were statistically validated with a coefficient of determination R^2 = 0.81 and 0.72, respectively, for 22 reservoirs out of 37 reservoirs that provide water supply to 47 power plants.
- Using a criteria based on observed (< 50% storage) and predicted (< 55% storage) reservoir data, we identified fifteen low-storage reservoirs in 2011, ten in 2022 and 20 in 1956 (the last year for the multiple-year drought scenario). Among them, four reservoirs (Addicks Reservoir, Texarkana Lake, Martin Lake, and Smithers Lake) are under low storage condition in all three drought scenarios. The affected reservoirs predicted by the model are mainly located in areas near Austin, Houston, San Antonio, and south of Lubbock.

[6] Note that this analysis was completed prior to finalization of Section 316(b) of the Clean Water Act that regulates the design and operation of intake structures (see: http://www2.epa.gov/cooling-water-intakes).

- Reservoir water storage declines gradually over the period of the multiple-year drought duration, suggesting that the reservoirs can mitigate effects of water shortage in the short-term drought scenario but would be less effective in the long-term drought scenario.
- Analysis of available water intake level for nine power plants found that none of the nine power plants would be unable to intake cooling water due to low reservoir water levels in the three drought scenarios. Such an analysis is recommended for all reservoirs, especially low-storage reservoirs predicted for the drought scenarios, upon acquiring water intake level data for other reservoirs with power plants.
- The different drought scenarios (2011, 2022, and 1950-1957) show different drought effects in terms of spatial distribution of water availability and reservoir storage reduction because of variation in the climate pattern.
- Vulnerable basins, identified by two matrices based on water use vs. water availability in the three drought scenarios, need to be carefully evaluated for future power plant siting to avoid basins with high water demand and limited water availability. The predictions for the 1956 scenario suggest more vulnerable basins near Dallas, Houston, Austin, San Antonio, Brownsville, and Lubbock than in other scenarios.

Potential Derating of Thermoelectric Cooling During Drought due to Effluent Discharge Temperature Limits[7]

The assessment of ERCOT thermal power plants to operate above Environmental Protection Agency (EPA) limits for effluent discharge temperatures indicated that a few power plants and significant quantity of generation capacity has operated at or near these temperature limits in the past. In addition, due to observed increasing temperatures, the major factor affecting effluent temperatures, ambient temperature, can be expected to lead to future derating potential (near 1,000,000 MWh per summer month) limited by cooling water effluent temperatures. However, while there were some power plants that were projected to be exposed to curtailment due to these EPA temperature limits, the study estimated that there is six times more electricity generation potential (~6,000,000 MWh per summer month) available from other existing generators that can occur without power plants reaching thermal effluent temperature limits that could be used to compensate.

- The regression models derived for this study reasonably model average monthly effluent temperatures for most of the open loop and recirculating cooling pond systems in ERCOT.
- The data on effluent water thermal discharges from power plants reveals that at least two power plants (Martin Lake, Coleto Creek) have operated above their average temperature effluent discharge limits over the time period of 2007-2011.
- By 2030, it is possible that up to six power plants could have effluent discharge thermally-limiting their generation at ~20,000-200,000 MWh per month if they attempt to operate at 2011 capacity factors.
- By 2030, it is possible that up to thirteen power plants could have effluent discharge thermally-limiting their generation at ~1,000,000 MWh per month if they attempted to operate at 100% summer capacity factors.

[7] Note that this analysis was completed prior to finalization of Section 316(b) of the Clean Water Act that regulates the design and operation of intake structures (see: http://www2.epa.gov/cooling-water-intakes).

- There are approximately 6,000,000 MWh of electricity available (up to 100% capacity factor in summer months) from thermal generators that would not be limited by effluent temperature limits.

A much more detailed accounting of this work is available in the Argonne Report ANL/EVS/R-13/2, titled "*Impact of Future Climate Variability on ERCOT Thermoelectric Power Generation*". Additional details concerning the thermal discharge modeling is available in the paper titled "*Implications of Thermal Discharge Limits on Future Power Generation in Texas*" published in the Proceedings of the ASME 2013 International Mechanical Engineering Congress & Exposition (see Appendix A to access these papers).

7.3. Assessment of Climate Impacts on WECC Hydroelectricity Generation

Hydroelectricity generation highly relies on in-stream and reservoir water availability. A large number of hydropower plants in WECC are located in Pacific Northwest (PNW) River Basin. Our initial study, as discussed in Section 8.1, identified that PNW River Basin is one of USGS 2-digit HUC river basins that are most vulnerable to the 10^{th} percentile drought. The purpose of this study was to evaluate potential risk for hydroelectricity generation due to projected drought scenarios in the medium-term (through the year of 2030). A series of data and modeling tools developed in the IEWP were used to project future climate and water demand, streamflow and reservoir discharge in response to projected climate and water demand, and predicted monthly hydropower generation corresponding to reservoir discharge. The results were used to estimate the potential reduction in hydroelectricity generation during the drought year or drought season.

The project team constructed a hydrologic model for the PNW River Basin with a modified SWAT modeling tool. On the basis of historical droughts and the projected drought year for 2020-2030, three drought scenarios were identified. The hydrologic model was used to simulate evapotranspiration, streamflow, soil moisture, irrigation and reservoir discharge based on various dam operation rules and targets using climate data for three drought scenarios. The model also incorporates the projected future water demand in 2030 (e.g., municipal, agricultural, electricity generation). The projected monthly reservoir discharges were used to predict the monthly hydropower generation for most of hydropower plants that have a capacity greater than 100 MW in PNW River Basin for each drought scenario. The main findings are as follows:

- Three drought scenarios based on historical drought in 1977 and 2001 and projected future drought in 2025 represent slightly different drought patterns in PNW River Basin. The projected 2025 drought extends low precipitation to the Cascade Range, the western part of PNW, where annual precipitation is normally above 30 inches while the 1977 and 2001 droughts had extremely low precipitation across the entire area east of Cascade Range and extended to Canada.
- The hydrologic model predictions for reservoir storage and discharge during the 2001 drought year were validated for 39 reservoirs that support hydropower plants.
- The plant-specific regression models derived in this study predict monthly hydropower generation based on reservoir discharges and other site specific parameters with a

coefficient of determination $R^2 > 0.9$ for 77% of hydropower plants and $R^2 = 0.8\text{-}0.9$ for 23% of hydropower plants.

- The hydroelectricity generation would be reduced by 20% to 24% for three drought scenarios (1977, 2001, and 2025 climate scenarios plus future water demands) compared to the normal years. Although the generation reduction is in a similar range, the spatial distribution of impacted hydropower plants varies among three drought scenarios due to variation in the climate pattern.

Task 7 Key Products: Power plants at greatest risk to the impacts of drought were identified. The analysis considered the hazards of low flows, insufficient reservoir storage, and elevated water temperatures under intensifying drought conditions projected for the future (Figure 10).

TASK 8: ENERGY FOR WATER

As water use expands, so too does the demand for electricity to pump, convey, treat (both drinking and wastewater), and distribute water (EPRI 2008). Nationwide, about two percent of United States power generation is used for water supply and treatment, which, is comparable to several other electricity intensive industrial sectors (EPRI 2002). Additionally, electricity represents approximately 75 percent of the operational cost of municipal water processing and distribution (Powicki 2002). While models developed under the previous tasks addressed the growing demand for water, here the associated energy use to deliver that water was determined. Analyses under this task estimated the energy expended to deliver water to its point of use; specifically, energy to treat municipal drinking/wastewater, energy to move water in large interbasin conveyance projects, and energy to pump water for irrigated agriculture.

Results from this analysis are useful to the Western and Texas interconnections as they provide better estimates of electricity loads supporting long-term transmission planning. Specifically, this analysis informs how local electricity demands could increase due to expanding water and wastewater infrastructure.

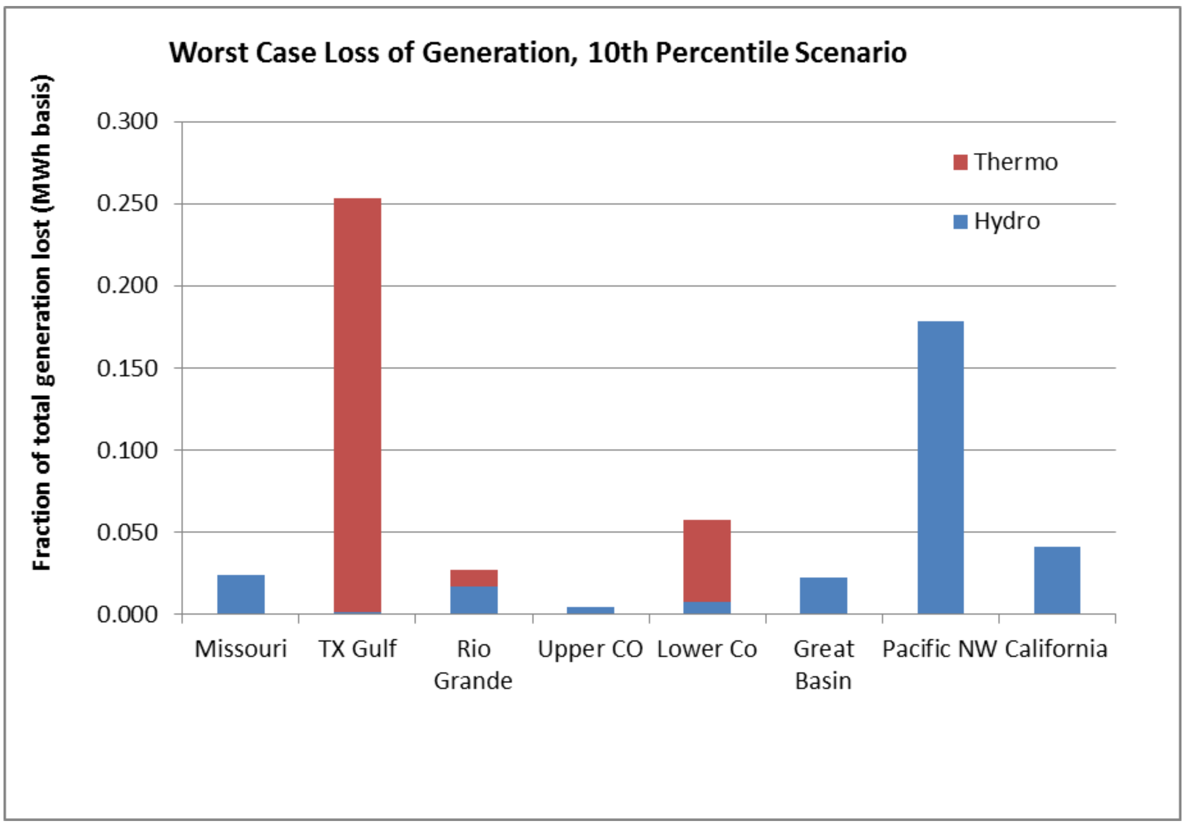


Figure 10. Map of electric generation at drought risk in the major river basins of the Western United Stated (see Appendix A: Harto et al. 2012). Data particular to the Texas Gulf Coast and Columbia River basin analyses are contained in the study specific reports that can be accessed through links in Appendix A.

8.1. Map West-Wide Electricity for Water Use

EPRI was one of the first to explore the energy-for-water nexus in their 1996 report, "*Water and Wastewater Industries: Characteristics and Energy Management Opportunities*." The original EPRI report was well received by the both electric power companies and water supply and wastewater treatment organizations. Since its publication, it has been used and cited extensively as one of the premier resources for the water-energy connection. Indeed, the report is still being referenced to this date. As this report is now dated, a joint effort between EPRI and the Water Research Foundation is currently in the process of updating this work.

The energy intensity of water varies depending on the source (i.e., surface or groundwater) and the quality of the water. Cities that rely on shallow groundwater require only moderate amounts of energy to treat and distribute water whereas cities that import surface water from great distances generally realize much higher energy use. There have been several studies that have evaluated energy use by municipal water and wastewater utilities. EPRI calculated unit electricity requirement for the supply of fresh water and the treatment of wastewater based on a survey of facilities across the United States (EPRI 2002). A similar study was also conducted by the American Water Works Association Research Foundation (AWWArf 2007). These studies produced models for estimating electricity usage based on the water/wastewater throughput, source of raw water, size of plant, and the type/degree of treatment. Additionally, the California Energy Commission (California Public Utilities Commission 2011) and the University of Texas (Stillwell et al. 2009) have conducted comprehensive evaluations of energy in water use for the states of California and Texas, respectively.

Electricity also plays a key role in irrigated agriculture. In fact, the U.S. Department of Agriculture has historically tracked the use and cost of energy in supply water for crop irrigation (U.S. Department of Agriculture 2007). The use of electricity is highly location dependent, related to the amount of water used in irrigation, the source of water and the distance/depth over which the water is conveyed. If the water source is groundwater, pumping requirements for supply of freshwater from aquifers vary with depth: 540 kWh per million gallons from a depth of 120 feet, 2,000 kWh per million gallons from 400 feet (Cohen 2004). These energy needs increase in areas where groundwater levels are declining. In fact, EPRI projects energy use for irrigation will triple between 2000 and 2050 based on land use and groundwater depletion trends.

To improve understanding of the electricity-for-water interdependency, electricity used in providing water services was mapped at the regional, state and county level for the 17-conterminous states in the Western United States. This study was unique in estimating electricity use for large-scale conveyance and agricultural pumping, as well as mapping these electricity uses along with that for drinking and wastewater services at a state and county level. This analysis resulted in several new and important insights:

- While it has been recognized that drinking and wastewater account for roughly 2% of total electricity use in the United States, results suggest that in the West an additional 1.2-1.6% is consumed by large-scale conveyance projects and another 2.6-3.7% is consumed by agricultural pumping.
- It has been recognized that California expends a significant amount of electricity to provide water services, consuming more than double the electricity of any other western

state. In fact, 9-10% of all electricity use in California goes to providing water services. What was not realized is that other states; for example, Idaho (34-49%), Montana (14-19%), Arizona (12-16%) and Nebraska (9-12%), use a larger fraction of their electricity on water services. In contrast, North Dakota and Oklahoma use less than 2% of their electricity on water services.

- The mix of energy use across the four water service sectors varies significantly by state. California (7.9-8.0 TWh/yr) and Arizona (4.8-7.1 TWh/yr) expend, by far, the most electricity on large-scale conveyance. California (6.1-8.6 TWh/yr) and Idaho (3.3-4.8 TWh/yr) use the most electricity for agricultural groundwater pumping, while Idaho (4.0-5.8 TWh/yr) and Montana (1.5-2.2 TWh/yr) use the most for surface water pumping. The most populous states, California (7.4 TWh/yr) and Texas (5.9 TWh/yr) consume the most electricity for drinking and wastewater services.
- The intensity of electricity use varies considerably across states and between services. The intensity per acre for agricultural groundwater pumping ranges from 0.3 to 8.8 MWh/acre/yr, and 0.04 to 2.8 MWh/acre/yr for surface water pumping, while electricity use per capita ranges from 0.11 to 0.29 MWh/person/yr for drinking water and 0.01-0.28 MWh/person/yr for wastewater.
- The geographic footprint of electricity use at the county level differs considerably between the four water service sectors. In terms of total use, every county in the West expends some electricity to lift, convey and treat water; however, use ranges from a 10 MWh/yr to 5.8 TWh/yr.
- Differences in the geographic footprint of electricity use, intensity and mix reflects characteristics unique to that region, including such factors as water demand (differs by sector), water supply (differs by source), climate, infrastructure, technology, resource allocation policies, and regulation.

This improved understanding of electricity use by the water sector has important implications for long-term electric transmission planning in the Western United States:

- Electricity use associated with the water service sector accounts for a significant fraction of the load in the West, between 5.8 and 7.4% of all electricity use. This represents roughly 25% of all industrial use of electricity in the West.
- Both the total electric load and fraction of load associated with water services vary strongly by region. In fact, the total load varies by two orders of magnitude by state and six orders of magnitude between counties. Such information would provide valuable insight for operations of the transmission network. These data are also important for informing water and electric policies set at different institutional levels (e.g., state, county, interconnection, utility).
- The electric load differs significantly across water service sectors. This is important as load shape varies by sector. Wastewater service loads are relatively constant both diurnally and seasonally, while drinking water loads fluctuate in response to the daily patterns of residential water use and seasonal patterns of landscape irrigation. Agricultural pumping has a distinct seasonal fluctuation while diurnal trends depend on local practices and operational constraints. Load shape for large-scale conveyance ultimately depends on the purpose of the supply project (e.g., irrigation, municipal).

- The intensity of electricity use (e.g., irrigation, drinking and wastewater) varies considerably on a regional basis. Analysis of these differences could provide insight into opportunities for improved energy efficiency.

A full accounting of the method used to estimate electricity for water in the Western United States can be found in the paper titled, "*Geographic footprint of electricity use for water services in the Western U.S.*", published in Environmental Science and Technology in 2014 (see Appendix A to access paper). Maps showing the estimated electricity use across different water supply sectors are likewise available in the paper and at the project's website: [http://energy.sandia.gov/climate-earth-systems/water-security-program/water-energy-and-natural-resource-systems/energy-and-water-in-the-western-and-texas-interconnects/.](http://energy.sandia.gov/climate-earth-systems/water-security-program/water-energy-and-natural-resource-systems/energy-and-water-in-the-western-and-texas-interconnects/)

Task 8 Key Products: The electricity used to provide water-related services was mapped at a county level throughout the Western U.S. Considered was the electricity required for interbasin conveyance, agricultural pumping, drinking water and wastewater services (Figure 11). These data quantify for the first time the amount of electricity used to deliver water for the expressed purpose of informing future transmission planning.

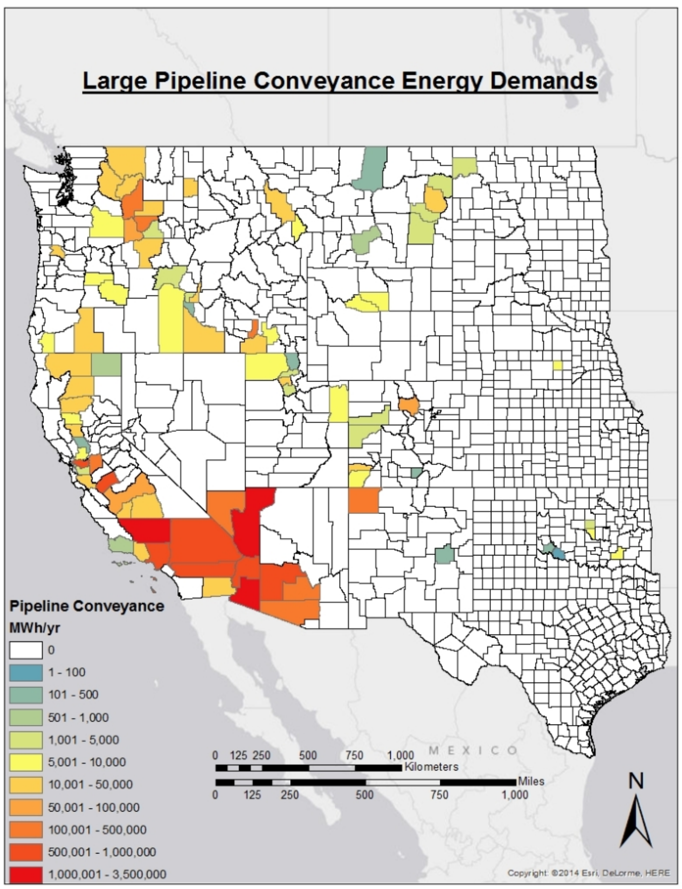


Figure 11. Map of electric use by county to move water in large interbasin conveyance projects. Additional energy for water maps can be found in Tidwell et al. 2014 (see Appendix A to access paper).

TASK 9: DECISION SUPPORT SYSTEM INTERFACE

The prior tasks focused on the collection of large suites of data that vary in space and time. These include such information as projected thermoelectric water use, municipal water demand, gauged stream flow, ecologically sensitive areas, and drought projections to name a few. The purpose of this task is to integrate all of this data into a consistent database and to develop a set of interfaces that allow different communities to interact with the data. This task provides the interface for stakeholders as well as WECC and ERCOT modelers to access the data collected by the IEWP.

9.1. Energy-Water Dashboard

This effort involved the creation of a custom mapping application built within the ESRI ArcGIS Online development environment. The interface provides an interactive dashboard to access the energy-water data sets compiled in the tasks above. The dashboard provides an interactive environment with tools for controlling the viewing, managing and analysis of the geospatial data. Specifically, the dashboard facilitates the viewing of raw data (e.g., municipal water demand, location and type of existing thermoelectric power plants, thermoelectric water consumption) at a variety of different spatial scales (e.g., interconnection state, county, HUC-8 watershed, or point level).

The dashboard can be accessed at: http://energy.sandia.gov/climate-earth-systems/water-security-program/water-energy-and-natural-resource-systems/energy-and-water-in-the-western-and-texas-interconnects/energy-and-water-data-portal/. This site provides access to:

- Electric power generation and water use data,
- Water availability, cost and use data, and
- Aquatic and riparian environmental data.

At this location both access to the raw data for download and dashboard for interacting and viewing the data are available. Examples of a few of the interfaces are provided in Figure 12.

9.2. Water Data Exchange (WaDE)

Given that the demand for water is always changing, the associated availability of water is in constant flux. In order to establish a basis for reproducible water modeling that can meet long-term western water-energy needs, the WSWC began a separate effort to create a framework for sharing and publishing relevant water planning and water use information generated by primarily state agency, as well as some select federal and local governmental agencies. The Water Data Exchange (WaDE) project is a collaborative effort between the WSWC, the Western States Federal Agency Support Team (WestFAST), the WGA, and the DOE National Laboratories. The purpose of WaDE is to better enable the western states and others to share water information with each other and to support regional-scale analyses of both physical and legal/institutional water availability, if the participating partners are generating and wish to share WaDE-targeted datasets. These data would also support modeling efforts within federal agencies that have an interest in water quantity and use, such as the USGS' Water Census/National Water Assessment initiative. WaDE also seeks to encourage and improve the sharing of federal data that support state water planning efforts.

WaDE is a long-term project that uses a web-services-based approach. This allows each participating state to maintain its own set of shared information, while allowing common datasets among the states to be mapped to a standard format. Using automated processes, these data are published over the web using eXtensible Markup Language (XML) and are discoverable via a centralized data catalog and web portal, maintained by the WSWC.

WaDE can be accessed through the energy-water dashboard (above) or directly at: http://www.westernstateswater.org/wade/.

Task 9 Key Products: A project website was established making the data and analysis produced by the project available to our project partners and the general public (Figure 12).

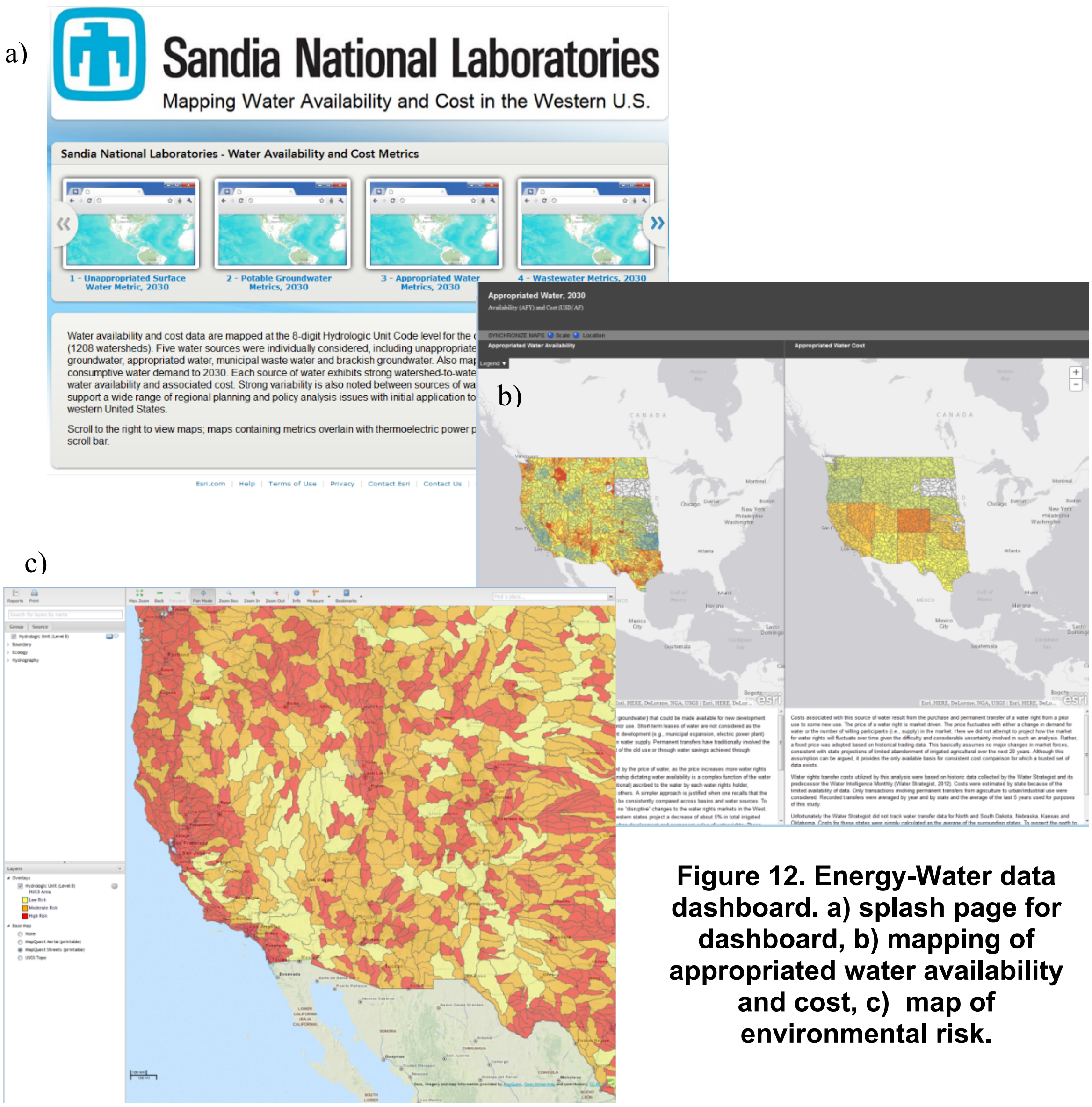


Figure 12. Energy-Water data dashboard. a) splash page for dashboard, b) mapping of appropriated water availability and cost, c) map of environmental risk.

TASK 10: TRANSMISSION PLANNING SUPPORT

The ultimate value of the IEWP is in the service it provides to WECC and ERCOT in support of their long-range transmission planning. This final task involved coordination and engagement between the National Laboratory team and transmission system planners. Specifically, the data collected and models developed as a part of the IEWP were utilized to support WECC and ERCOT by allowing water to be introduced as a new constraint and parameter in their electric transmission planning models. Three interconnection planning studies were conducted under this task. Specifically, WECC's long range planning was organized according to two target planning horizons, a 10-year and a 20-year planning horizon, while the ERCOT planning timeframe was limited to a single 20-year planning cycle. In addition a book chapter was published under this task through a related collaboration with WGA that focused on policy-related aspects of integrated energy-water planning.

10.1. Initial 10-Year WECC Transmission Study

Support for WECC's 10-year planning study involved investigating the water implications of four alternative study cases: Transmission Expansion Planning Policy Committee Base Case, State Provincial Steering Committee Reference Case, High Demand Case and the High Demand Side Management Case. This initial study occurred very early in the project, and thus utilized analysis tools and data that were in the development stage, and as such the results were viewed as preliminary. Nevertheless results provided insight for:

- Establishing some working numbers relative to thermoelectric water use, where it is located, and where/how it is likely to grow.
- Beginning dialogue toward developing water related metrics that can be used in long-range transmission planning.
- Cultivating experience in integrating water resource planning with long term electric power transmission planning.

Four key findings from this preliminary analysis were identified, which included:

- Thermoelectric generation has the potential to drive a significant increase in water consumption by 2020 depending on the modeling scenario.
- Water demands for thermoelectric use are relatively small in relation to water demands for agriculture; however, thermoelectric demands are growing while the agricultural sector has remained steady over the past 40 years.
- A key feature of the projected growth in thermoelectric water demand is that it corresponds to basins where it will compete with rapid growth in the municipal and industrial sectors. Most of the projected thermoelectric growth is also planned for basins with limited water availability.
- The study cases do perform differently with respect to water withdrawal and consumption suggesting that problems can be mitigated and solutions engineered to address water and energy nexus issues in the West.

The full Sand Report titled, "*Energy-Water Analysis of the 10-Year WECC Transmission Planning Study Case*" is available through Sandia National Laboratories (see Appendix A to access paper).

10.2. 20-Year WECC Transmission Study

In the 10-year planning study, the water related implications of different future expansion scenarios were evaluated. The 20-year planning study complimented and extended the 10-year plan by engaging directly with electricity and water managers to integrate water-related concerns into long-range transmission planning. Issues of water availability were integrated into WECC's 2013 20-Year Regional Transmission Expansion Planning exercise (http://www.wecc.biz/committees/BOD/TEPPC/Pages/2013Plan_20-Year.aspx); specifically, water availability and cost metrics developed for the WECC service area (United States footprint only) with the help and guidance of each state's water management agency (See sections 5 and 6 above). This water information was used to inform capital expansion (new transmission and generation) decisions for a variety of scenarios and study requests crafted and vetted by stakeholders. These scenarios covered a range of potential future electricity demands, energy policies, technology evolution pathways, and fuel prices. The objective of the integrated planning was to reduce the impact of thermoelectric expansion on limited water resources.

The WECC planning exercise was organized around five energy scenarios: a Reference Case assumed business as usual, while the other four WECC scenarios were constructed to generally represent four quadrants distinguished by low-to-high economic growth and evolutionary-to-paradigm changing technology innovation in electric supply and distribution. Across these five cases thermoelectric water consumption was found to increase by as much as 36% for some futures while decreasing by as much as 40% for others. New thermoelectric generation tended to be geographically dispersed and of low water intensity thus limiting impacts on water resources, with 90% of watersheds experiencing some change in thermoelectric water demand able to meet the new demand with less than 10% of their available water supply.

The geospatial footprint of changes to thermoelectric water use likewise showed considerable variation across the five cases with the largest differences in the Mountain West where two of the cases include significant displacement of coal-fired generation resulting in broad reduction in thermoelectric water use. Analyses also suggested that much of the water for new thermoelectric development, over 65% in all five cases, will likely need to come from non-traditional sources of water (e.g., wastewater, brackish groundwater). Utilization of non-traditional sources of water will be marked by higher prices for water, with some of the highest prices likely in Southern California driven in part by limited freshwater and by policies that strongly favor the use of non-potable water for new thermoelectric development.

A full accounting of the methods and results are available in a paper that is currently in review, titled "***Integrated energy-water planning in the Western Interconnection***."

10.3. 20-Year ERCOT Transmission Study

Project support for ERCOT's interconnection planning was largely satisfied through the analysis documented in the Argonne Report, "*Impact of Future Climate Variability on ERCOT Thermoelectric Power Generation*" (see Section 8.2). In addition, ERCOT contracted with Black & Veatch to review the data and analyses produced by the IEWP to assist in linking these studies to ERCOT needs and the development of a gap analysis to enable more detailed risk analyses of a multi-year drought scenario. The Black & Veatch report, "*Water Use and Availability in the ERCOT Region*" is available at the following URL: http://www.ercot.com/content/committees/other/lts/keydocs/2013/ERCOT_Water_Use_and_Availablility_-_DrtRpt_1DF.pdf. Also see Appendix A to access these papers.

10.4. Book Chapter in Climate, Energy and Water

Efforts were also made to distribute results and lessons learned outside the Western United States. Working with the WGA a chapter titled "*Integrated Modeling of the Energy-Water Nexus in the American West*", was included in the book, "Climate, Energy and Water" edited by J. Pittock, K. Hussey and S. Dovers (see Appendix A to access paper). This chapter describes the development of an integrated set of data and models and their use in planning and policy development in the Western United States. The chapter also addressed the public policy challenges of working across largely distinct sectors to develop integrated policy and planning strategies, and how regional models can inform discussions, illustrate resource tradeoffs and advance dialogue across sectors. While the chapter focused on a specific example of regional energy-water modeling in the Western United States, lessons learned from this effort can be instructive for other regions that require tools to frame policy making at the energy-water interface.

Two other articles were also prepared to raise general awareness for the integrated energy-water analysis that was being conducted. These articles each provide the basic purpose of the project and a limited outline of the work performed. These articles include (see Appendix A to access these papers):

- "*Planning for the Electricity-Water Nexus*" in *Water Resources IMPACT*,
- "*Integrated Energy-Water Planning in the Western and Texas Interconnections*" presented at the ASME 2013 Power Conference.

Task 10 Key Products: For the first time water availability was used to inform generation expansion planning by WECC and ERCOT. Additionally, projections of intensifying drought and its effect on reservoir levels, and thermal effluent discharge permitting were used to inform operational and expansion planning by ERCOT. Details of these studies are documented in a variety of reports that can be accessed through the links available in Appendix A.

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APPENDIX A: PUBLISHED PAPERS

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APPENDIX B: PRESENTATIONS

Cook, M.A., Webber, M. E. "Mitigating the Impacts of Droughts and Heat Waves at Thermoelectric Power Plants in the United States." Proceedings of the 2015 ASME Power & Energy Conference, June 28-July 2, 2015, San Diego, CA, USA. (2015).

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Harto, C., C. Clark, T. Kimmell, and R. Horner, 2013, "Water Consumption for Fossil Fuel Exploration and Production," presented at the Groundwater Protection Council Annual Forum, St. Louis, MO, September 23-25.

M.A. Cook, M.E. Webber, "An Analysis of Climate Effects on Cooling Water Temperature in Texas." 2014 ASME Power Conference. July 29-31, 2014, Baltimore, MD, USA. (2014).

Macknick, J., LCA X conference. "Water Usage of Electricity Generating Technologies in Life Cycle Assessments." November, 2010. Portland, OR.

Macknick, J., American Water Resource Association (AWRA) 2011 Spring Specialty Conference. "Water Consumption Impacts of Renewable Technologies" April, 2011. Baltimore, MD.

Macknick, J., Union of Concerned Scientists Young Scholars Program Webinar. "Water Requirements of the Electricity Sector." June, 2011. Golden, CO.

Macknick, J., American Society of Mechanical Engineers (ASME) Power Division meeting. "Water Consumption and Withdrawal Impacts of Electricity Generating Technologies." July, 2011. Denver, CO.

Macknick, J., Asia-Pacific Clean Energy Summit and Expo. "Water Consumption and Withdrawal Impacts of the Electricity Sector." September, 2011. Honolulu, HI.

Macknick, J., World Renewable Energy Forum-American Solar Energy Society. "Water impacts of renewable electricity technologies." May, 2012. Denver, CO.

Macknick, J., National Center for Atmospheric Research (NCAR) Integrated Assessment Modeling Group Annual Meeting. "Water and integrated assessment modeling." July, 2012. Boulder, CO.

Macknick, J., Association of State Energy Research and Technology Transfer Institutions (ASERTTI) Webinar. "Energy and water in policy and energy resource planning." September, 2012. Denver, CO.

Macknick, J., EUCI Water Summit. “Life cycle water use for electricity generation: A review and harmonization of literature estimates.” October, 2012. Denver, CO.

Macknick, J., Bloomberg New Energy Finance Water Leadership Forum. “Overview of the Energy-Water Nexus.” October, 2012. San Diego, CA.

Macknick, J., American Society of Mechanical Engineers (ASME) Energy Water Nexus Webinars. “Life cycle water use for electricity generation: A review and harmonization of literature estimates.” December, 2012. Golden, CO.

Macknick, J., U.S. Association for Energy Economics (National Capital Area Chapter)/Center for Strategic and International Studies (CSIS). “Energy Production and Water Use Trends.” April, 2013. Washington, DC.

Macknick, J., MIT Energy Initiative-Center for Strategic and International Studies (CSIS). “Water and Electricity.” May, 2013. Washington, DC.

Saha, S., I. Hlohowskyj, J. Hayse, J. Kuiper, K. Rollins, L. Fox, and R. Black, 2013, “Identifying Potential Conflicts with Threatened and Endangered Species from Energy-Related Water Withdrawal in the Western United States,” presented at the 2013 American Water Resources Association Annual Water Resources Conference, November 4-7, 2013, Portland, OR.

Tidwell, V.C., Energy and Water a Nexus of Tradeoffs, Engineering and Social Response to the Energy-Climate Nexus, NSF Headquarters, Arlington, DC, June 24, 2011

Tidwell, V.C., Energy and Water in the Western and Texas Interconnections, Spring Meeting of the Western States Water Council, Seattle, WA, June 7, 2012.

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Tidwell, V.C., Energy-Water Integrated Decision Support System, Energy-Water Nexus in Electric Power Production Atlantic Council of the U.S., Washington, D.C., May 17, 2011.

Tidwell, V.C., Energy-Water Nexus Overview, Joint U.S.-China Meeting: Ten Year Framework on Energy and Environmental Cooperation Emerging Issue Discussion “Energy-Water Nexus in Cities”, Washington, DC, March 18, 2014.

Tidwell, V.C., Energy-Water Nexus, CEREL Annual Program Conference, Golden, CO, November 3-5, 2010.

Tidwell, V.C., Energy-Water Nexus, Western Electric Power Sector/Water Sector Collaboration Workshop, Monrovia, CA, November 8-9, 2010.

Tidwell, V.C., Energy-Water Nexus: Integrated Modeling and Scenario Analysis, Union of Concerned Scientist, Boston, MA, March 2010.

Tidwell, V.C., Energy-Water Nexus: Integrated Modeling and Scenario Analysis, 2010 Annual MIT Energy Conference, Boston, MA, March 2010.

Tidwell, V.C., Energy-Water Nexus: Overview, Southwest Renewable Conference, Santa Fe, NM, September 2010.

Tidwell, V.C., Energy-Water Planning in the Western U.S., New Mexico Tech Seminar Series, Socorro, NM, November 12, 2012.

Tidwell, V.C., Energy-Water-Economy Nexus, Growing Blue Seminar on the Water-Economy Nexus, Washington, DC, September 18, 2012.

Tidwell, V.C., Integrated Energy-Water Planning in the Western and Texas Interconnections, Fall Meeting of the American Geophysical Union, San Francisco, CA, December 8, 2013.

Tidwell, V.C., Mapping Water Availability and Cost in the Western U.S., EPA Technical Workshop on Water Acquisition Modeling, Arlington, VA, June 4, 2013.

Tidwell, V.C., Mapping Water Availability and Cost in the Western U.S., U.S. Water Alliance Webinar on Hydraulic Fracturing, January 15, 2013.

Tidwell, V.C., Regional Variations of Water Scarcity and its Impact on Power Generation, NAS/GAO Assessment of Water Conservation Technologies in Energy Production, Washington, D.C. May 29-30, 2013.

Tidwell, V.C., State of America's Water: Present and Future, Webinar sponsored by Columbia University and CUASHI, February 10, 2015.

Tidwell, V.C., The Energy Water Nexus, Clean Texas Forum, Austin, TX, June 2010.

Tidwell, V.C., Thermoelectric Cooling Overview and New Modeling in the Western U.S., Reducing Energy's Impacts to Water and Biodiversity Hosted by The Nature Conservancy, Denver, CO, July 12, 2012.

Tidwell, V.C., Value of Water in Energy Production, EPA Value of Water Workshop, Washington, DC, September 19, 2012.

Tidwell, V.C., Water Availability and Power Generation, National Academies of Science Roundtable on Science and Technology, Washington, DC, December 5, 2013.

Tidwell, V.C., Water for Electricity Production Forecasts, Primary Fuels for Power and Transportation in the US, Atlantic Council of the U.S., Washington, D.C., November 10, 2011.

Tidwell, V.C., Water for Energy Production, National Association of Water Companies, Miami, FL, October 8-9, 2012.

Tidwell, V.C., Where Will the Water Come From? Review of Water Availability in the West, Transformation Solutions for Water in the West, Albuquerque, NM September 5, 2013.

Yan, E., Gasper, J., Tidwell, V., Wigmosta, M., and King, C., Impacts of Potential Future Drought on Thermoelectricity Generation, Groundwater Protection Council Annual Forum 2013, St. Louis, Missouri, September 23-25, 2013.

Yan, Y.E., Potential Future Drought Impacts on Water Availability in Texas-Gulf Basin, Geological Society of America Annual Meeting, Denver, Colorado, October 27-30, 2013.

Yan, E., Wigmosta, M., Tidwell, V., and King, C., Impacts of Potential Future Drought on Electricity Generation, Fall Meeting of American Geophysical Union, San Francisco, Calif., December 9, 2013.

Yan, E., Tidwell, V., and Wigmosta, M., Assessing Vulnerability of Electricity Generation Under Potential Future Droughts, Fall Meeting of American Geophysical Union, San Francisco, Calif., 15-19 Dec. 2014.

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