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Energy-Water Analysis of the 10-Year WECC Transmission Planning Study Cases

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Abstract

In 2011 the Department of Energy's Office of Electricity embarked on a comprehensive program to assist our Nation's three primary electric interconnections with long term transmission planning. Given the growing concern over water resources in the western U.S. the Western Electricity Coordinating Council (WECC) requested assistance with integrating water resource considerations into their broader electric transmission planning. The result is a project with three overarching objectives:

1. Develop an integrated Energy-Water Decision Support System (DSS) that will enable planners in the Western Interconnection to analyze the potential implications of water stress for transmission and resource planning.
2. Pursue the formulation and development of the Energy-Water DSS through a strongly collaborative process between the Western Electricity Coordinating Council (WECC), Western Governors' Association (WGA), the Western States Water Council (WSWC) and their associated stakeholder teams.
3. Exercise the Energy-Water DSS to investigate water stress implications of the transmission planning scenarios put forward by WECC, WGA, and WSWC.

The foundation for the Energy-Water DSS is Sandia National Laboratories' Energy-Power-Water Simulation (EPWSim) model (Tidwell et al. 2009). The modeling framework targets the shared needs of energy and water producers, resource managers, regulators, and decision makers at the federal, state and local levels. This framework provides an interactive environment to explore trade-offs, and "best" alternatives among a broad list of energy/water options and objectives. The decision support framework is formulated in a modular architecture, facilitating tailored analyses over different geographical regions and scales (e.g., state, county, watershed, interconnection). An interactive interface allows direct control of the model and access to real-time results displayed as charts, graphs and maps. The framework currently supports modules for

calculating water withdrawal and consumption for current and planned electric power generation; projected water demand from competing use sectors; and, surface and groundwater availability.

The lead laboratory for this effort is Sandia National Laboratories (Sandia) supported by other national laboratories, a university, and an industrial research institute. Specific participants include 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).

WECC's long range planning is organized according to two target planning horizons, a 10-year and a 20-year. This study supports WECC in the 10-year planning endeavor. In this case the water implications associated with four of WECC's alternative future study cases (described below) are calculated and reported. In future phases of planning we will work with WECC to craft study cases that aim to reduce the thermoelectric footprint of the interconnection and/or limit production in the most water stressed regions of the West.

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1. Introduction

In 2005 thermoelectric power production accounted for withdrawals of 140 billion gallons per day (BGD) representing 41% of total freshwater withdrawals, making it the largest user of water in the U.S., slightly ahead of irrigated agriculture (Kenny et al. 2009). In contrast thermoelectric water consumption is projected at 3.7 BGD or about 3% of total U.S. consumption (NETL 2008). Thermoelectric water consumption is roughly equivalent to that of all other industrial demands and represents one of the fastest growing sectors since 1980. In fact thermoelectric consumption is projected to increase by 42 to 63% between 2005 and 2030 (NETL 2008). This projected range in growth is a function of many factors including the fuel mix of the future power plant fleet, cooling technology, and green house gas emissions controls. As such, water availability will be an important consideration in the siting of any new power plant; however, water is not the only consideration. Other important siting requirements include access to fuels, transmission capacity, proximity to population centers/sensitive areas, environmental constraints, and cost.

1.1 Background on Energy and Water in the Western and Texas Interconnections Project

The Department of Energy's Office of Electricity has embarked on a comprehensive program to assist our Nation's three primary electric interconnections with long term transmission planning. Given the growing concern over water resources in the western U.S. the Western Electricity Coordinating Council (WECC) requested assistance with integrating water resource considerations into their broader electric transmission planning. The result is a project with three overarching objectives:

4. Develop an integrated Energy-Water Decision Support System (DSS) that will enable planners in the Western Interconnection to analyze the potential implications of water stress for transmission and resource planning.
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The lead laboratory for this effort is Sandia National Laboratories (Sandia) supported by other national laboratories, a university, and an industrial research institute. Specific participants include 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).

Although not addressed here, a complimentary project with the Electric Reliability Council of Texas (ERCOT) is in progress aimed at assisting in long term transmission planning and accompanying water resource issues.

1.2 Purpose of This Study

WECC's long range planning is organized according to two target planning horizons, a 10-year and a 20-year. This study supports WECC in the 10-year planning endeavor. In this case the water implications associated with four of WECC's alternative future study cases (described below) are calculated and reported. In future phases of planning we will work with WECC to craft study cases that aim to reduce the thermoelectric footprint of the interconnection and/or limit production in the most water stressed regions of the West.

This initial study utilizes analysis tools and data (e.g., the Energy, Water and Power Simulation model, see description below) that are very much in the development stage. Over the next two years of this project significant improvements are scheduled for both the model and the data that drives the model (see Next Steps below). As such the results given below should be viewed as preliminary. Reasons for conducting this analysis so early in the project include:

1) Establish working numbers relative to thermoelectric water use, where it is located, and where/how it is likely to grow.
2) Begin dialogue toward developing water related metrics that can be used in long-range transmission planning.
3) Cultivate experience in integrating water resource planning with long term electric power transmission planning.

As a first step toward understanding how information from this and future water related analyses might support long-range transmission planning, four considerations are provided:

1) Identify regions where siting of future electric power generation may be at risk due to potential water scarcity;
2) Evaluate power plant and electric system vulnerabilities due to drought;
3) Identify and deploy technological or management options for planners and plant managers to account for water availability when siting and designing electric generation; and
4) Prepare governors, industry, and regulators to understand the long-term challenges and potential trade-offs associated with electricity and water supply decisions.

2. Methods

This analysis makes use of the Energy, Water and Power Simulation (EPWSim) model developed by Sandia National Laboratory (Tidwell et al. 2009). This decision framework is formulated within a system dynamics architecture (e.g., Sterman 2000) and implemented within the commercial software package Studio Expert 2008, produced by Powersim, Inc. (www.powersim.com). The model is designed to operate on an annual time step with a spatial extent that includes the WECC service area. The duration of the simulation extends from 2010 to 2020, the current planning horizon for WECC. EPWSim has been modified to accept thermoelectric power production data directly from WECC's PROMOD modeling. Specifically, WECC provides PROMOD output in the form of annual and monthly power production for each thermoelectric power plant (existing and future) in the WECC. This data is then used to calculate the water implications of the proposed fleet/operational schedules.

At its highest level, EPWSim is organized according to four primary sectors, demography, thermoelectric water demand, non-thermoelectric water demand, and water supply. The demographic sector model simulates changes in population and gross state product (GSP) that in turn drives the demand for water in the non-thermoelectric sector. Within the thermoelectric water demand module, thermoelectric power production output from WECC's PROMOD model is used to calculate associated water withdrawals and consumption at each thermoelectric plant in the WECC. The model allows control of the type of cooling (i.e., open-loop, closed-loop tower, closed-loop pond, or air cooled) and source of water (surface water, groundwater, saline) utilized in all new construction. For the non-thermoelectric water demand module both withdrawals and consumption are calculated according to the primary use sectors, municipal, industrial, mining, livestock, and agriculture. These growing demands are then compared to various water supply metrics to identify regions of limited water availability.

The nexus between electric power generation and water resource use must be viewed through the lens of multiple reference systems (e.g., interconnection, watersheds, states, and counties). To facilitate cross reference system analysis, the model is seeded with data representing the highest level of detail that is publically available. These data include such factors as population at the county level, changes in per capita water use at the state level, and stream gauge data at the watershed level. From these disparate scales the data are translated to a compatible reference system for analysis and observation. Translation is accomplished according to a simple areal or population weighted aggregation scheme. Lookup tables of the weighting functions necessary to move from one reference system to another have been developed to streamline this process.

Below a brief description of each model sector is provided.

2.1 Demographic Sector

Population and gross state product (GSP) are the primary factors influencing the demand for non-thermoelectric water within the model. Both are simulated on an annual basis, computed at the county level. Population and gross state product growth rates are treated as exogenous variables to the model and thus allow full control by the user. The manner in which population and gross state product influence the demand for water is defined in the non-thermoelectric water demand module description below.

Population growth is assumed to follow an exponential trajectory according to the relation

$$\begin{aligned} P_c(t) &= P_c(t-1) + \Delta P_c(t) \\ \Delta P_c(t) &= P_c(t-1) * PGR_c * \Delta t \end{aligned} \qquad 1$$

where P [persons] is the population, ΔP [persons] is the change in population experienced in a year, PGR is the population growth rate [yr^{-1}], t is time, Δt is the time step (one year), and the subscript c designates the county level. The source of data for the model is the 2000 Census (U.S. Census Bureau 2004). Specifically, the measured population in 2000 is used as the model's initial condition, while *PGR*s are determined from the change in population over the period 1990-2000. The measured *PGR* values can be used or adjusted by the model user.

Gross state product is modeled in essentially the same fashion

$$\begin{aligned} GSP_s(t) &= GSP_s(t-1) + \Delta GSP_s(t) \\ \Delta GSP_s(t) &= GSP_s(t-1) * GSPGR_s * \Delta t \end{aligned} \qquad 2$$

where GSP [$] is the gross state product, ΔGSP [$] is the change in gross state product experienced in a year, $GSPGR$ is the gross state product growth rate [yr^{-1}] and the subscript s designates a state level. The source of data for the model is the Bureau of Economic Analysis (BEA 2007). As the name implies, gross state product calculations are implemented at the state level. In this way, *GSP* values for 2000 form the initial conditions for the model, while *GSPGR*s are determined from the change in gross state product over the period 1990-2000. *GSP* is then estimated at a county level by simply downscaling the state level value by the ratio of county population to state population. In a fashion similar to population, the *GSPGR* values based on historical trends can be used or adjusted by the model user.

2.2 Thermoelectric Water Demand

The thermoelectric water demand module calculates water withdrawals and consumption for the existing and future power plant fleet. These calculations are based on output taken directly from WECC's PROMOD simulations. Four separate PROMOD output files are used as input to the EPWSim calculations, each associated with a different WECC study case. The PROMOD data are structured according to individual thermoelectric power plants in the WECC. These plants are organized according to their state of operation as either existing, under construction, planned and future. Each plant is characterized by its name, bus designator, state in which it is located, capacity, type of plant, and annual/monthly power production in megawatt-hours (MWh). Power plants located in Alberta, British Columbia and Mexico were not included in this current analysis (future improvements planned as part of this project involve expansion of the model to include the full WECC service area).

What is lacking from the PROMOD data set is information with which to locate the plant by county or watershed. To accomplish this step, each power plant from PROMOD has been associated with a power plant from the 2010 EIA database (EIA 2010), which provides the location of the plant in terms of its latitude and longitude. Association of an "existing" PROMOD power plant with that of a power plant in EIA is based on matching all available

PROMOD information with that found in EIA. Specifically, information on plant name, the bus name (which often corresponded to the name of a city or county), plant capacity, type of plant, and the state location were used to match plants. In total 827 existing power plants were associated in this manner. A very solid match (matching multiple criteria) was possible for most of the plants. In fact, only about 50 of the plant matches were based on only two or three criteria.

Obviously, the under construction, planned and future power plants are not included in the EIA database. A total of 153 power plants fall into these categories. To determine the location of these plants required a different approach. In this case a web search was performed based on the name of the plant. In most cases we were able to identify the plant and get a location. For the few that could not be located in this manner the state and bus name were used to estimate the location of the plant.

The provided PROMOD data sets only detail operations in a single year, the final year of the planning horizon (2020). To configure the data to calculate future water demand by year (2010-2020) some assumptions concerning the date a future power plant comes on line were necessary. To do this plants categorized as under construction were assumed to come on line in the years 2011-2013, planned coming on line from 2014-2016, and future plants coming on line 2017-2020. This distribution is roughly based on the time required to move a plant from construction, planned or unplanned status to operational. Power production rates are assumed to remain constant year to year.

Water withdrawal and consumption values are calculated on a plant by plant basis, according to the type of plant, its projected cooling type and the production rate supplied by PROMOD. For the 153 new power plants this calculation is accomplished by multiplying the production rate, p_i, by the associated water withdrawal factor, $wwf_{f,c}$,, or water consumption factor, $wcf_{f,c}$

$$\begin{aligned} ww_i &= p_i * wwf_{f,c} \\ wc_i &= p_i * wcf_{f,c} \end{aligned} \qquad 3$$

where *ww* indicates water withdrawal, *wc* indicates water consumption and the subscript *i* designates the plant, *f* the fuel type and *c* the cooling type. The water withdrawal/consumption factors are based on the work of the National Renewable Energy Laboratory. These factors along with a brief description of their origin are given in Appendix A. The fuel type of the future power plants is determined by WECC and include Biomass, Cogeneration, Combined Cycle, Combustion Turbine, Geothermal, Internal Combustion, Nuclear, Solar-CSP, Steam-Coal, and Steam-Other. The cooling type can be varied to quantify the impact of different cooling technologies.

As existing plants utilize older, less efficient technologies, these water withdrawal/consumption factors don't provide an accurate picture of water use. In this case information on water use available through the eGRID database (EPA 2010) and county level water use statistics gathered by the USGS (2005) are utilized. Use of the two different databases is necessitated because only about half of the existing plants have reported water use data in the eGRID database. Where eGRID data is available, it is used as the basis for water withdrawal and consumption. Where lacking those plants were sorted according to county and a preliminary estimate of their withdrawal and consumption is made using equation 3. These values are then adjusted in a proportional manner so as to match the measured USGS data (2005 data for withdrawal and 1995 data for consumption). As production rates vary between years and between the different WECC study cases, adjustment to these historical water use rates is necessary. This is accomplished through a proportional adjustment using the production rate associated with the measured water use rate, p_o, and that of the future power production rate, p_f

$$wu_f = wu_o * \frac{p_f}{p_o} \qquad 4$$

where *wu* denotes water use (either withdrawal or consumption) and the subscripts *o* and *f* stand for initial and future, respectively.

The final step involves determining the source of water for the power plant. This is accomplished using the EPA (2010) and USGS (2005) data. For plants with source water specified in the eGRID database, that designation is used. Otherwise the USGS data was used in a manner similar to that described for establishing water withdrawal and consumption. Distribution of source water between groundwater and surface water for future plants is handled in a manner consistent with Equation 9 below.

2.3 Non-Thermoelectric Water Demand

The non-thermoelectric water demand module within EPWSim projects the future demand for water according to five different use sectors: municipal (including domestic, public supply, and commercial), industrial, agriculture, mining and livestock. Water withdrawal and consumption are tracked separately as are the resulting return flows. Also modeled is the source of the withdrawal, whether that be surface water, groundwater, or a non-potable source.

Water use statistics published by the U.S. Geological Survey (USGS) serve as the primary data source for the EPWSim analyses (Kenny et al. 2009; Hutson et al. 2005; Solley et al. 1990; 1995). Every five years since 1950 the nation's water-use data have been compiled and published by the USGS. Collection of this data is a collaborative effort between the USGS, state and local water agencies, and utilities. However, the level of detail at which these data are reported varies from year to year. Data from the 1985, 1990, and 1995 campaigns provide the most comprehensive picture of water use in the U.S. and also are the last years that consumptive water use was compiled. The last published water census by the USGS is 2005 (no reported consumptive use). As such, our projections of future water withdrawals utilize data from 1985-2005 while consumptive use projections are limited to data from the 1985-1995 campaigns.

Municipal water withdrawal, Q_M, is modeled at the county level according to the relation

$$\begin{aligned} Q_{M,c}(t) &= P_c(t) * PCU_c(t) \\ PCU_c(t) &= PCU_c(t_{2005}) + (\Delta PCU_s * t_e) \end{aligned} \qquad 5$$

where *P* [person] is the population, *PCU* [L^3/person*t] is the per capita water withdrawal, ΔPCU is the rate of change in per capita water withdrawal [L^3/Person*t^2], *t* is time, t_e is the elapsed time since 2005, and the subscripts c and s denote county and state levels of aggregation, respectively. In this way, municipal water withdrawal is a function of both changing population and per capita water withdrawal. Changes in population are calculated according to the county level population growth rates reported by the Census Bureau (2004), as described above, while ΔPCU is based on historical trends (see below). Recognizing that care must be exercised when extending historical trends into the future, limits are placed on the total allowable change. Specifically, ΔPCU is not allowed to increase or decrease by more than 20% over the duration of the simulation. This limit is set based on the assumption that changes beyond ±20% would likely require major structural changes to the system, for example the extent to which an individual home owner might implement conservation measures. Once this maximum change is achieved ΔPCU is held constant throughout the rest of the simulation. Per capita water withdrawal rates published for 2005, $PCU(t_{2005})$, serve as the initial condition for the model.

Rates of change in per capita water withdrawal, ΔPCU, were calculated by simple linear regression using data from the USGS. Recognizing that meaningful trends in *PCU* could not be extracted at the county/watershed level (data were erratic, displaying little correlation across the three data sets), ΔPCU values were calculated from data aggregated at the state level. Each regression was inspected according to "goodness of fit". In cases where the regression did not accurately represent the perceived trends (i.e., $R^2<0.6$) data were fitted by hand.

Industrial water withdrawal is relatively insensitive to changes in local population; rather, economic conditions, as represented by gross state product, act as a better indicator. As such, industrial water withdrawal, Q_I, is modeled as

$$\begin{aligned} Q_{I,c}(t) &= GSP_c(t) * WUI_c(t) \\ WUI_c(t) &= WUI_c(t_{2005}) + (\Delta WUI_s * t_e) \end{aligned} \tag{6}$$

where *GSP* is gross state product [$], *WUI* is the water withdrawal intensity [$L^3/\$*t$] and ΔWUI is the rate of change in *WUI* [$L^3/\$*t^2$]. In this case, industrial water withdrawal is a function of both changing gross state product and water withdrawal intensity (the amount of water required to produce a dollar of gross state product). Modeling of gross state product is described above, while modeling of *WUI* and ΔWUI are handled in a completely analogous manner to that described for *PCU* and ΔPCU above.

Irrigated agriculture, Q_A, is a function of the area irrigated, climate conditions and conservation practices

$$\begin{aligned} Q_{A,c}(t) &= A_c(t) * IR_c(t) \\ A_c(t) &= A_c(t_{2005}) + (\Delta A_s * t_e) \\ IR_c(t) &= IR_c(t_{2005}) + (\Delta IR_s * t_e) \end{aligned} \tag{7}$$

where *A* is the area irrigated [L^2], *IR* is the irrigation requirement [L^3/t], is ΔA the rate of change in the irrigated area [L^2/t] and ΔIR is the rate of change in the irrigation requirement [L^3/t^2] (irrigation requirement responds both to climate and conservation drivers). Over the last 35 years, water withdrawal in the agricultural sector has remained relatively constant largely due to limited increases in the area irrigated and offsetting improvements in irrigation efficiencies (KENNY ET AL. 2009). For this reason, irrigation water withdrawal is assumed to remain constant over the duration of the simulation. Nevertheless, the model is designed to easily permit future changes to irrigated agriculture.

Other water use sectors such as mining and livestock fail to show a strong trend with population, GSP, or any other simple metric. Thus, water withdrawal in the livestock sector, Q_L, is simply modeled by extending its historical water withdrawal trend into the future

$$Q_{L,c}(t) = Q_{L,c}(t_{2005}) + (\Delta Q_{L,s} * t_e) \tag{8}$$

where ΔQ_L is the rate of change in water withdrawal by the livestock sector [L^3/t^2]. It is calculated and implemented in a fashion similar to ΔPCU and ΔWUI above. Likewise, future water withdrawal by the mining sector is modeled according to Equation 8, with an appropriate change in parameters.

Once water withdrawal is calculated the fraction consumed and discharged to the waste water treatment plant is determined. Consumptive use is calculated in an identical fashion to that in equations 5-8 above, again using the data available from the USGS (2005). The only difference is that consumptive use trends were calculated from data limited to the USGS census in 1985, 1990 and 1995. Also, the 1995 data serve as point from which future consumptive use values are calculated. Waste water discharges are calculated as the difference between use and consumption.

As the demand for water in a particular sector changes over time, so too will the mix of withdrawals from groundwater, surface water and non-potable sources. Historical trends relative to changes in groundwater abstraction are used to project future supply choices

$$GWf_{n,c}(t) = GWf_{n,c}(t_{2005}) + (\Delta GWf_{n,s} * t_e) \tag{9}$$

where $GWF_{n,c}(t_{2005})$ is the fraction of supply taken from groundwater in 2005 [%], $\Delta GWf_{n,s}$ is rate of change in the fraction taken from groundwater [%/t] and the subscript n designates the water use sector. $\Delta GWf_{n,s}$ is calculated and applied similarly to that of ΔPCU and ΔWUI. Likewise the percent water coming from non-potable sources is allowed to change, in this case according to a user defined rate of change (set by a slider bar). The resulting supply taken from surface water is fully determined by that not taken from groundwater or non-potable sources.

2.4 Water Supply

Stream gauge statistics based on extended sampling periods provide one of the best measures of surface water availability. As these gauged flows are affected by activities upstream of the gauge, the measured statistics account for upstream reservoir operations, evaporative losses, groundwater-stream interaction, withdrawals, etc. In this way, the mean daily flow provides a good measure of the average surface water supply available at the gauge location, while the accompanying exceedance flows provide a measure of the variability in supply at that point.

Likewise, the gauged average daily base flow index (that portion of the stream flow contributed by groundwater discharge) provides a good measure of the sustainable groundwater recharge available for use.

The basis of the water supply modeling is the USGS National Hydrographic Dataset (NHD). Specifically, the USGS has stream flow data from 23,000 gauges in which the available sampling record has been statistically analyzed to give the minimum and maximum daily flows, mean daily flow, key percentiles (1, 5, 10, 20, 25, 50, 75, 80, 90, 95, 99) of daily flow (exceedance values), and the base flow index (Stewart et al. 2006). For each watershed the NHD gauge with the longest record and which is the closest to the point of watershed discharge has been identified. Specifically, surface and groundwater availability has been compiled at the accounting unit (6-digit Hydrologic Unit Code [HUC]) level (167 watersheds across the western U.S.). As future activities upstream of the gauge will affect streamflow, the 2006 stream gauge statistics are adjusted in the model for changes in consumptive use upstream of the gauge. Specifically, changes in water consumption (post 2006) are sequentially aggregated across watersheds from headwater to the gauge. The aggregated consumption is then subtracted from the long term gauge statistics to yield an adjusted measure of water availability.

By combining projected water demands with the physical water supply provides a meaningful way to project regions prone to limited water availability. That is, where the demand for water approaches the available water supply, tension over water allocation is possible.

2.5 Interactive Interface

The decision support tool is designed to be accessible to the professional and lay public alike, requiring no specialized software (Excel is the only requirement). The model operates on a laptop computer and can be used to demonstrate key variables and processes associated with the electric power-water nexus. The model operates in real-time with a user-friendly interface that includes slider bars, buttons and switches for changing key input variables, and real-time output graphs, tables, and geospatial maps (displayed interactively through Google Earth™) showing results. These features allow a wide range of users to experiment with alternative electric power-water use strategies and learn from the results. Ultimately, the model can be distributed to users on CD or via the internet.

2.6 Database

Data supporting EPWSim is organized and managed within an Excel Database that communicates directly with the model software. The database stores initial conditions as well as key parameters and rates of change needed by the model. The database is organized according to a number of worksheets each of which contain data supporting a specific module of the model. Specifically, there are worksheets that contain data concerning, population; gross state product; power plant locations; thermoelectric water use factors (by plant type); water use rates by sector and location; mean and exceedance gauge data by watershed; and, associated lookup tables for translation between different reference systems.

Beyond the baseline data used by the model, the database also includes various calculations needed to prepare these data for use in the model. Calls to the database from the model are fully automated within the simulation environment.

3. Results

Our analysis starts with a review of conditions as of 2010; that is, the water demand across different use sectors; current competition between thermoelectric power production and other water use sectors; and, the state of water availability across the U.S. Attention then turns to projecting future electric power and water demands. To help with this four alternative study cases, as described below, are explored. In each case the consequences for water withdrawals and consumption are considered as well as how such change influences the nexus between water and energy (e.g., where water might limit the production of electricity). It should be noted that the scenarios considered here are but a small subset of scenarios, policies, and action metrics that could be investigated.

In efforts to see the big picture in the detailed results given below, we begin by stating four key conclusions from this initial analysis:

> <u>Conclusion 1:</u> Thermoelectric generation has the potential to drive a significant increase in water consumption by 2020.
>
> <u>Conclusion 2:</u> Water demands for thermoelectric use are relatively small in relation to water demands for agriculture; however, thermoelectric demands are growing while agriculture has remained steady over the past 40 years.
>
> <u>Conclusion 3:</u> 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 characterized by limited water availability.
>
> <u>Conclusion 4:</u> The study cases do perform differently with respect to water withdrawal and consumption suggesting the opportunity to engineer solutions to the water and energy nexus in the West.

3.1 Water and Electric Power in 2010

Figure 1 shows the distribution of water withdrawal and consumption in 2010 across the use sectors of municipal, industrial, thermoelectric, mining, livestock and agriculture for the WECC Interconnection (U.S. use only, future analyses will consider the full WECC service area). In total, 117 BGD of freshwater are withdrawn from surface and groundwater resources while 92.6 BGD are consumed (water that is lost to evaporation and thus not returned directly to a surface or groundwater body for further use in the basin). In terms of freshwater withdrawals thermoelectric production requires 1.9 BGD or 2% of the regional withdrawals. If saline water is considered a total of 9.6 BGD are withdrawn making thermoelectric power production the third largest user of water in the western interconnect. The largest freshwater withdrawal is by irrigated agriculture at 96 BGD (82%), followed by municipal at 14.6 BGD (12%). Other withdrawals include industry at 1.6 BGD (1%), mining at 0.5 BGD (1%) and livestock at 2.7 BGD (2%). Of these withdrawals, 29.6 BGD is extracted from groundwater resources.

The consumptive water use picture is similar. Irrigated agriculture dominates consumption at 87.6 BGD, or 95% of all consumption. Other freshwater consumptive uses include municipal at 3.2 BGD (3%), livestock at 0.7 BGD (1%), industrial at 0.4 BGD (0.4%) mining at 0.4 BGD (0.4%) and thermoelectric at 0.4 BGD (0.4%). Although irrigation dominates both water withdrawal and consumption this sector has realized effectively no growth over the last 40 years (KENNY ET AL. 2009). Likewise, livestock and mining have maintained relatively level use over this same time period. In contrast, municipal, industrial, and thermoelectric sectors have been growing and are expected to continue growing, as will be shown later.

Of particular interest to this project is the thermoelectric power sector. To take a closer look at this sector, thermoelectric power production and its associated water withdrawal and consumption is disaggregated by power plant fuel type (Figure 2). A review of Figure 2 indicates that thermoelectric power production in the WECC is predominately from coal-stream production followed by natural gas combined cycle and nuclear. Thermoelectric water withdrawals are almost evenly distributed between these three fuel types. These withdrawals are largely the result of a limited number of power plants with open-loop cooling. Thermoelectric water consumption shows a very different trend with coal-fired plants being responsible for the vast majority of the consumption reflecting the relatively large number of plants and their associated high consumptive use of water (see Appendix A).

Figures 1 and 2, which are aggregated at the interconnection-level, tell only a part of the story. In particular, water withdrawal and consumption are not uniformly distributed across the interconnection. Figure 3 presents water withdrawal and consumption by state. While the water use picture in each state is dominated by irrigation, the total withdrawal and consumption across states differ considerably. The states also differ in the degree to which the non-agricultural water use sectors contribute to the water withdrawal and consumption statistics (e.g., more populous states are characterized by higher non-agricultural water use). Withdrawals for thermoelectric power production are evident in California, Washington and Wyoming.

These water demands are further disaggregated to the watershed level (Figure 4). The most striking feature of these maps is the very different spatial arrangement of the demands. Thermoelectric withdrawals and consumption vary from watershed to watershed with many watersheds having no water use. Only a few watersheds are characterized by large thermoelectric withdrawals, where the handful of plants that utilize open-loop cooling are located. In contrast, thermoelectric consumption is more evenly distributed with an apparent trend toward higher consumption to the east and lower consumption in the west. This trend reflects the tendency toward more coal-fired plants in the east relative to gas-fired in the west.

In contrast, non-thermoelectric water use is measured in every watershed and the withdrawal and consumption patterns are very similar to each other. While non-thermoelectric withdrawal and consumption patterns are similar these patterns are very different from that of the thermoelectric sector. The non-thermoelectric water use pattern is dominated by irrigated agriculture, following key basins such as the Central Valley of California, Columbia River, Snake River, Platte River, and the Lower Colorado.

Like water withdrawal and consumption, water supply is not uniformly distributed across the West, ranging from a temperate climate in the Northwest to an arid climate in the desert Southwest. Defining the water supply available for human use is a complex and often contentious issue. Water supply depends on variability of the climate, the physical hydrology of the basin, the engineered infrastructure to store and convey the water, the legal institutions that manage and allocate the resource, as well as the personal values of those living in the basin. Given this complexity we cannot definitively define the water supply; rather, we are forced to depend on proxies that provide insight into specific aspects of water supply. Here the mean gauged stream flow (a measure of surface water that is on average physically available in a watershed), the 5^{th} percentile stream flow (a measure of surface water available on the driest days of the year), and gauged base flow (a measure of the sustainable recharge to the watershed's groundwater aquifers) is used.

Limited water availability for future development is likely to occur where the demand for water exceeds the accessible supply. Several general displays have been developed to explore the ratio of supply to demand; specifically, maps are developed at the 6-digit HUC level based on the ratio of water supply to water demand. Where this ratio is large, limited water availability is unlikely, where the ratio is small supply is on the order of demand thus there is little room for new growth. For purposes of this analysis, areas prone to limited water availability are taken as regions with a supply to demand ratio of 2 or less. While this value is somewhat arbitrary it does represent a natural threshold in the data. As noted above, three different metrics have been formulated one for surface water availability, another for low flow conditions, and a third for groundwater availability. These are shown in Figure 5.

A quick review of the mean surface water supply to demand ratio (Figure 5a) clearly reveals that much of the western U.S. is likely subject to limited water availability (as measured by this metric), with only the far north and Upper Colorado River characterized by ratios above 2. This result simply reflects both the aridity of the West and the high water use due to irrigated agriculture. The low flow ratio (Figure 5b) shows similar results to that of the mean surface water availability but at increased spatial extent. Limited groundwater availability (Figure 5c) is indicated largely in the Great Plains, in the Southwest, and the Great Basin again reflecting the combined effect of arid climate and irrigated agriculture. While we recognize that these are imperfect metrics results are similar to water stress regions identified by the U.S. Bureau of Reclamation in the Water 2025 Assessment (2010) and the U.S. Geological Survey in their 2009 Groundwater Report (Reilly 2008).

3.2. Study Case Analyses

Figure 5 clearly indicates that much of the western U.S. is characterized by limited water availability for future development and in fact, many areas are already realizing the squeeze of water resource issues. However, every indication suggests that the demand for water is going to increase. Based on projections from the U.S. Census Bureau, population within the WECC is expected to grow from 75M in 2010 to 83M by 2020, an 11% increase. Over the same period of time electric power demand is project to grow from 664 to 740 million megawatt hours (MMWh) (EIA 2010), also an 11% increase.

We do not know exactly how population will grow, how power and water use characteristics will change in time, how the electric power plant fleet will evolve to meet the growing needs, or do we know what policies may be enacted that impact the energy and water sectors. For this reason we utilize a series of potential future realities, termed study cases, to explore the nexus between energy and water. These include:

1. Transmission Expansion Planning Policy Committee (TEPPC) Base Case. This test case is designated as PC0. This study case is based on Balancing Authority load forecasts and renewable resource utilization that complies with state Renewable Portfolio Standard (RPS) targets.
2. State Provincial Steering Committee (SPSC) Reference Case. This test case is designated as PC1. This study case replaces Balancing Authority loads with state-adjusted load forecasts. Renewable resources have been modified to reflect RPS targets based on the state-adjusted loads.
3. SPSC High Load Case. This test case is designated as PC2. This study case utilizes the state-adjusted load forecasts and increases them by 10%. Renewable resources have been modified to reflect RPS targets based on the state-adjusted loads.
4. SPSC High Demand Side Management Case. This test case is designated as PC3. This study case decreases the state-adjusted load forecasts to reflect achievement of the "full economic energy efficiency potential throughout the West". Renewable resources have been modified to reflect RPS targets based on the state-adjusted loads.

We now project into the future 10 years, to the year 2020. As future demands are uncertain the analysis utilizes four alternative study case realities (as described above). The ultimate goal is to quantify tradeoffs in terms of water withdrawal and consumption relative to the four study cases. Also of interest is understanding the extent to which new thermoelectric power production will compete with growing demands in other water use sectors for limited water resources in the western U.S. Other analyses will help identify new power plants sited in basins prone to limited water availability (e.g., locations where permitting is likely to be difficult). Taken together this information will help better inform long-range transmission planning.

Power Production: Ultimately, new water demands for WECC operations will depend on the extent of thermoelectric power production. Each of the four study cases result in a different level of total thermoelectric power production (Table 1). As would be expected the SPSC High Demand Case yields the highest production at 591 MMWh while the SPSC High Demand Side Management study case yields the lowest demand (443 MMWh), representing a 33% difference between high and low production. Figure 6 shows the mix of new thermoelectric power production by fuel type for the TEPPC Base Case. Much of this new production comes from natural gas combined cycle (NGCC) plants with supporting supplies from geothermal, solar CSP and coal-steam (Figure 6). Limited new production is also provided by gas-combustion cycle, and biofuels. This mix of new production is very closely replicated in the other three study cases. As such, noted differences in production across the study cases (Table 1) are largely the result of changes to operations of existing power plants. The SPSC Reference case is characterized by a decrease in existing coal-steam and NGCC production relative to the Base Case, while the High Demand Case involves increased production by existing NGCC and to a lesser extent Biofuel plants. The High DSM case involves reductions to coal-steam and NGCC plants and to a lesser extent solar CSP relative to the base case.

Table 1: Thermoelectric Power Production for the four study cases.

Study Case	Power Production (MMWh)
PC0, TEPPC	552
PC1, SPSC	517
PC2, SPSC	591
PC3, SPSC	443

Thermoelectric Withdrawal and Consumption: Variation in thermoelectric power production and mix of power plant fuel type across the four study cases result in differences in thermoelectric water demands. Figure 7 gives the projected changes in water withdrawal and consumption relative to the 2010 levels of 1911 and 386 MGD (estimated from available EIA and USGS data, as discussed in the Methods Section, and adjusted for 2010 production rates), respectively. Highest withdrawal and consumption are associated with the High Demand study case while the lowest demands are associated with the High DSM case, the highest and lowest power production cases respectively. In terms of withdrawal the High Demand case results in an increase of 192 MGD or 10% increase over 2010 levels, while withdrawals for the High DSM case decrease by 291 MGD, a 15% reduction (this reduction is due to decreased production at existing power plants many of which utilize open loop cooling). Consumption on the other hand increases in all four cases with a high of 111 MGD (28% increase over 2010) for the High Demand case and a low of 40 MGD (10% increase over 2010) for the High DSM case.

The water withdrawal and consumption calculations above require some assumptions about the cooling type employed in the newly constructed power plants. Plants utilizing open loop cooling tend to withdraw large quantities of water but consume relatively little, while closed loop systems withdraw considerably less water but consume most of that withdrawn (see Appendix A). For purposes of this study it has been assumed new construction will not utilize open loop cooling. This assumption is made in the face of proposed regulation prohibiting open-loop cooling (CWA S316)[1]. Cooling type selection between closed-loop tower, closed-loop pond and dry cooling is distributed according to the current mix employed in the U.S. The result of these assumptions is that new withdrawals are of very similar magnitude to consumption. Another result is that the thermoelectric withdrawal intensity (defined as the ratio of total gallons of freshwater withdrawn for thermoelectric power production to KWh of power produced) decreases while the thermoelectric consumption intensity (similarly defined as above but using consumption instead of withdrawal) increases (Figure 8). This simply reflects the water withdrawal/consumption intensity of closed loop cooling systems relative to that of the aggregate fleet (which includes some open loop cooling with high water withdrawal and low consumption). There is relatively little difference in intensity across the four study cases.

Differences in water demand across the four study cases are the result of two separate factors, that due to new power plant construction and that due to changes in operations at existing plants.

[1] Most new power plant construction favors closed-loop cooling systems. This proposed regulation is likely to seriously limit any consideration of use of open loop cooing systems in new construction. Additionally, there are very few freshwater sources in the western U.S. capable of supporting open loop cooling. All these reasons combined are expected to discourage construction of open loop cooling systems. However, this assumption can easily be changed in the model.

As noted above, construction and operation of the new power plant fleet is quite consistent across the four study cases and so too are the associated new water withdrawals and consumption. Withdrawals associated with new plant construction are limited to a range of 108 MGD to 87 MGD, while consumption varies between 100 MGD to 83 MGD (across the four study cases). In contrast changes in withdrawal across all existing power plants range from an increase of 86 MGD to a decrease of 374 MGD, while consumption varies between an increase of 11 MGD to a decrease of 43 MGD. Thus, the apparent differences between the four study cases are due largely to changes in operations at existing plants.

The manner with which water withdrawal and consumption for new construction is distributed by fuel type is given in Figure 6. It is noted that water withdrawal and consumption are similarly distributed by fuel type. Comparing new power production with new water withdrawal/consumption indicates a distinct difference in water use across the different fuel types (also see Appendix A). Specifically, NGCC has lower water withdrawal and consumption requirements relative to that for either coal-steam, geothermal or solar CSP (e.g., NGCC has the largest new power production; however, coal-steam, geothermal and solar CSP all have greater water demands).

Of particular interest is where these new water demands for thermoelectric production are located. Figure 9 shows the water consumption for new power plants constructed between 2010 and 2020 for the TEPPC Base Case. As noted above there is very little difference between the four study cases and hence maps for these other study cases are not given. Likewise withdrawals are essentially the same as that given for consumption and hence results are not duplicated here. From the map of water consumption it is evident that new thermoelectric power production is not uniformly distributed over the west. Rather, production tends to be concentrated in southern California, western Arizona and southern Nevada. Demands are also focused in a couple of watersheds in the Great Plains. These demands are particularly important as they represent new demands which must be satisfied with existing and limited water resources.

Future thermoelectric demands are also influenced by changes in production at existing plants. Figure 10 shows total thermoelectric water consumption by 6-digit watershed for the four study cases. As noted previously, most of the differences evident in these maps are due to changes in production at existing plants. Reduced production and thus demand at an existing plant represents an opportunity to transfer the un-needed water to a new use, namely a new thermoelectric power plant. Although careful inspection is required to see differences such trends are evident along the southern coast of California, the Central Valley of California and around southern Nevada.

For completeness, Figure 11 shows 2020 withdrawals of saline water for thermoelectric cooling. A total of 5600 MGD of saline water is withdrawn and 12 MGD are consumed. Much of the coastal saline water use is associated with open loop cooling and thus the reason for the relatively high withdrawals. In this phase of analysis, no new use of saline water use for thermoelectric production has been projected; however, this is an option we will be considering in detail as this project progresses.

Competing Demands: New water demands in the thermoelectric power sector will have to compete with rapid growth in the municipal and industrial sectors. Between 2010 and 2020 municipal and industrial withdrawals are projected to increase by 837 MGD and 154 MGD while consumptive use is expected to see a rise of 364 MGD and 43 MGD, respectively. Figure 7 compares the projected growth between thermoelectric, municipal and industrial sectors. In rough terms growth in the thermoelectric sector (all study cases) is comparable to the growth projected for all other industrial needs and is about 25% of the growth projected for the municipal sector. Little to no growth is projected for the agricultural, livestock and mining sectors as economic expansion in these sectors has largely been offset by improvements in water use efficiency over the last 40 years.

An important aspect of this growth is that it will largely be focused around the large urban centers in the West. Figure 12 shows where new demands for non-thermoelectric water (municipal and industrial) consumption are likely to be concentrated. Significant growth is found along the west coast, southern Arizona, southern Nevada, and the front range in Utah and Colorado.   This growth in non-thermoelectric demand in many cases overlaps projected new demands for thermoelectric power production (Figure 12). Competing demands are particularly evident along the California coast, southern California and southern Nevada.

Thermoelectric Development in Regions with Limited Water Availability: Of particular interest to this study is where current and projected thermoelectric power production is likely to be impacted by water availability. As a first step in this endeavor the three water availability metrics (surface water, low flow, and groundwater) shown in Figure 5 have been updated to reflect water usage in 2020. Comparison of the 2010 (Figure 5) and 2020 water stress maps show almost no difference. This should come as little surprise as the increase in consumptive use over this time is only on the order of 1% (see above). This increase in consumption is generally small relative to the absolute water supply, particularly in the less water stress prone watersheds. Given the small differences between 2010 and 2020 the 2020 maps are not presented here.

The next step involves distinguishing the water source for new thermoelectric withdrawals and consumption. As noted above, for the current analysis we have assumed a potable water source will be pursued either surface water or groundwater; however, the analysis will be broadened to non-potable sources in the next phase of analysis. The future source distribution for new thermoelectric power plants is simply assumed to follow the current groundwater to surface water distribution by 6-digit HUC watershed.

The final step to identify at risk plants involves mapping new consumption by thermoelectric cooling (TEPPC Base Case) onto watersheds in basins with limited water availability; that is, those watersheds where the supply to demand ratio is below two (i.e., watersheds marked white in Figure 5). Specifically, Figure 13 shows projected future water consumption by thermoelectric power production to be met by a surface water source and which corresponds to a watershed with limited surface water availability. This map shows where it will be unusually difficult or expensive to obtain a surface water right/permit for a new thermoelectric power plant. Table 2 indicates that a total of 56.6 MMWh of new electric power production is needed in basins prone to limited surface water availability. Water consumption of 74 MGD is associated with this at risk power production.

Figure 13 also displays the projected future thermoelectric water consumption (2010-2020 for TEPPC Base Case) to be served by a groundwater source that corresponds to a watershed with limited groundwater availability (Figure 5). This map shows where it will likely be difficult to site a power plant due to limited groundwater availability. Table 2 indicates that a total of 0.38 MMWh of new thermoelectric power production is projected for basins with limited groundwater availability. The corresponding water consumption is 0.8 MGD. In total, 57 MMWh out of 74 MMWh of total future projected thermoelectric power production is from basins with limited surface or groundwater availability; that is, 77% of all future thermoelectric production.

Finally, Figure 13 shows current and projected thermoelectric water consumption (TEPPC Base Case) served by a surface water source and that corresponds to a watershed with limited low flow water availability (Figure 5). This map shows where both current and future power plants are likely to face challenges due to low flow induced water shortages. Table 2 indicates that a total of 1569 MWh/day (the amount of power potentially lost on a low water day) of electric power production out of the 1944 MWh/day (81%) of current and projected production lies within basins prone to drought stress. Corresponding water consumption for plants subject to water shortage is 433 MGD.

Table 2: Power plant siting at risk from water stress.

	Surface Water Stress		**Groundwater Stress**		**Low Flow Stress**	
	MGD	MMWh	MGD	MMWh	MGD	MWh/day
PC0	74	56.6	0.8	0.38	433	1569
PC1	71.1	52.1	0.7	0.38	419	1468
PC2	73.6	61.1	0.68	0.40	444	1646
PC3	60	41	0.67	0.37	382	1247

Table 2 also provides water at risk of surface water, groundwater and low flow availability for the other three study cases. As discussed previously, there is relatively little difference in the newly constructed power plant fleet (built between 2010 and 2020) across the four study cases. This similarity is reflected in the consistency in values between the four study cases. The largest differences are seen for the High DSM case, which experiences the lowest at risk water and power. Given the consistency of values across the study cases, individual maps for the other three study cases are not given.

Energy-Water Nexus Strategies: The results above provide a good "first look" at what the future water demands for thermoelectric power production might look like. These data also give some insight into how potential conflict around the energy-water nexus might be eased. In comparing the four study cases, it is very evident that reduced energy demand through conservation (e.g., the High DSM case) has a significant impact on the future demand for water. Although more difficult to see in the data is that changes in the mix of power plant fuel type also influence the amount of water withdrawn and consumed (see Figures 2 and 6).

There are several ways that planners could further use this data to reduce impacts on water resources and thus ease conflict around siting of future power plants. One option involves coordinating the retirement (or substantial reduction in operation) of a power plant with the siting of another. That is coordinate these actions so that the water rights associated with the retired plant could be transferred to the new plant. In this way no "new" demand for water would be realized.

Figure 13 can be viewed as a priority list for new power plant construction where alternative sources of water might be considered (i.e., new plants sited in basins with limited water availability). One option would be to consider use of dry or hybrid cooling at some of these power plants. Of course such decision must also consider factors such as cost, availability of land, and operational efficiency of the plants (loss of power production during hot periods). Plants sited in basins with limited water availability might also consider use of a non-freshwater source, such as brackish, saline, municipal waste water or produced water. Figure 11 shows were saline water is currently being used by the electric power industry. Characterization of these non-potable sources of water will be a focus of future phases of analysis.

If air cooling or non-potable water sources are not an option there are a few of other solutions. First, considerations of changing the plant fuel type to a lower water use or non-thermoelectric type could be made. Second, the plant could be moved to another basin where competition for water is less acute. Finally, the plant could look to retire water from a low value use and transfer it to thermoelectric production.

In the next phase of analysis these tradeoffs will be integrated directly into the 20-year transmission planning process as an objective or constraint on the multi-criteria optimization problem.

4. Next Steps

The study results reported above are based on the EPWSIM model and associated data. This model was developed under the auspices of other project funding. While EPWSIM provides valuable insights to the energy-water nexus, it is limited in many ways. For this reason significant efforts associated with the Energy and Water in the Western and Texas Interconnections Project are aimed at upgrading and expanding this model and associated data. Below a brief overview of planned changes to the model and database are given.

Thermoelectric Water Use Calculator: Initial estimates of water withdrawals and consumption at existing and future power plants have been provided in the results section. These results are based on information from a wide variety of sources including EIA and the USGS. There are significant limitations associated with each of these data sources, many of which the EIA and USGS are working to correct. As such, efforts are being made to improve on the current data toward estimating water use at a unit level basis. Key features to the analysis is to improve on existing information on unit type details, associated cooling technology, and source of water (surface water, groundwater, municipal supplied, municipal waste water, saline, or brackish).

Efforts will likewise be made to acquire operational water use data from the current fleet of power plants. This analysis will also provide insight into drought related impacts on water use (e.g., effects of humidity and temperature). Other issues to be considered include potential impacts due to new policies on open-loop cooling and/or carbon emissions.

Other Water for Energy Requirements: Significant future water use may be required in the extraction and processing of primary energy fuel sources. These include traditional sources such as coal, natural gas, uranium, oil, as well as liquid fuels for transportation. Our analysis will also look at potential trends in non-traditional sources such as biofuels, oil shales, and gas shales. These efforts will work to characterize the likely extent of water withdrawals and consumption for both extraction of these fuels and their processing. Where these demands for water will be located is also be a key feature of our analysis. A variety of future scenarios will be developed to address potential evolutionary paths that these traditional and non-traditional fuels may take.

Water Supply/Demand/Institutional Controls: Future water demands for energy development need to be put in the broader context of competition with other water use sectors as well as the future availability of water. An initial analysis has been provided above; however, significant opportunities have been identified toward its improvement. Specific improvements include the need to utilize state water planning data as the basis for projecting future demands and supply; the need to characterize institutional controls (e.g., water rights, compacts) that regulate access to physical water; and, expanding and vetting the metrics utilized in assessing water availability.

The project team will work directly with state water managers to acquire, integrate and vet regional water use and supply data into the energy-water decision support system. This effort will utilize information from regional water planning as the basis of the analysis. These plans generally include information on current water use and projected water use (high and low cases). These plans also include information on current water supply and any planned projects to augment supply (e.g., reservoir, interbasin transfers, desalination projects). This analysis will also address non-fresh sources such as municipal wastewater, brackish water, saline water, and produced water.

Just because water is physically available in a basin does not mean that it is available for use. Interstate/international compacts and water rights further regulate how much water can be used in a basin and for what use. The project team will work with state water managers to model the institutional controls on water within their state. Key information needs include river compacts and treaties, unappropriated water, agricultural water rights, adjudication status, status of Indian water rights, location of special administrative areas, and special regulatory policies.

Ultimately all of this water related information will need to be distilled down to a few key metrics, similar to those given in Figure 5. Ultimately these metrics will be designed to indicate where development of water for thermoelectric water use would be most welcome. This development potential must distinguish between surface water, groundwater and the various non-potable water supplies. Such maps of water availability have significant implications for water management within a given state. For this reason, water managers will need to be intimately involved in deciding how to craft appropriate metrics and approve their final form.

Drought Vulnerability: Water supplies limited by drought pose a threat to power production at existing and future thermoelectric power plants. A limited analysis of this effect is given in by current and future plants located in basins subject to low flow water stress. Drought will also impact production at hydroelectric power facilities. Recently a study has been completed to review pertinent literature on drought and its impact on western water supply. This information was combined with available power plant drought contingency plan information to assess regional vulnerability to drought. This was done for both hydroelectric and thermoelectric facilities. Results are currently being reviewed to determine whether a more detailed analysis on a plant by plant basis is warranted.

Transmission Planning Integration: Another key improvement over this analysis will be the integration of water data directly into the transmission planning process. Specifically, water related data will be used to set objectives and/or constraints in WECC's multi-criteria optimization process that will be used to maximize the placement of future power and transmission expansion projects. This will allow iteration on the transmission process so as to achieve a future that minimizes impact on regional water resources balanced with other key considerations such as cost, reliability, and transmission/operational efficiency.

5. Summary

This analysis supports WECC's 10-year planning study by investigating the water implications of four alternative study cases: TEPPC Base Case, SPSC Reference Case, High Demand Case and the High DSM Case. This initial study utilized analysis tools and data (e.g., the Energy, Water and Power Simulation model, see description below) that are in the development stage. Over the next two years of this project significant improvements are scheduled for both the model and the data that drives the model. As such the results given above should be viewed as preliminary. However, these results should assist in:

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

Four key findings from this preliminary analysis have been identified, which include:

Conclusion 1: Thermoelectric generation has the potential to drive a significant increase in water consumption by 2020.

Conclusion 2: Water demands for thermoelectric use are relatively small in relation to water demands for agriculture; however, thermoelectric demands are growing while agriculture has remained steady over the past 40 years.

Conclusion 3: 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.

Conclusion 4: The study cases do perform differently with respect to water withdrawal and consumption suggesting the opportunity to engineer solutions to the water and energy nexus in the West.

The study results reported above are based on the EPWSIM model and associated data. While EPWSIM provides valuable insights to the energy-water nexus, it is limited in many ways. For this reason significant efforts associated with the Energy and Water in the Western and Texas Interconnections Project are aimed at upgrading and expanding this model and associated data. Planned additions include expanding the thermoelectric water use calculator; including water use for the extraction and refining of primary energy fuels; integration of state level data and engagement of state water managers in characterizing current and future water demands, water supplies, and institutional controls; assessment of power plant vulnerability to drought; and, integration of water data directly into long-term transmission planning.

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Appendix A: Water Withdrawal and Consumption and Parasitic Energy Factors

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Overview:

This document contains initial water withdrawal/consumption factors and parasitic energy use factors, developed for use in the Energy-Water Analysis for the Western and Texas Interconnects**.** Table 1 contains initial water consumption factors for renewable electricity technologies. Table 2 contains initial water consumption factors for non-renewable electricity technologies. Table 3 contains initial water withdrawal factors for non-renewable electricity technologies. Renewable water withdrawal factors are assumed to equal water consumption factors. Table 4 contains parasitic loss factors for different types of cooling systems.

Methods:

We consider water withdrawals and consumption for the operational phase only. Operational water use in this study includes cleaning, cooling, and other process-related needs that occur during electricity generation, such as flue gas desulfurization (FGD) in coal facilities. The energy technologies addressed here consist of configurations of coal, natural gas, nuclear, geothermal, biopower, wind, solar photovoltaic (PV), and concentrating solar power (CSP) technologies. Cooling system technologies considered include wet recirculating technologies (cooling towers), once-through cooling system (open loop cooling), air-cooled condensing (dry cooling), hybrid wet and dry cooling systems (hybrid cooling), and pond cooling systems.

Estimates of water consumption and withdrawal have been calculated irrespective of geographic location. Withdrawal and consumption factors are often reported in terms of water intensity that are annual averages; water intensity of facilities may change from diurnal and seasonal variations in temperatures and humidity levels, but these inter-annual variations are not examined. This review did not alter (except for unit conversion) or audit for accuracy the estimates of water use published in studies. Also, because estimates are used as published, considerable methodological inconsistency is inherent which limits comparability. Additionally, no distinction is made between water types, which may include freshwater, saline water, or municipal waste water. Data sources include published academic literature, state and Federal government agency reports, non-governmental organizations' (NGO) reports, and industry submissions to government agencies for permitting procedures.

Certain sources report ranges of water consumption and withdrawal factors in place of specific values. If traceable individual case studies form the basis for the range given, the individual values are included as independent estimates within the set of estimates that are statistically analyzed. If a range is given and the underlying data points are not given, then the midpoint of that range is used for calculating an average value, and the high and low extremes are used for determining extreme ranges. This method of addressing ranges may lead to a slight bias toward data sources reporting explicit cases, and may also underestimate actual water use at facilities, as the midpoint of the range extremes are in general less than values reported from individual facilities.

Linking to WECC Fuel Type Designations:

The table below provides more detailed information than is currently designated in the WECC PROMOD database. This particularly applies to new power plants where water withdrawal and consumption are based on the water use factors (and not on historic demands). Below we note the associations we used between the WECC fuel type designations and the fuel type water use factors utilized.

WECC Designator	Water Use Factor from Table Below
Biomass	Steam
Cogeneration	No Water Use
Combined Cycle	Natural Gas Combined Cycle
Combustion Turbine	No Water Use
Geothermal	Average of All Technologies
Internal Combustion	No Water Use
Nuclear	Generic
Solar-CSP	Average of Trough and Power Tower
Steam-Coal	Generic
Steam-Other	Natural Gas Steam

Cooling technology is defined according to the study case assumptions.

Table 1. Water consumption factors for renewable technologies[2] (Gal/MWh)									
Plant Type	**Cooling**	**Technology**	**Primary factor**	**Low**	**High**	**Min**	**Max**	**n**	**Sources**
PV	N/A	Utility Scale PV	16	0	32	0	33	3	11,18,20
Wind	N/A	Wind Turbine	0	0	1	0	1	2	1,12
CSP	Tower	Trough	896	796	995	725	1109	17	5,11,14,16,18,27,28,30-35
		Power Tower	793	738	847	751	912	4	18,27,28,31
	Dry	Trough	73	61	84	43	79	10	14,32-34
		Power Tower	26	26	26	26	26	1	3
	Hybrid	Trough	263	126	399	117	397	3	6,32
		Power Tower	170	57	283	102	302	2	6
	N/A	Stirling	5	4	5	4	6	2	4,18
		Fresnel	1000	1000	1000	1000	1000	1	6
Biopower	Tower	Steam	638	412	863	480	965	4	4,8,9
		Biogas	235	235	235	235	235	1	19
	Once-through	Steam	300	300	300	300	300	1	8
	Pond	Steam	390	390	390	390	390	1	8
	Dry	Biogas	35	35	35	35	35	1	9
Geothermal	Tower	Dry Steam-(freshwater)	0	0	0	0	0	1	11
		Dry Steam-(geothermal fluid)	1796	1796	1796	1796	1796	1	11
		Flash-(freshwater)	12	2	22	5	19	2	4,17
		Flash-(geothermal fluid)	2583	1853	3314	2067	3100	2	17
		Binary	3088	1872	4303	1700	3963	3	11,15
		EGS	4272	3057	5488	2885	5147	4	9,11,15
	Dry	Flash	0	0	0	0	0	1	9
		Binary	0	0	0	0	0	1	9
		EGS	1185	1185	1185	1185	1185	1	9
	Hybrid	Binary	221	221	221	221	221	1	15
		EGS	1406	1406	1406	1406	1406	2	9,15

[2] Primary factors represent simple averages, whereas low and high values represent averages minus and plus one standard deviation, respectively.

Table 2. Water consumption factors for conventional technologies[3] (Gal/MWh)									
Plant Type	**Cooling**	**Technology**	**Primary Factor**	**Low**	**High**	**Min**	**Max**	**n**	**Sources**
Nuclear	Tower	Generic	684	542	825	581	845	5	8,11,26,29
	Once-through	Generic	212	49	376	100	400	3	8,21,26
	Pond	Generic	560	560	560	560	560	1	8
Natural Gas	Tower	Combined Cycle	227	159	296	130	300	5	8,18,24-26
		Steam	853	639	1068	662	1170	4	4,11,22,29
		Combined Cycle with CCS	487	487	487	487	487	1	23
	Once-through	Combined Cycle	73	27	120	20	100	3	8,22,26
		Steam	240	169	311	95	291	2	4,11
	Pond	Combined Cycle	240	240	240	240	240	1	26
	Dry	Combined Cycle	2	0	5	0	4	2	8,26
	Inlet	Steam	340	340	340	340	340	1	4
Coal	Tower	Generic	702	423	981	480	1100	5	7,8,20,21,36
		Subcritical	519	398	640	394	678	6	23,24,26
		Supercritical	525	468	582	458	594	6	23,24,26
		IGCC	383	356	411	358	439	7	23,24
		Subcritical with CCS	1329	1329	1329	1329	1329	1	23
		Supercritical with CCS	1148	1148	1148	1148	1148	1	23
		IGCC with CCS	501	475	527	479	530	3	23
	Once-through	Generic	239	118	360	100	317	3	8,11,21
		Subcritical	107	73	141	71	138	3	26
		Supercritical	97	67	127	64	124	3	26
	Pond	Generic	390	390	390	390	390	1	8
		Subcritical	773	739	807	737	804	3	26
		Supercritical	37	6	67	4	64	3	26

[3] Primary factors represent simple averages, whereas low and high values represent averages minus and plus one standard deviation, respectively.

Table 3. Water withdrawal factors for conventional technologies[4] (Gal/MWh)									
Plant Type	**Cooling**	**Technology**	**Primary Factor**	**Low**	**High**	**Min**	**Max**	**n**	**Sources**
Nuclear	Tower	Generic	1026	919	1132	800	1101	2	8,26
	Once-through	Generic	40066	32418	47713	25000	60000	3	8,21,26
	Pond	Generic	800	800	800	500	1100	1	8
Natural Gas	Tower	Combined Cycle	210	157	263	150	250	3	8,26
		Steam	1203	1199	1206	950	1460	2	4,22
		Combined Cycle with CCS	N/A	N/A	N/A	N/A	N/A		
	Once-through	Combined Cycle	11380	8028	14732	7500	20000	2	8,26
		Steam	35000	35000	35000	10000	60000	1	4
	Pond	Combined Cycle	5950	5950	5950	5950	5950	1	26
	Dry	Combined Cycle	2	0	5	0	4	2	8,26
	Inlet	Steam	425	425	425	100	750	1	4
Coal	Tower	Generic	920	586	1254	500	1200	3	8,20,21
		Subcritical	500	472	528	463	531	4	26
		Supercritical	642	617	667	609	669	4	26
		IGCC	605	605	605	605	605	1	20
		Subcritical with CCS	N/A[5]	N/A	N/A	N/A	N/A		
		Supercritical with CCS	N/A	N/A	N/A	N/A	N/A		
		IGCC with CCS	1009	1009	1009	1009	1009	1	20
	Once-through	Generic	31102	21912	40292	20000	50000	3	8,12,21
		Subcritical	27082	27048	27116	27046	27113	3	26
		Supercritical	22584	22554	22614	22551	22611	3	26
	Pond	Generic	450	450	450	300	600	1	8
		Subcritical	17896	17862	17930	17859	17927	3	26
		Supercritical	15029	14998	15060	14996	15057	3	26

[4] Primary factors represent simple averages, whereas low and high values represent averages minus and plus one standard deviation, respectively.
[5] N/A: Data not available

Table 4. Parasitic energy factors		
Cooling System	**Parasitic energy factor**	**Source**
Once-through/Pond	1.0	
Recirculating (Nuclear)	.9908	USEPA (2009)
Recirculating (Fossil)	.9927	USEPA (2009)
Recirculating (Combined Cycle)	.9976	USEPA (2009)
Hybrid	.99	Turchi *et al*. 2010
Dry	.965	Turchi *et al*. 2010

Sources:

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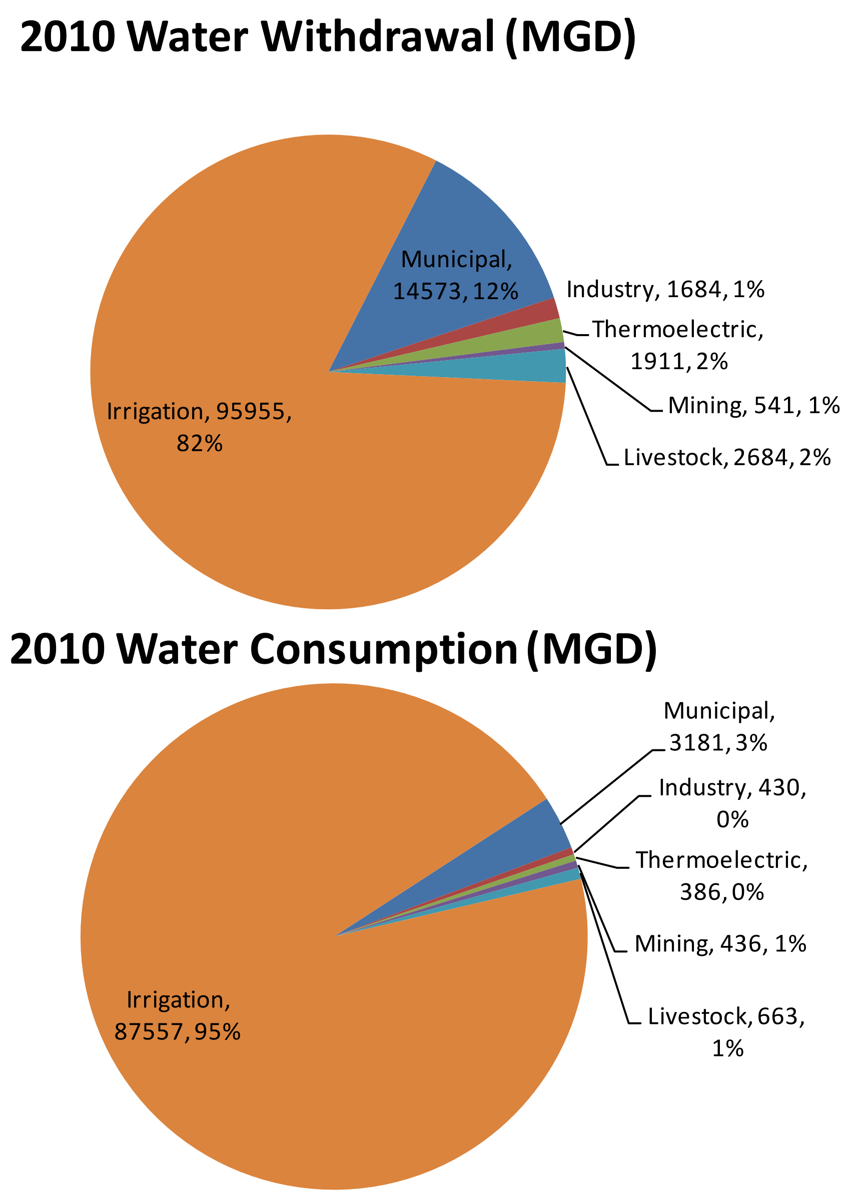


Figure 1: *Pie charts displaying water withdrawal (top) and water consumption (bottom) for the western interconnection in 2010 by use sector.*

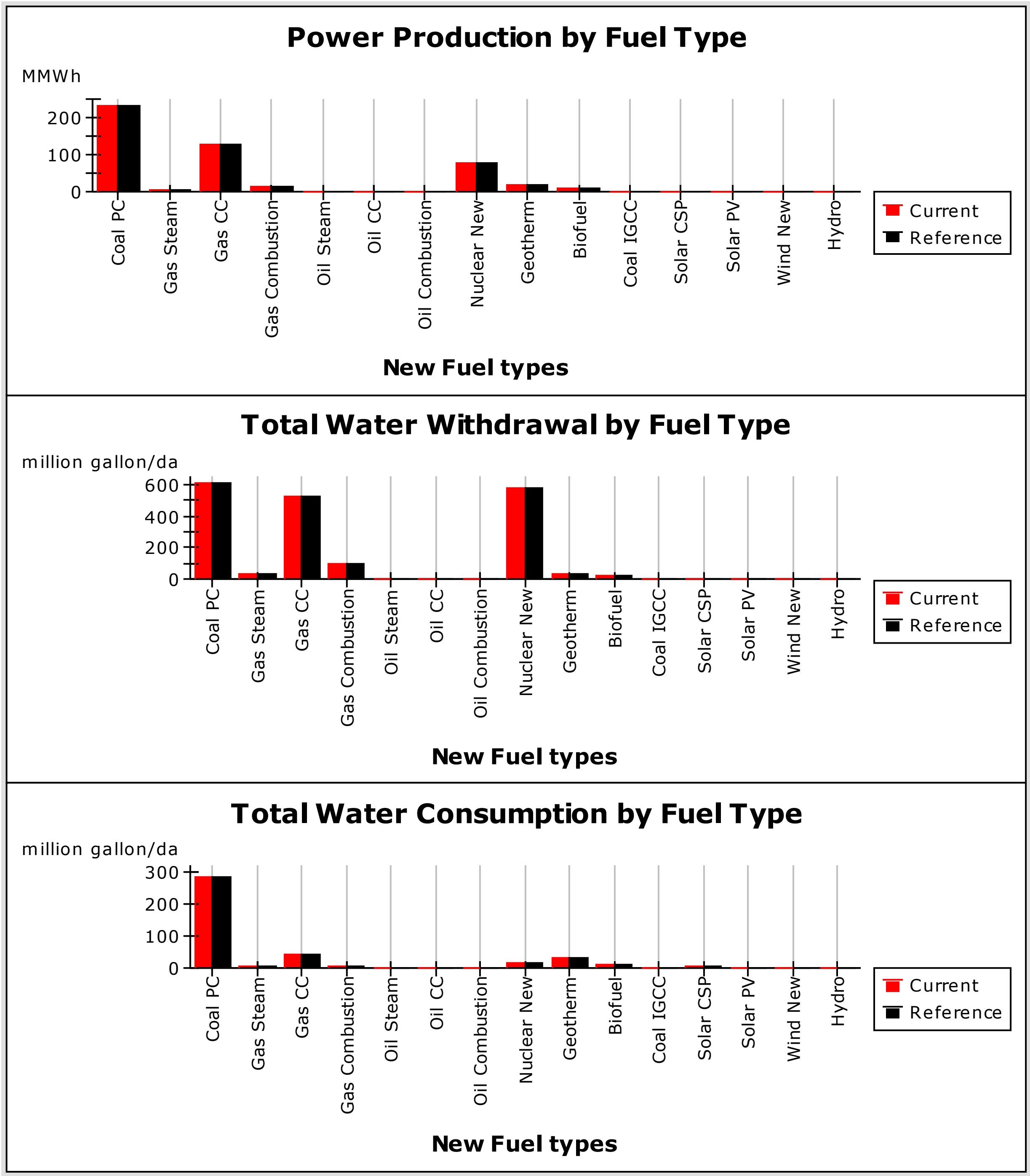


Figure 2: Thermoelectric power production (top), water withdrawal (middle) and water consumption (bottom) by power plant fuel type for WECC in 2010.

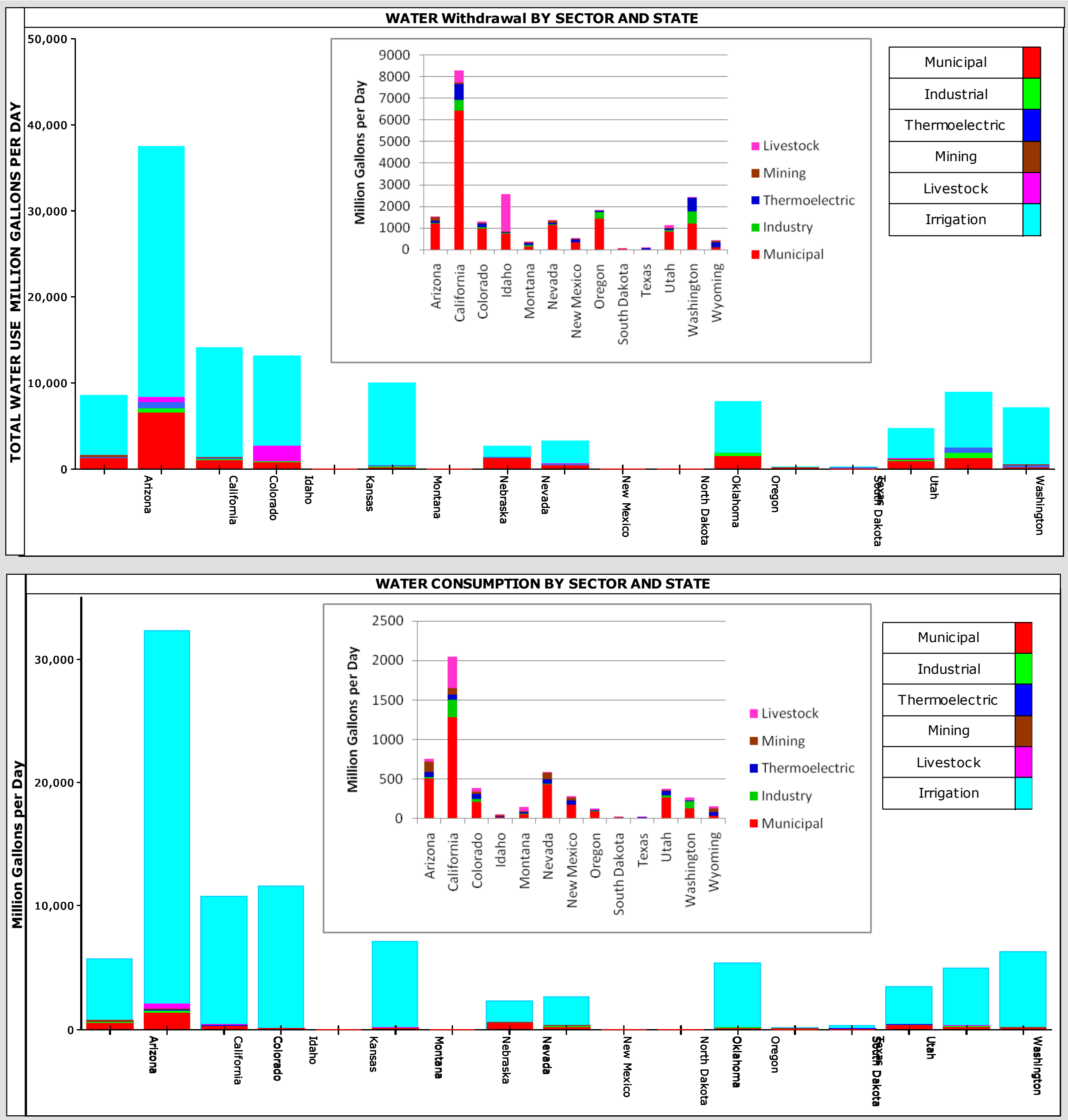


Figure 3: 2010 water withdrawal (top) and consumption (bottom) by state. For each state withdrawal/consumption by water sector is indicated as a stacked bar chart. The inset charts show water withdrawal and consumption by sector and state with irrigation removed to facilitate observation of other sector use.

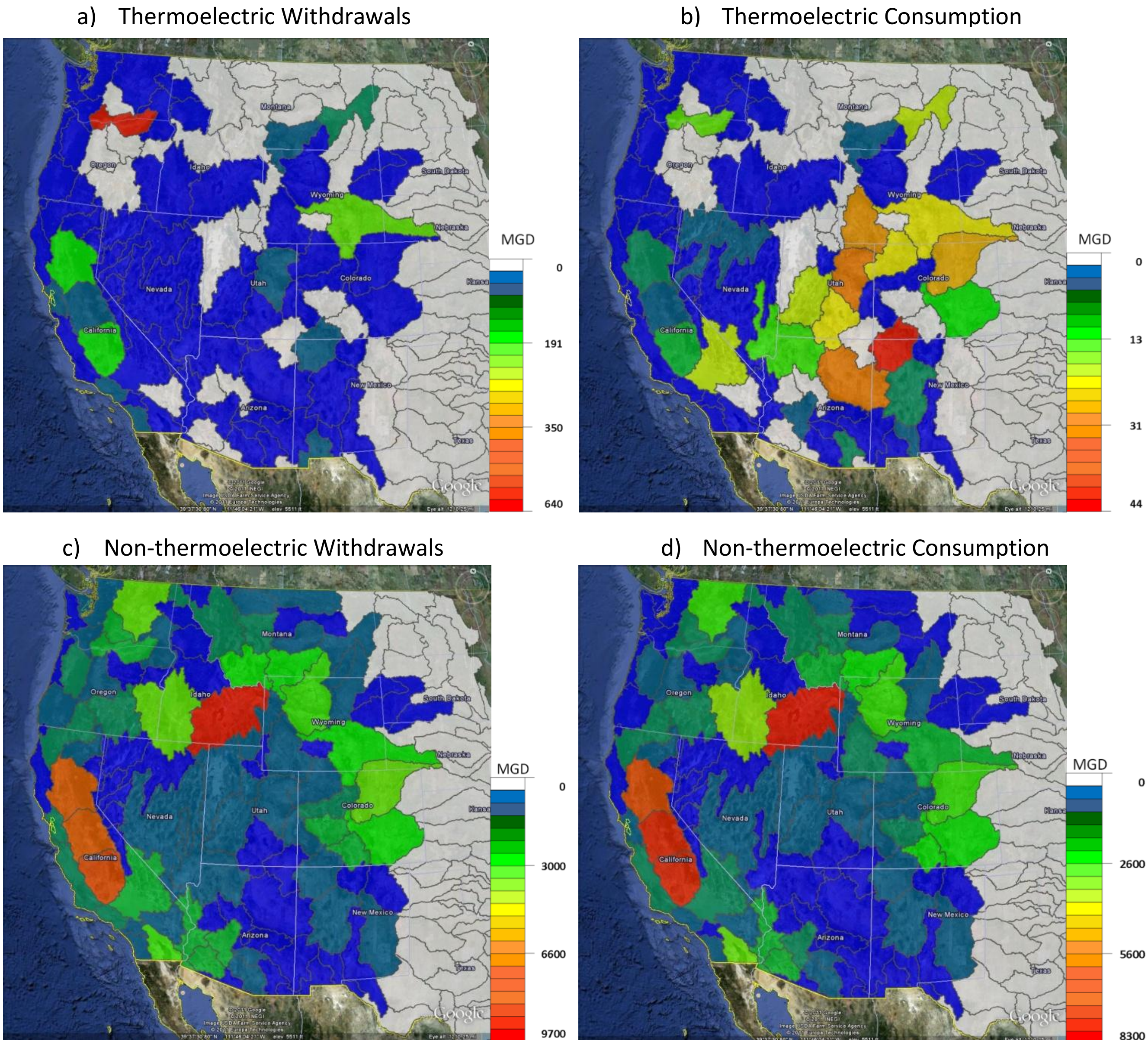


Figure 4: Thermoelectric withdrawal (a) and consumption (b) along with non-thermoelectric water withdrawal (c) and consumption (d) in the continental U.S. in 2010. Data are displayed at the 6-digit watershed level in units of million gallons per day (MGD).

a) Surface Water Availability Metric b) Low Flow Water Availability Metric

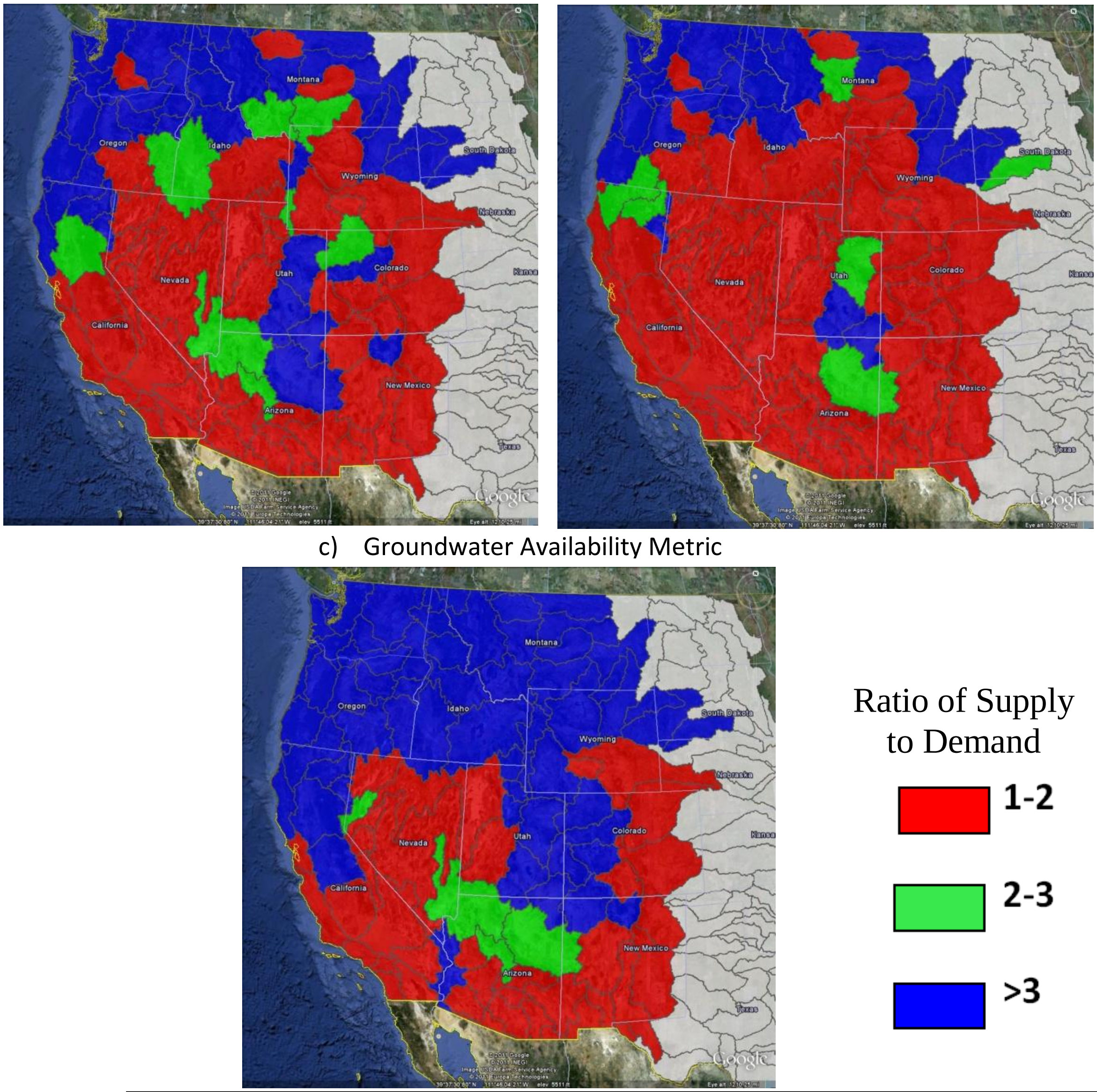


Figure 5: Maps showing potential water availability for surface water (a), low flow surface water (b), and groundwater (c) at the 6-digit HUC level for the western U.S. The map showing areas of potential limited surface water availability was constructed by taking the ratio of mean gauged stream flow for the watershed to the sum of consumptive water use in that watershed plus all upstream watersheds. The map showing areas of potential low flow water availability was constructed in the same manner except the 5th percentile flow (flow value realized during the driest 15 days of the year) was used instead of the mean gauged stream flow. The map showing potential limited groundwater availability was constructed by taking the ratio of gauged baseflow (measure of sustainable recharge) for the watershed to the groundwater pumping in the watershed.

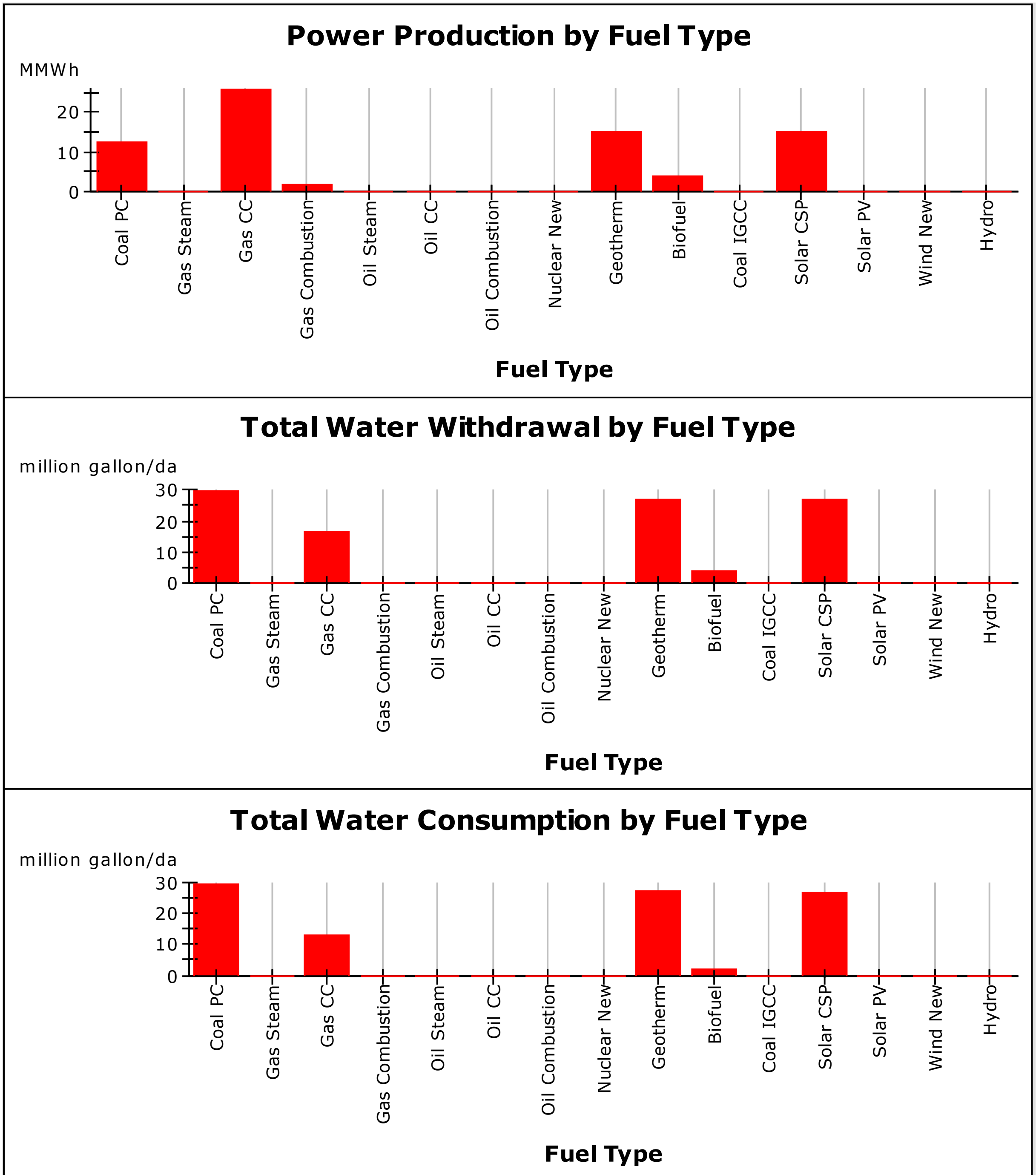
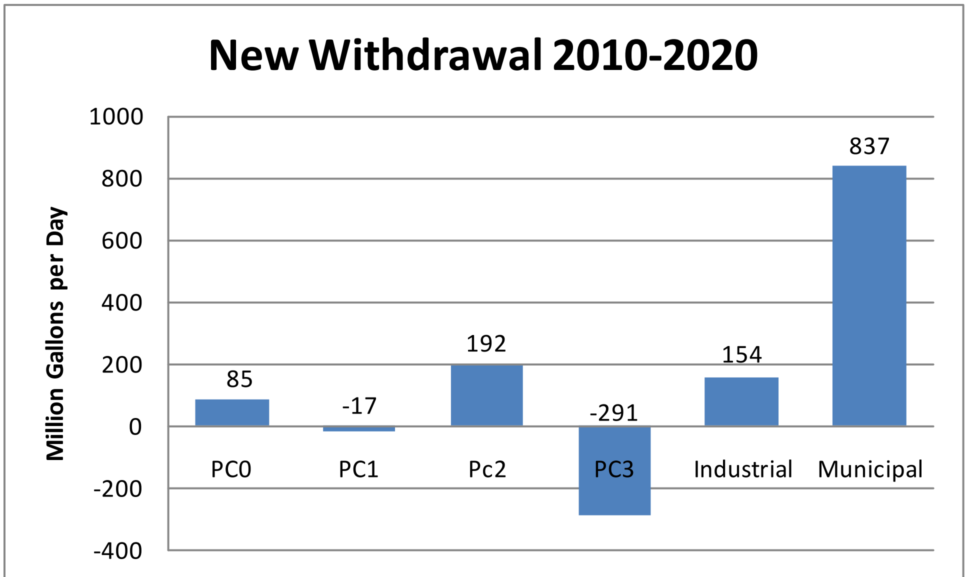


Figure 6: Thermoelectric power production (top), water withdrawal (middle) and water consumption (bottom) distributed by fuel type for new power plant construction from 2010-2020. Data presented here are for the TEPPC Base Case. The other three study cases have very similar results for proposed new power production and hence water demand.



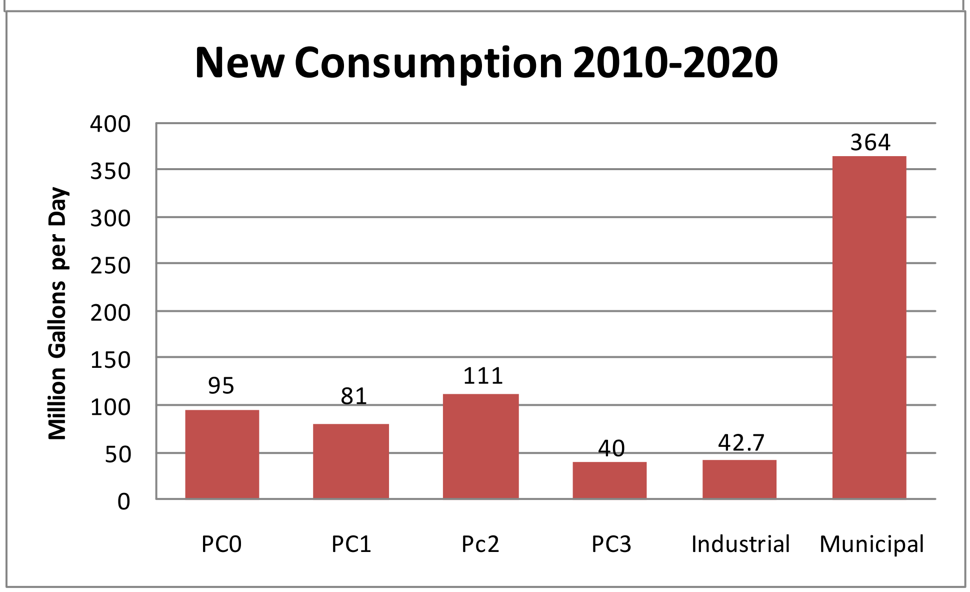


Figure 7: Change in thermoelectric water withdrawal (top) and thermoelectric water consumption (bottom) between 2010 and 2020. Comparison is drawn between the four WECC study cases. Also shown are the projected increases in municipal and industrial water withdrawal and consumption (other water use sectors are projected to have relatively little change over this time frame).

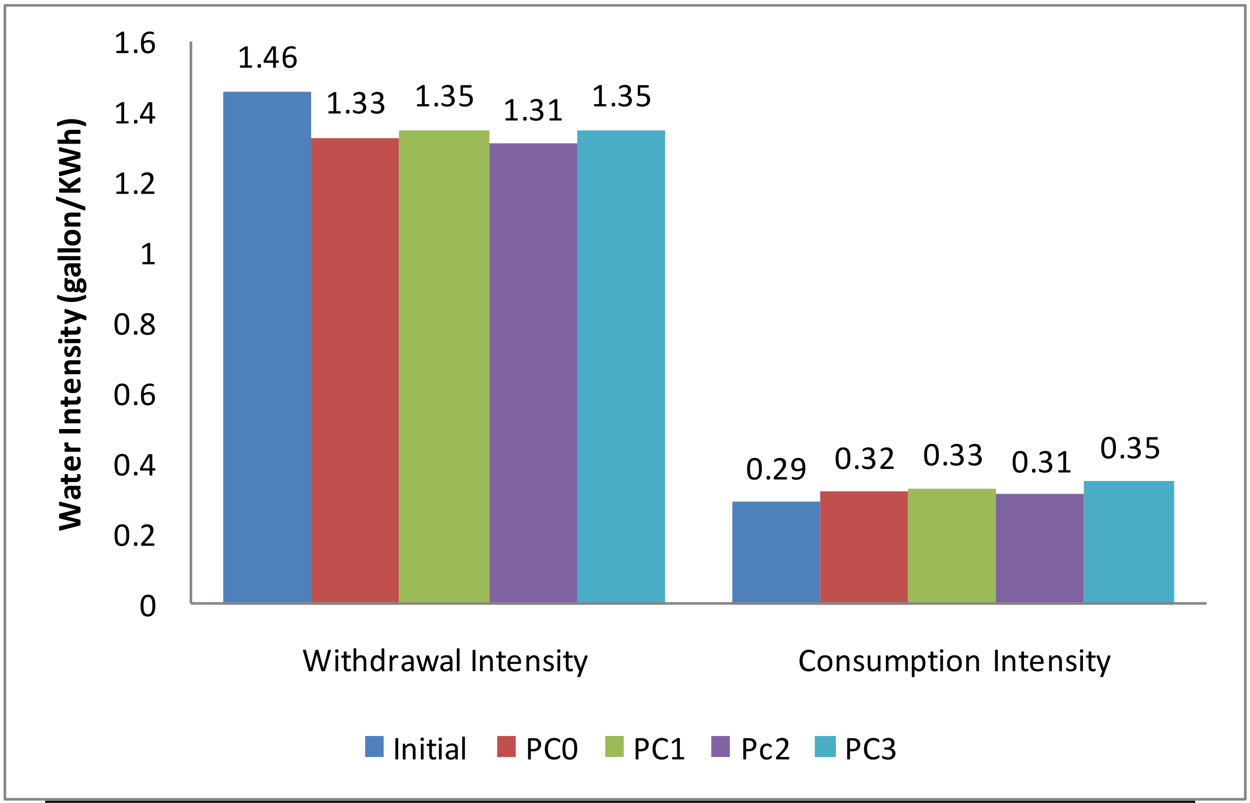


Figure 8: Thermoelectric water withdrawal and consumption intensity defined as the ratio of water withdrawal/consumption to total thermoelectric power production. Intensities are compared for the year 2010 (initial) to that in 2020 for the four WECC study cases.

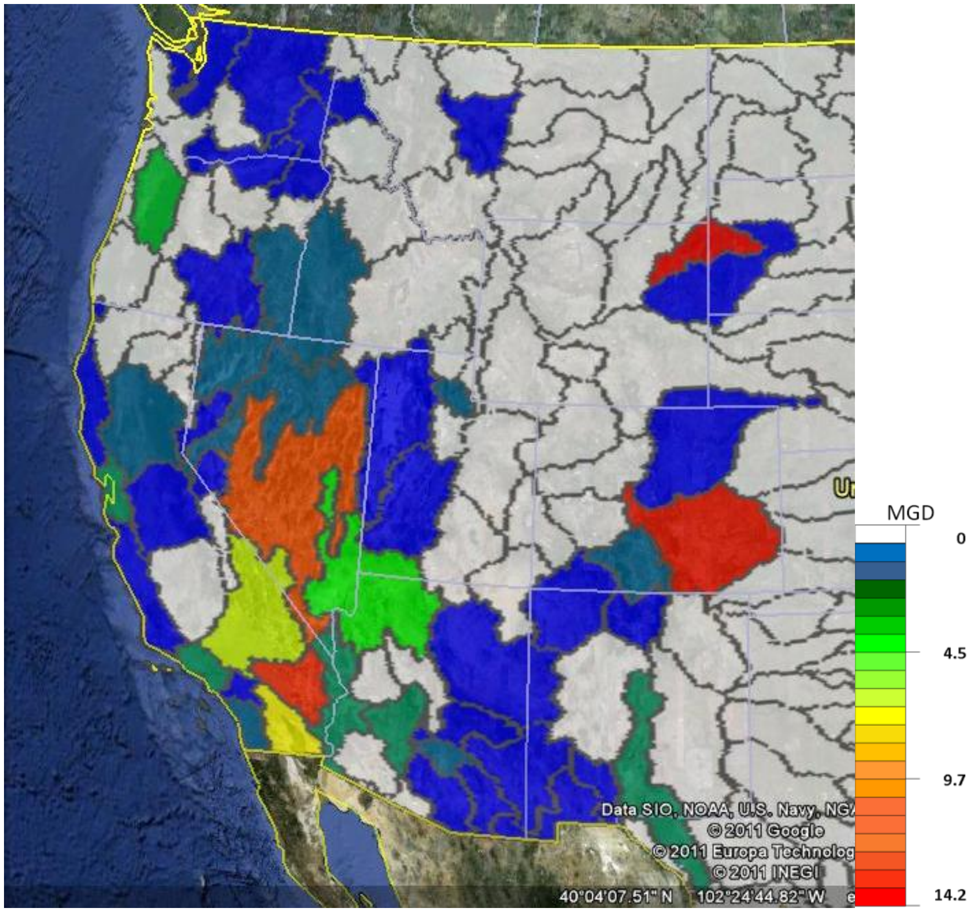


Figure 9: Water consumption for new thermoelectric power plants constructed between 2010 and 2020. Data presented here are for the TEPPC Base Case. New water consumption for the other three study cases is essentially the same as shown here.

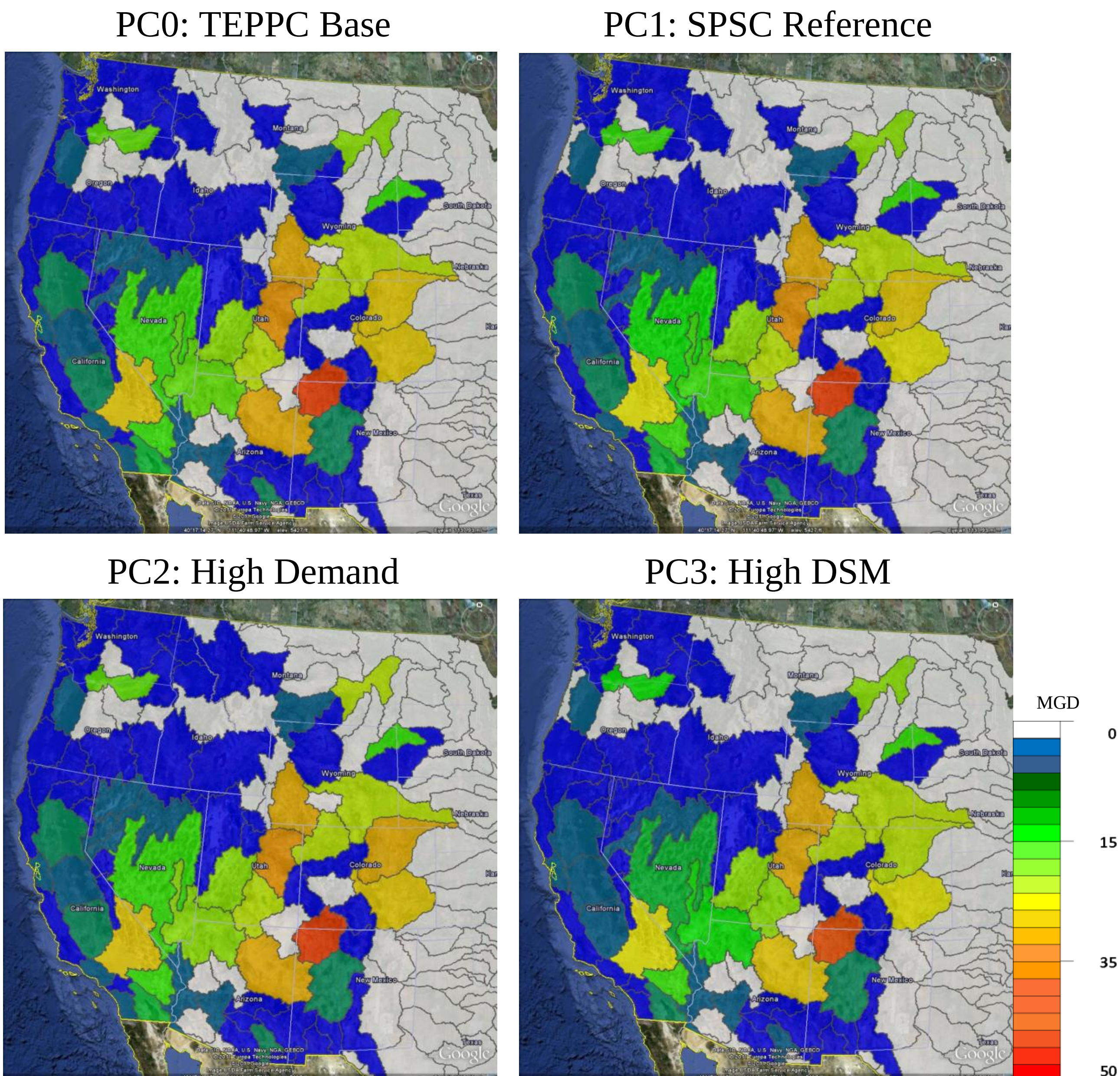


Figure 10: Total thermoelectric water consumption (new and existing power plant fleet) projected for the year 2020. Maps for all four study cases are given. Differences largely reflect changes to operations at existing power plants.

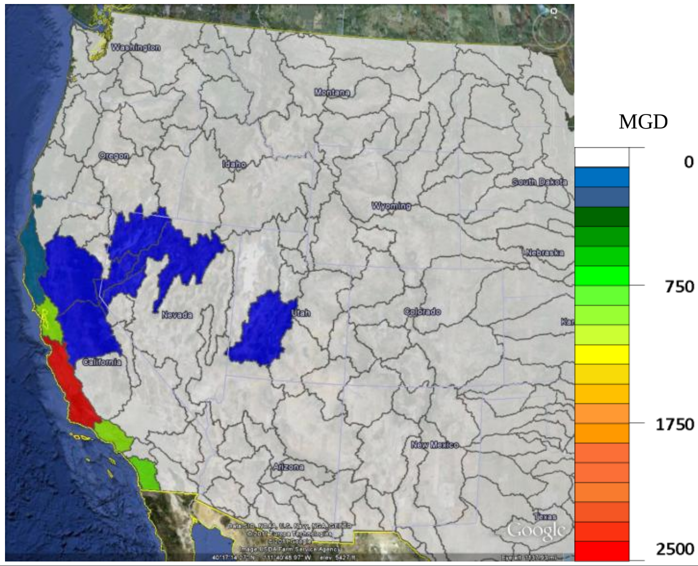


Figure 11: Saline water withdrawals for thermoelectric power production in 2010.

Non-Thermoelectric Consumption   Thermoelectric Consumption

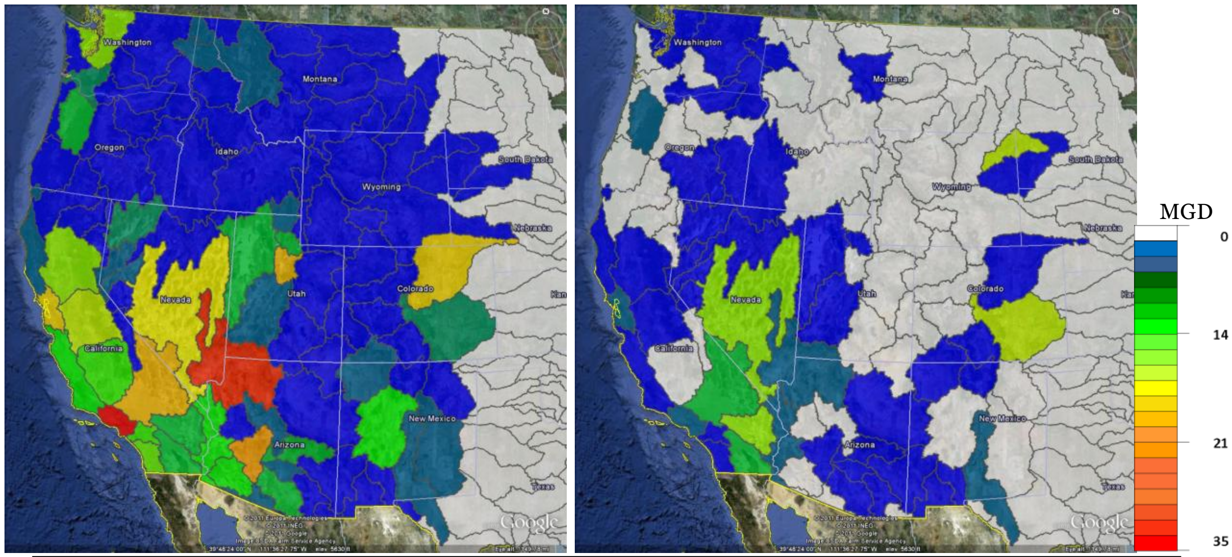
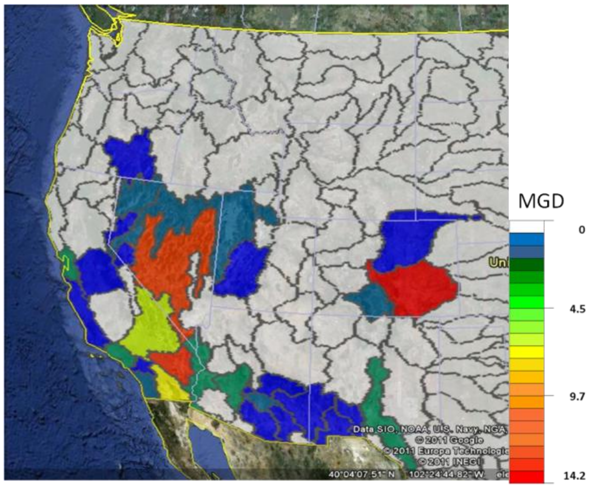
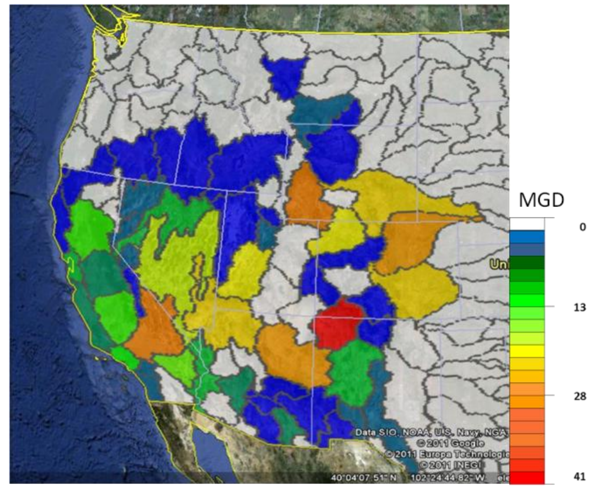


Figure 12: Projected growth in non-thermoelectric (left) and thermoelectric water consumption (right) from 2010 to 2020. Non-thermoelectric growth is largely the result of new municipal and industrial demands.

Plants at Risk by Surface Water Stress



Plants at Risk by Low Flow Stress



Plants at Risk by Groundwater Stress

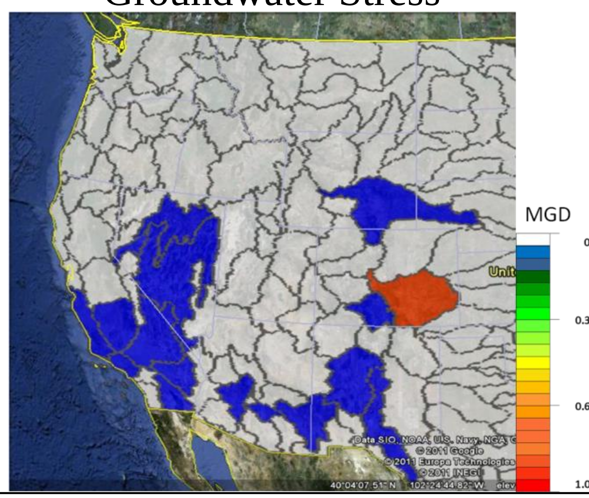


Figure 13: New thermoelectric water consumption projected for basins at risk of limited surface water availability (top left), low flow water availability (top right), and limited groundwater availability (bottom). Maps are constructed by identifying projected new thermoelectric consumption (Figure 9) located in basins with limited surface, low flow or groundwater availability (Figure 5). Data used here are for the TEPPC Base Case.

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