Modeling Water Withdrawal and Consumption for Electricity Generation in the United States

Kenneth Strzepek, Jonathan Baker, William Farmer
and C. Adam Schlosser

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Kenneth Strzepek*, Jonathan Baker†, William Farmer‡ and C. Adam Schlosser§

Abstract

Water withdrawals for thermoelectric cooling account for a significant portion of total water use in the United States. Any change in electrical energy generation policy and technologies has the potential to have a major impact on the management of local and regional water resources. In this report, a model of ***Wi****thdrawal and* ***C****onsumption for* ***T****hermo-electric* ***S****ystems (WiCTS) is formalized. This empirically-based framework employs specific water-use rates that are scaled according to energy production, and thus, WiTCS is able to estimate regional water withdrawals and consumption for any electricity generation portfolio. These terms are calculated based on water withdrawal and consumption data taken from the United States Geological Survey (USGS) inventories and a recent NREL report. To illustrate the model capabilities, we assess the impact of a high-penetration of renewable electricity-generation technologies on water withdrawals and consumption in the United States. These energy portfolio scenarios are taken from the Renewable Energy Futures (REF) calculations performed by The U.S. National Renewable Energy Laboratory (NREL) of the U.S. Department of Energy (DOE). Results of the model indicate that significant reductions in water use are achieved under the renewable technology portfolio. Further experiments illustrate additional capabilities of the model. We investigate the impacts of assuming geothermal and concentrated solar power technologies employing wet cooling systems versus dry as well as assuming all wet cooling technologies use closed cycle cooling technologies. Results indicate that water consumption and withdrawals increase under the first assumption, and that water consumption increases under the second assumption while water withdrawals decrease.*

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1. INTRODUCTION

The majority of electric power plants in the United States generate electricity by means of a steam generator[1]. After being used to drive the turbine, the steam must be condensed to liquid form and sent to a boiler, where it will again be turned in to steam to continue driving the turbines. This process of cooling the used steam is known as thermoelectric cooling (Torcellini, Long and Judkoff, 2003). Thermoelectric cooling systems typically make use of water from a nearby source, such as a lake or river. The water is diverted from the source and passed through a heat exchanger to condense the steam after it has been used to drive the turbine. The process of diverting water from a source is referred to as “withdrawal” which is distinct from consumption. Consumption refers to water that is lost to the water source/cooling system, primarily through evaporation. To speak generally of both withdrawal and consumption, this report uses the term “water use”.

The amount of water withdrawals required for thermoelectric cooling in the United States is substantial. The most recent United States Geological Survey (USGS) estimates that 49% of all water withdrawals in the United States were for thermoelectric cooling (Kenny *et al.*, 2009). As such, water use in the electric power industry has been the subject of some interest in the past.

The Electric Power Research Institute (EPRI) supported a study investigating current and future water consumption in thirteen regions in the United States (EPRI, 2002). The study forecasts fresh water consumption through 2020. Power generation forecasts are based on EPRI’s “Energy-Environment Policy Integration and Coordination” Study and the DOE Energy Information Administration (EIA) *Annual Energy Outlook 2000*. The EPRI study provides estimates of typical water withdrawal and/or consumption rates per unit power for various power

[1] A steam generator uses steam to drive a turbine that in turn drives an electric generator to produce an alternating electric current.

generating technologies. In order to estimate water consumption, they estimate the percentage of these technologies in the thirteen geographic regions considered. The study reports water consumption for various technology portfolio assumptions (Water, 2002).

The National Renewable Energy Laboratory (NREL) also supported a study investigating water consumption in power plants (Torcellini, Long and Judkoff, 2003). The NREL study presents fresh water consumption per kWhr at the end user site for thermoelectric and hydroelectric power plants. The study also incorporates the water used to mine the fossil fuels used in the thermoelectric plants. The study presents water consumption rates at the national scale, within the Western Interconnect, Eastern Interconnect, and the Texas Interconnect, and by state. The analysis does not, however, make any distinction between any type of thermoelectric technology, simply considering consumption in the entire thermoelectric sector.

Dziegielewski *et al.* (2006) uses EIA data form 767, and results from questionnaires and several power plant site visits to develop an analysis of average water withdrawal and consumptive rates in fossil fuel and nuclear plants. The study presents average water withdrawal rates for various fossil fuel cooling systems. The study additionally presents benchmark withdrawal and consumptive rates for once through systems, recirculation systems (i.e. once through systems with a pond) and closed cycle systems for fossil fuel and nuclear power plants based on a weighted average and regression analysis approach. The study also investigates the technical efficiencies of the above technologies using a stochastic production frontier approach.

Feeley *et al.* (2008) discuss water withdrawals and consumption through 2030 for five cases of electricity generation development based on national average specific water withdrawal and consumption rates for various technologies and cooling system options. They also present water savings associated with various new technologies being investigated under National Energy Technology Laboratory's Innovation for Existing Plants Program for one of the electricity generation development cases, akin to this report's CCF Policy presented in section 4.3. Water impacts are assessed within the 13 North American Electric Reliability Corporation (NERC) regions based on the specific water use rates and projected electricity generation growth.

Roy *et al.* (2010) present freshwater withdrawal estimates in 2030 and 2050 due to growing withdrawals from the thermoelectric and municipal sectors (other sectors, such as agriculture, are assumed to remain constant at 2005 levels). To develop the growth estimate of thermoelectric water withdrawals, Roy *et al.* use the most recent USGS report of water use in the United States as the base withdrawals, a national withdrawal rate for all wet closed cycle cooling technologies developed from Feeley *et al.* and projections of electricity generation from EIA in NERC regions. Total withdrawal rates in 2030 and 2050 are then compared to estimated available precipitation with and without a consideration of potential changes in climate. Roy *et al.* also develop a water sustainability index to indicate regions' risk of water shortages. As it relates to the thermoelectric sector, though the resolution is at the county level, the study only focused on freshwater withdrawals. Consumption and a treatment of saline water are not considered.

In this report, we present an empirically based model that has been constructed to estimate the total withdrawal and consumption of various electricity generating technologies with regionally explicit detail. The model is then applied to a case study to quantify the water use impact of various future electricity growth and deployment scenarios, with an emphasis on renewable energy technologies as well as the choice of cooling technologies. The studies cited above all rely on (or seek to develop) technically specific national averages of water use rates. The one exception is the NREL study, which resolved thermoelectric consumption by state. However, the NREL study did not make any distinction between various cooling technologies used in the thermoelectric sector. This study attempts to describe water use rates at a more refined geographic scale and with some distinction between cooling technologies. This construction allows us to investigate regional effects that may become important in the future. The enhanced geographic resolution, however, comes at the expense of technological specificity. Any attempt to develop an "average" power plant's water usage rate on a relatively refined geographic level with currently available data would probably indicate a false precision. Without a complete power plant database, then, it seems there is a tradeoff between geographic resolution and technological specificity.

The remainder of this document is structured as follows. Section 2 provides a brief description of the various cooling technology options. Section 3 describes the water model and supporting data sources. Section 4 describes the various scenarios considered by the model and the exogenous power generation scenarios used by the water use model. Section 5 presents results and Section 6 concludes with a discussion of the implications of the results.

2. OVERVIEW OF COOLING TECHNOLOGIES

At the topmost level of classification, there are two types of thermal cooling technologies, wet and dry cooling, so called because wet cooling requires water use whereas dry cooling does not.

Among wet cooling technologies, by far the most common thermal cooling option, there are two types, once-through systems and closed cycle systems, which are sometimes referred to as recirculation systems. Torcellini, Long and Judkoff (2003) provide a nice overview of the basic mechanisms of once-through cooling systems, closed cycle systems and dry cooling systems. Following is a list of common thermal cooling system options:

1. Wet-Cooling
    - Once-Through
    - Closed Cycle
        i. Cooling pond option
        ii. Cooling tower option
2. Dry-Cooling

Thermal Electric or Steam-driven electric turbines require the steam to be condensed to liquid after passing through the turbine. Depending on the efficiency of the steam-boiler the amount of heat that must be dissipated per unit energy generated is constant. The heat generated in the cooling of the steam in transferred via a heat exchanger to the cooling system. The cooling system must dissipate this heat to the atmosphere. The heat is dissipated via three thermodynamic processes: 1) sensible heat loss 2) latent heat loss and 3) radiative heat loss. The four cooling systems described above (once-through, closed cycle with cooling ponds, closed cycled with cooling towers and dry cooling) are dominated by one of these three heat loss processes. For a summary of withdrawal and consumptive use for the various types of cooling systems, refer to Table ES-1 in Dziegielewski *et al.* (2006).

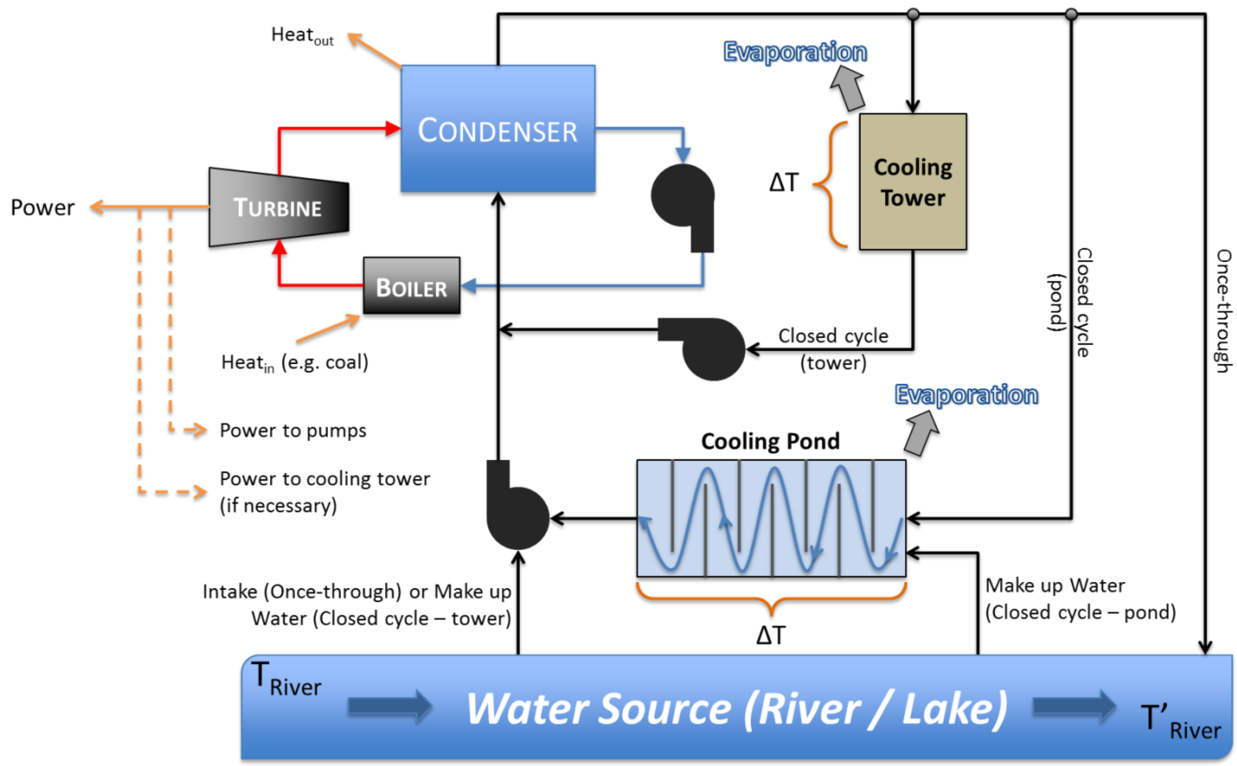

Figure 1. Illustration of power plant cooling system options.

Referring to **Figure 1**, once-through cooling systems withdraw water from the water source, send the water through a heat exchanger and then discharge the now heated cooling water directly back into the water source where significant mixing takes place. The primary heat loss processes are radiative heat loss and sensible heat loss with some evaporative losses. Once-through cooling has a very low consumption to withdrawal ratio (1% to 3%) and has relatively less consumption per energy generated than closed cycle systems using cooling towers or ponds. Once-through cooling is relatively inexpensive (compared to systems described below with cooling towers and/or ponds) however; discharging heated water directly into the river may violate environmental standards. In addition, water pumping costs are relatively high with respect to closed cycle systems since none of the water is recycled back through the cooling system.

Closed cycle cooling systems use either a cooling tower or cooling pond. Cooling towers withdraw small volumes of water that is heated via a heat exchanger. This now heated water is discharged at the top of natural or mechanical draft towers. As the heated water falls through the draft, its heat is used to vaporize a portion of the falling water. Thus, any water that reaches the bottom of the tower has lost heat primarily by evaporation but also marginally via sensible and radiative heat losses. A large percentage, 60% to 75%, of the withdrawn water is lost in the form of vapor out of the tower. This consumptive loss represents a larger consumptive loss per unit energy generated than when compared to consumptive loss per unit energy generated in once-through systems (Dziegielewski *et al.*, 2006). The lost water is replaced by make-up withdrawals from a local water source. Since, however, less water is withdrawn in these systems compared to once-through systems (Dziegielewski *et al.*, 2006), costs associated with water withdrawals (pumping and if applicable raw water costs) are lower. However, using a closed cycle system reduces the efficiency of the power plant due to the higher temperature of the recirculating cooling water compared to the temperature of the cooling water withdrawn directly from the water source in once-through systems.

As mentioned above, the two common types of cooling towers are natural-draft and mechanical-draft. Natural-draft cooling towers have a hyperbolic shape which naturally induces flow of air through the tower. No electricity is needed to operate one of these towers. However, they generally need to be very tall and large, requiring extra land compared to mechanical draft cooling towers. Mechanical-draft cooling towers are much smaller units that use electrical fans to pump air through the towers. These cooling towers require power to run the fans and pumps, thus reducing the efficiency of the power plant, but do not require very much land. Mechanical-draft cooling towers are currently the most common cooling tower used for water cooling.

A second option for closed cycle systems is to use cooling ponds in place of towers. Cooling ponds look like once-through cooling systems to the power plant but the heated water is discharged to a large shallow pond where the water is either cooled enough to be discharged to a receiving water body or cooled additionally to be recycled without discharge. Cooling ponds use all three types of heat loss with the significance of latent heat of evaporation being between once-through systems and closed cycle cooling towers. In closed cycle cooling ponds more heat is lost to evaporation and thus consumption per unit energy generated is higher than consumption per unit energy generated associated with once-through systems whereas consumption per unit energy generated is approximately equal or lower (depending on the fuel source) than consumption per unit energy generated associated with cooling towers (Dziegielewski *et al.*, 2006). One advantage of a cooling pond is that it does not require any electricity to operate. However, a substantial amount of land is required for a cooling pond—often hundreds of acres.

It is unlikely that a plant would have a cooling pond as well as cooling towers. Some plants, however, use a combination of once-through and closed cycle cooling systems depending on the season. The data, described in Section 3.3, underlying our water model allows us to implicitly include all wet cooling options. It does not, however, allow us to explicitly model such hybrid plants.

The last type of cooling system, dry-cooling, uses only air to cool the condenser—there is no water consumption. In this system large volumes of air are blown over a heat exchanger and the heat is lost by sensible heat without evaporation. Due to the energy required to run the fans, power plant generation efficiency and revenue are reduced compared to the other systems mentioned above. However, in arid regions where water is very expensive, dry-cooling is becoming increasingly popular.

To summarize, each of the cooling-system designs considered in this study has distinct water use characteristics in achieving the same goal. Once through cooling withdraws large volumes of water (from a river or lake typically) that are then discharged directly to large water bodies (or the same river or lake from which it was withdrawn). Heat is then dissipated by mixing with cooler water and other non-evaporative processes. Closed cycle systems (cooling towers and cooling ponds) dissipate heat primarily via evaporation. The closed cycle systems withdraw significantly less water that once through but consume over 60% of these withdrawals to provide evaporative cooling while once-through consumes between 1% and 3% of associated withdrawals (Solley *et al.*, 1998). As such, closed cycle systems consume more water per unit energy generated but once-through systems withdraw many times the volume of closed cycle systems (Dziegielewski *et al.*, 2006). Dry cooling consumes no water but requires fans to blow large volumes of air over a heat exchanger.

In this report, electricity generation technologies are distinguished by their use of cooling technologies; *wet*, *dry* or *non-thermal*. A coal plant, for example, would be classified a *wet* electricity generation technology[3], whereas a wind turbine would be classified as a *non-thermal* electricity generation technology since it does not employ any thermal cooling technology[4].

[3] A coal plant could be classified a *dry* cooling technology, but as stated before, the majority of power plants with thermal cooling systems are wet cooled.

[4] In fact, non-thermal electricity generation technologies do not employ any kind of cooling technology.

3. WATER MODEL DESCRIPTION

The Withdrawal and Consumption for Thermo-electric Systems model, or WiCTS, estimates water withdrawals and consumption for wet, dry and non-thermal cooling technologies. In calculating the withdrawal and consumption totals, WiCTS considers water withdrawals and consumption for each power technology. WiCTS is developed in the GAMS programming language.

3.1 Estimating Water Withdrawals

WiCTS calculates fresh and saline water withdrawals and consumption for four categories of water type/wet cooling technology combinations, shown in **Table 1**, plus water withdrawals and consumption for six non-thermal/dry cooling technologies, shown in **Table 2**.

Table 1. Water type – wet cooling technology combinations.

Name	Description
OTF	Fresh water used in once-through cooling technology
OTS	Saline water used in once-through cooling technology
CCF	Fresh water used in closed cycle cooling technology
CCS	Saline water used in closed cycle cooling technology

Table 2. Non-thermal/dry technologies considered by WiCTS.

Name	Description
geo	Geothermal – dry cooled
CSP	Concentrated Solar Power (both variable and no storage)—dry cooled
DPV	Distributed Photovoltaic
UPV	Utility Scale Photovoltaic
Wons	Onshore Wind
Woffs	Offshore Wind

3.1.1 Estimating Water Withdrawals for Wet Cooling Technologies

WiCTS takes as exogenous forcing electricity generation forecasts in Energy Generating Regions (EGR) for any electricity generation scenario. In each ERG, we use the USGS water withdrawal data to develop a water withdrawal per power generated ratio, henceforth called specific water withdrawal coefficient, for the categories listed in Table 1. Section 3.3.1 describes the USGS data in more detail.

Under this current construct, WiCTS assumes that the distribution of water source and cooling technology remains constant over time, and thus the specific water withdrawal coefficient is time invariant. Further developments to the model framework, however, will allow for time-varying coefficients. Using this static coefficient, the water withdrawals in any EGR for a given power generation (estimated by any electricity generation model) can be calculated. The principle underlying the method is described by Eq. 1 below:

$$WW_i(EGR) = \frac{WW_i^{USGS}(EGR)}{P_{tot}^{USGS}(EGR)} \times P_{wet}^{scen}(EGR) \tag{1}$$

where $WW_i(EGR)$ refers to the model estimated water withdrawals in Mega gallons per day for the i^{th} water type – cooling technology combination shown in Table 1 in a given EGR, $WW_i^{USGS}(EGR)$ refers to the 2005 USGS estimate of water withdrawals in Mega gallons per day for the i^{th} water type – cooling technology combination in a given EGR, $P_{tot}^{USGS}(EGR)$ refers to the USGS reported total power generated in a given EGR in 2005 (USGS, 2005), and $P_{wet}^{scen}(EGR)$ is the electricity scenario determined power generation for all technologies using wet cooling systems in a given EGR. Note that the specific water withdrawal coefficient is defined by the fraction in Eq. 1. Regional plots of these coefficients for each water type *i* are presented in APPENDIX A.

For investigating the impacts of certain policies, Eq. 1 requires additional specificity of technologies. Thus, the specific water withdrawal coefficient is separated into a power generation coefficient and specific water withdrawal by power type coefficient shown in Eq. 2. The method for estimating water withdrawals, therefore, is described below in Eq. 2, which the reader will note reduces to Eq. 1 above:

$$WW_i(EGR) = \frac{P_i^{USGS}(EGR)}{P_{tot}^{USGS}(EGR)} \times \frac{WW_i^{USGS}(EGR)}{P_i^{USGS}(EGR)} \times P_i^{scen}(EGR) \tag{2}$$

where $P_i^{USGS}(EGR)$ refers to the power generated for the i^{th} water type – cooling technology combination. One limitation to the method described in Eq. 2 is that $P_i^{USGS}(EGR)$ is not directly reported by the USGS data. USGS reports total power generated using either once-through or closed cycle cooling technology, and overall total power generated. We calculate $P_i^{USGS}(EGR)$ by multiplying the power generated using a given cooling technology by the ratio of the specific water type withdrawal to the total water withdrawals for the respective cooling technology. This method is illustrated in Eq. 3a for *i* = OTF and Eq. 3b for *i* = CCS:

$$P_{\mathrm{OTF}}^{\mathrm{USGS}}(ECR) = P_{\mathrm{OT\text{-}tot}}^{\mathrm{USGS}}(ECR) \times \frac{WW_{\mathrm{OTF}}^{\mathrm{USGS}}(ECR)}{WW_{\mathrm{OT\text{-}tot}}^{\mathrm{USGS}}(ECR)} \tag{3a}$$

$$P_{\mathrm{CCS}}^{\mathrm{USGS}}(ECR) = P_{\mathrm{CC\text{-}tot}}^{\mathrm{USGS}}(ECR) \times \frac{WW_{\mathrm{CCS}}^{\mathrm{USGS}}(ECR)}{WW_{\mathrm{CC\text{-}tot}}^{\mathrm{USGS}}(ECR)} \tag{3b}$$

where the subscripts OT-tot and CC-tot refer to the total quantity (either power or water withdrawal) associated with once-through or closed cycle cooling technology respectively.

Substituting the relationship in Eq. 3 into Eq. 2, the reader will note that for a given cooling technology, either once-through or closed cycle, the specific water withdrawal by power type ratio is equivalent regardless of whether the water is fresh or saline. The implicit assumption behind the model is, therefore, that fresh and saline water have the same heat capacity. This is, of course, not entirely accurate as ocean water has a salinity of about 3.5% and therefore a heat capacity of ~3.5% lower than that of pure water. However, as "fresh" water in rivers contains a small amount of salt and other deposits, the bias that this assumption introduces is small.

The two ratios in Eq. 2, the power generation coefficient and specific water withdrawal by power type coefficient, are generated as separate components and used as input coefficients to the main component of WiCTS that applies Eq. 2. In this way, the coefficients generated using the USGS data can then be adjusted to describe certain policies or to correct for outliers. More detail concerning the coefficients can be found in APPENDIX B.

3.1.2 Estimating Water Withdrawals for Non-thermal/Dry Cooling Technologies

A similar method is used for calculating water withdrawals associated with non-thermal and dry cooling technologies. For each technology *j*, listed in Table 2, water withdrawals are calculated as follows:

$$WW_j(ECR) = OU_j \times P_j^{\mathrm{scen}}(ECR) \tag{4}$$

where OU_j is analogous to the specific water withdrawal coefficient and refers to the operational water use coefficient developed by Macknick (2010) and discussed in more detail in section 3.3.2.

3.2 Estimating Water Consumption

For wet cooling technologies, in principle, water consumption varies seasonally and geographically. For the purposes of this study, we have used fixed consumptive factors; 2% for once-through cooling technologies (E. Adams 2010, pers. comm., 26 August) and 60% for closed cycle cooling technologies (Solley, Pierce and Perlman, 1998). The fixed consumptive factors are applied to the majority of EGR regions. There are, however, regions where the fixed consumptive factor produced water consumption that exceeded reasonable values. A more comprehensive discussion regarding this topic is presented in APPENDIX C.

For non-thermal/dry cooling technologies, we assume that water withdrawals equal consumption. This is on account of the fact that the water diverted to wind turbines, for example, is likely from municipal sources. Any water then used to clean the blades would then be fully consumed. Thus, Eq. 4 describes the method for estimated withdrawals and consumption for non-thermal and dry cooling technologies. Additionally, we assume any water supplied by municipal sources is fresh, and therefore all water withdrawals for non-thermal and dry technologies are fresh water.

3.3 Data Sources

3.3.1 USGS Water Use Data

The USGS reports national water withdrawals used for thermoelectric cooling in 2005 at the county level by type (fresh or saline), source (surface or ground), and cooling technology (once-through or closed cycle) (Kenny *et al.*, 2009). We use this data to develop the specific water withdrawal coefficients considered for the categories listed in Table 1. In this study, we do not explicitly track the storage depletion of the water source (whether groundwater or surface flow) as it is withdrawn and/or consumed, and therefore we assume through our use of the specific water withdrawal coefficients that an ample supply of water is maintained. A more comprehensive model framework (Strzepek *et al.*, 2010), which also considers the effects of climate variation and potential climate change, has recently been developed to analyze these supply and demand relationships, and will be the subject of future work.

The USGS also reports power generation data by county associated with once-through and closed cycle cooling technologies (i.e. wet cooling technologies). Total power generated by county is also reported. A comparison between USGS electricity generation data and EIA electricity generation data showed close agreement. For a further discussion regarding this comparison, refer to APPENDIX D.

Three issues should be highlighted regarding the USGS water withdrawal data. First, the data are estimates of water *withdrawals*, which is distinct from water *consumption*. As discussed above, consumption refers to water that is lost from the system (typically through evaporation). Water withdrawals refer to water removed from its original location, such as a lake or river. Typically the water withdrawn is returned to the source. Second, the USGS water withdrawal estimates only estimate water withdrawals for electricity generating technologies classified as wet (i.e. thermoelectric power plants requiring water for cooling); any water required by wind farms, for example, is excluded (Kenny *et al.*, 2009). Third, among electricity generating technologies classified as wet, the USGS data only distinguishes between once-through cooling technology and recirculation cooling technology. No distinction is made for the fuel source of the plant (e.g., no distinction is made between a coal plant and a nuclear plant using once-through cooling).[5]

3.3.2 Operational Water Use for Non-thermal/Dry Cooling Technologies

Many non-thermal renewable electricity generation technologies do not require water for cooling but do require water for operation. For example, solar-thermal requires cleaning water for periodic cleaning of the mirrors. Macknick (2010) has compiled a set of water use coefficients estimating a national average operational water consumption per given unit of power generation for concentrated solar power, or CSP, wind, photovoltaic (PV), nuclear, natural gas, and coal. Nuclear, natural gas, and coal primarily use wet cooling systems, and as such, water withdrawals and consumption are estimated with greater regional accuracy using the method developed from the USGS data described by Eq. 2. The operational water use coefficients are valuable, however, in that they provide a means by which to estimate the water required by non-thermal and dry cooling technologies which allow us to quantitatively compare the water requirements of these technologies to the water requirements of the more water intensive wet cooling technologies.

Table 3 presents the operational water use coefficients corresponding to those technologies listed in Table 2. These coefficients become the OU_j in Eq. 4. Note that due to our assumption that withdrawals equal consumption for non-thermal and dry cooling technologies, using these

[5] In principle, different power generation technologies will have different water consumption per power generated requirements. See Macknick (2010) and Water (2002) for further discussion.

coefficients in Eq. 4 is appropriate for the calculation of both withdrawals and consumption, despite the fact that the coefficients represent consumption. To develop a sense for how these numbers compare to wet cooling systems, Macknick reports that the average coal plant in the US will consume 427 gal/MWhr[6], or nearly an order of magnitude larger.

Table 3. Operational water use coefficients (source: Macknick, 2010).

Technology	Operational water use coefficient	Unit
geo	81.4	[Gal/MWhr]
CSP	81.4	[Gal/MWhr]
DPV	29.8	[Gal/MWhr]
UPV	29.8	[Gal/MWhr]
Wons	0.6	[Gal/MWhr]
Woffs	0.6	[Gal/MWhr]

Macknick (2010) does not provide any operational water consumption coefficients for geothermal technology which is assumed to use dry cooling technology. We assume that similar dry cooling technology is employed for CSP and geothermal and consequentially equate the operational water consumption for geothermal technology to that of CSP. Macknick (2010) also does not distinguish between onshore and offshore wind power. In this study, we assume that both onshore and offshore wind power have the same operational water use coefficient. We further assume that the EGR assigned to the offshore wind generation will have to supply any water required by the offshore wind power. These assumptions allow us to analyze the amount of water required by offshore wind, rather than simply assuming it to be zero.

4. A CASE STUDY OF RENEWABLE ELECTRICITY FUTURES

As an application of WiCTS, we draw from a broader study of renewable electricity futures, the Renewable Electricity Futures Study (REFS), conducted by NREL for the DOE. The REFS scenarios provide projections of the deployment of future electricity generation technologies using the Regional Energy Deployment System (ReEDS) model (Short *et al.*, 2009). From these projections, we also consider two additional scenarios as sensitivity studies to the underlying assumptions of the REFS projections.

[6] Then, assuming that this represents 2% of total water withdrawals, a coal plant would withdraw on the order of 21,000 gal/MWhr.

4.1 The ReEDS Model and Scenarios

The Regional Energy Deployment System (ReEDS) model, developed by NREL, is a cost optimization model that forecasts electricity generation capacity and actual generation for a suite of technologies, shown in Table 3, in 134 geographic regions called Power Control Authority (PCA) regions, illustrated in **Figure 2** (Short *et al.*, 2009). The technologies considered by ReEDS represent both renewable and non-renewable technologies.

For the purpose of investigating water use associated with these electricity generating technologies, we classify ReEDS power generating technologies as wet, dry or non-thermal. The classification of cooling technologies is shown in Table 3. As has been discussed in Section 3.3.2, dry and non-thermal technologies are considered to require some water for cleaning and general operation. In the REFS scenarios, geothermal technology and CSP technologies are assumed to be dry.

The ReEDS model also includes hydroelectric generation. As discussed in Torcellini, Long and Judkoff (2003), there is, in principle, water consumption associated with hydroelectric power generation due to enhanced evaporation from the increased lake area created by the dam. Unlike Torcellini, Long and Judkoff (2003), we do not consider hydroelectric power generation in our estimates of water consumption for two reasons. First, all new hydroelectric power plants in the ReEDS model are assumed to be in-stream, and thus no new dams are required. Therefore, there will be no increase in water surface area and no increase in water consumption due the increase in hydroelectric power generation. Second, in this study, we are concerned with the *change* in water use due to future electricity generation portfolios. Since all new hydroelectric power plants consume no additional water, the amount of water consumed due to current hydroelectric power plants is not a concern for the purposes of this study. For an estimate on water consumption due to hydroelectric power plants, refer to Torcellini, Long and Judkoff (2003).

Figure 2. Illustration of the 134 PCA regions considered by the ReEDS model.

There are four primary scenarios considered in this report: the *Low-Demand Baseline*, *Core 80% REF*, *High-Demand Baseline*, and *High-Demand 80% REF*. There is also a *2006* scenario which represents the current power generation scenario[7]. In this report, these scenarios are referred to as the reference scenarios (abbreviated RFNC) to distinguish them from the alternative scenarios described in section 4.2 and 4.3.

The two Baseline scenarios represent an efficient demand but do not necessarily move towards renewable technologies. The Baseline scenarios are not, strictly speaking, business as usual. One could think of the Baseline scenarios as best case scenarios or an optimistic business as usual. The two 80% REF scenarios represent technology portfolios where 80% of the electricity demand is met by renewable technologies. The low demand and core scenarios are based on a low demand assumption for electricity. The two high demand scenarios are based on a high demand assumption for electricity. Using these scenarios as the driving P^{scen} of Eq. 2 and Eq. 4, we use the WiCTS model described above to estimate water withdrawals and consumption in each PCA (which becomes the ERG of Eq. 2 and Eq. 4) for the *2006* scenario and for the *Low-*

[7] 2006 is the base year in the ReEDS model, and in this sense 2006 represents the base year. The base year is taken to be the power generation portfolio in 2006 from the *Low-Demand Baseline* scenario.

Demand Baseline, *Core 80% REF*, *High-Demand Baseline*, and *High-Demand 80% REF* in the year 2050.

Table 4. ReEDS Generation Technologies.[8]

Name	Description	Cooling Classification
	Non-renewable Technologies	
Gas-CC	Gas turbine combined cycle	Wet
CoalOldScr	Pre-1995 coal plants equipped with an SO_2 scrubber	Wet
CoalOldUns	Pre-1995 coal plants without an SO2 scrubber	Wet
Coal-new	Non-IGCC plants built after 1995	Wet
Coal-IGCC	Integrated gasification combined cycle	Wet
O-g-s	Oil/gas/steam	Wet
nuclear	Nuclear power	Wet
	Renewable Technologies	
Geo	Includes hydrothermal and near-field enhanced geothermal systems	Dry
Biopower	Power from biomass	Wet
CofireOld	Pre-1995 coal plants, (with or without scrubber) retrofitted for co-firing; can burn 15% biomass	Wet
CofireNew	Post-1995 non-IGCC coal plant retrofitted, or a new co-firing plant; can burn 15% biomass	Wet
DPV	Distributed photovoltaic on rooftops	Non-thermal
UPV	Utility-scale photovoltaic	Non-thermal
CSP (no storage)	Concentrated solar power without thermal storage	Dry
CSP (variable storage)	Concentrated solar power with thermal storage	Dry
Wons	Onshore wind power	Non-thermal
Woffs	Offshore wind power	Non-thermal

4.2 Wet Scenario: CSP and Geothermal Employ Wet-Cooling Technology

The scenarios described above assume that geothermal and both types of CSP technologies employ dry cooling technology. In conversation with NREL, there seems to be some doubt

[8] The ReEDS model also includes the following electricity generation technologies not shown in Table 4: gas-combustion turbine, landfill gas, ocean power, coal and gas with CCS, and power imported from Canada. Gas-combustion turbines require no water, and we assume the same for landfill gas (the distribution of which remains constant for all scenarios). Ocean power and CCS technology, though considered by ReEDS, do not enter in to the REFS scenarios. Finally, though power imported from Canada will certainly have an impact on water use in Canada, it will not impact the water use in the United States. Furthermore, electricity from Canada represents a very small percentage of total electricity generation (< 2 %).

regarding the economic practicality of these assumptions. We therefore consider an alternative set of scenarios where geothermal and CSP technologies employ wet-cooling technology. These alternative scenarios are identified by or referred to as the *wet* scenarios.

4.3 CCF Policy: Closed Cycle Only Policy Scenario

Due in large measure to environmental concerns associated with once-through cooling technology[10] there is a current movement toward requiring only recirculation technology in the future. To investigate the implications of such a policy, we consider a scenario that describes the ubiquitous adoption of CCF cooling technology by 2050. This CCF policy is modeled in WiCTS by assigning a value of 1 to each CCF power generation coefficient in Eq. 2 and assigning a value of zero to the remaining power generation coefficients. The specific water withdrawal by power type coefficient is left unchanged. The little CCS that exists is assumed to be used primarily in nuclear power and by 2050 ReEDS has shut down a significant portion of nuclear plants (nuclear generation decreases by between 43% and 56% with respect to *2006* depending on the ReEDS scenario). Since the impact of CCS is already rather small, we assume that including CCS will not affect the results in a significant way. For these reasons, we only consider fresh water used in recirculation technology for the *CCF Policy* scenario.

[10] Once-through technology dumps large amounts of hot water back into lakes and rivers, contributing to fish-kills and increased algae growth. The environmental concern this creates, however, is not universal. There are situations where the warm water enhances certain fish populations and is therefore a boon to fishermen.

4.4. ReEDS Generation Technologies

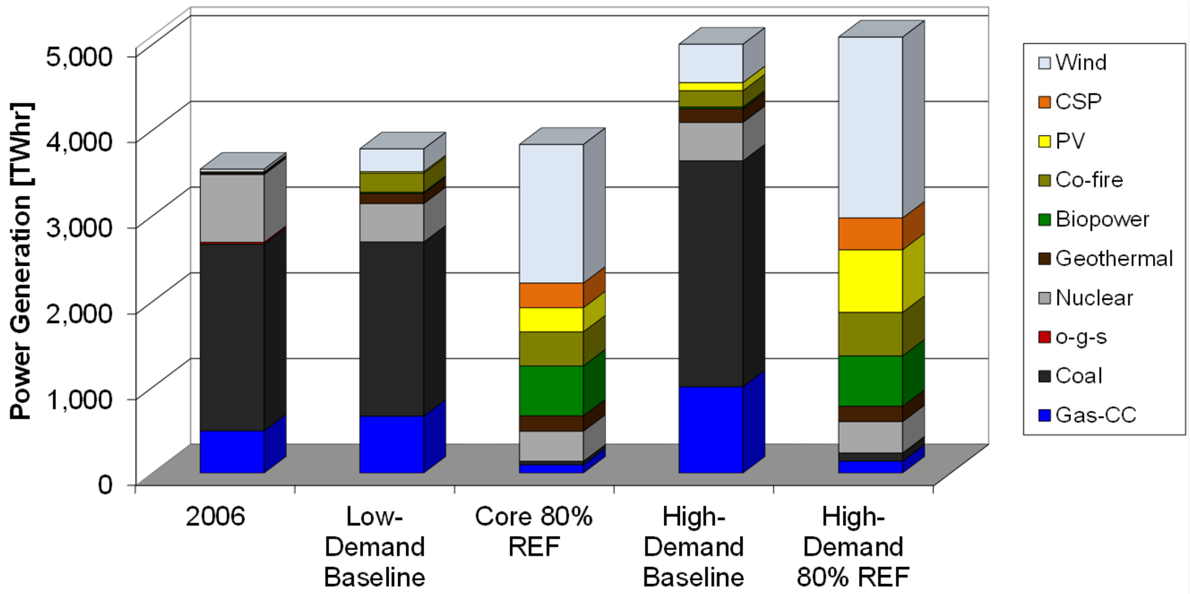

Figure 3. ReEDS power generation portfolios for the current scenario and four future scenarios.

Figure 3 shows the power generation technology portfolios for the power technologies considered in this study. Renewable technologies generate significantly more power in the *80% REF* scenarios compared to the *Baseline* or the *2006* scenarios. In addition, the power generation for the two *Baseline* scenarios is dominated by coal technologies, whereas the power generation for the *80% REF* scenarios is dominated by wind.

Table 4. Total electric power generation and total thermal power generation, with geothermal and CSP using dry cooling (RFNC) and wet cooling (WET).

	Total	Total Wet (RFNC)		Total Wet (WET)	
	[TWhr]	[TWhr]	%	[TWhr]	%
2006	3,540	3,500	99	3,510	99
Low-Demand Baseline	3,780	3,380	89	3,500	93
Core 80% REF	3,830	1,470	38	1,940	51
High-Demand Baseline	5,000	4,300	86	4,460	89
High-Demand 80% REF	5,090	1,700	33	2,250	44

Table 4 shows the total power generated by those technologies considered in this study as well as the total power generated by technologies employing wet-cooling under the reference scenarios (geothermal and CSP use dry cooling) and wet assumption (geothermal and CSP use wet cooling). Also shown is the proportion of the total power generated by "wet" technologies.

As shown by Eq. 2, power generation by technology type is a direct driver of water use in the WiCTS model. A large amount of power generated by wet technologies (e.g., coal technologies) suggests large rates of water use. A large amount of power generated by dry or non-thermal technologies suggests low rates of water use. Figure 3 and Table 4, therefore, suggest that the *80% REF* scenarios will use less water than the *2006* and two *Baseline* scenarios, but that under the *WET* scenarios (geothermal and CSP are wet cooled), slightly more water will be used compared to the *RFNC* scenarios.

5. RESULTS

5.1 Summary of Model Results

Figure 4 illustrates water withdrawals and water consumption for the *RFNC* scenarios described in Section 4.1 by cooling technology type; OTF, OTS, CCF, CCS and water use for non-thermal and dry technologies. The first conclusion that can be drawn from these graphs is that water use (both consumption and withdrawals) is dominated by wet cooling technologies. The non-thermal and dry cooling technologies play a negligible role in overall water use, contributing to less than two tenths of a percent of water withdrawals and less than 5% of water consumption.

Once-through cooling technology (OTF and OTS) is by far the primary driver of water withdrawals, accounting for over 92% of all withdrawals (irrespective of scenario).

Recirculation cooling technology, however, is the main driver of water consumption, although once-through cooling technology still contributes significantly to consumption. Recirculation technology accounts for between 54% and 57% of all water consumption.

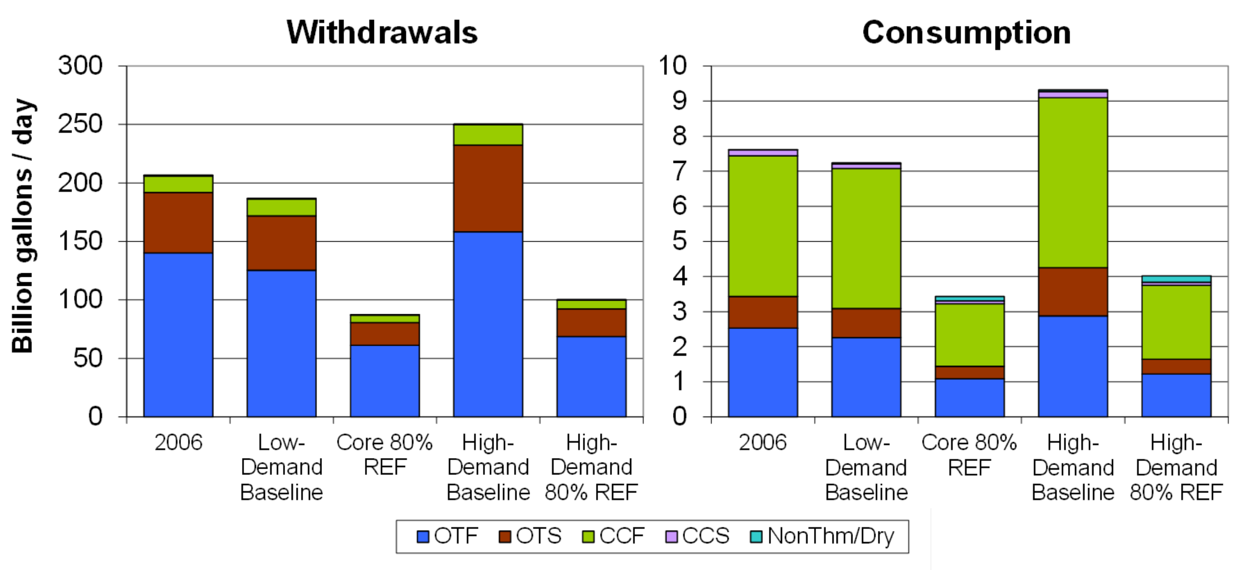

Figure 4. Water withdrawals and consumption for all reference scenarios.

Table 5 summarizes the results of the model for *RFNC* scenarios described in Section 4.1. Wet cooling technologies (for the reference scenarios) in the *2006* scenario make up 99% of total power generation, yet in the two *80% REF* scenarios, wet cooling technologies make up only 38% and 33% of total power generation (refer to Table 4). Many renewable technologies do not use wet cooling systems. Since wet cooling systems dominate water use, it is not surprising that, as Table 5 indicates, significant reductions in water withdrawals and consumption are possible by moving towards the renewable technology portfolios. The differences between each future scenario and the *2006* scenario are shown in **Table 6**, and the difference between the *80% REF* scenarios and their respective *Baseline* scenarios are shown in **Table 7**.

Referring to Table 7, it is interesting to note that water use reductions with respect to the *Baseline* scenarios are achieved in the *80% REF* scenarios despite the fact that more power is being generated in the *80% REF* scenarios compared to their *Baseline* counterparts (refer to Table 4 and Figure 3). This suggests that even under a very efficient electricity demand, water use is still higher compared to the renewable fuels portfolio where electricity demand is not met in as efficient a manner. This is due to the introduction of the renewable fuels portfolio where a significant percentage of power is generated using non-water intensive power generating technologies (e.g., wind power).

Table 5. Total water withdrawals and consumption.

Scenario	**Withdrawals [Mgal/day]**	**Consumption [Mgal/day]**
2006	206,500	7,620
Low-Demand Baseline	186,700	7,240
Core 80% REF	87,400	3,430
High-Demand Baseline	250,200	9,320
High-Demand 80% REF	100,300	4,020

Table 6. Future water use compared to *2006* water use (water use reductions are negative).

	Δ Withdrawals		**Δ Consumption**	
With respect to *2006*	**[Mgal/day]**	**%**	**[Mgal/day]**	**%**
Low–Demand Baseline	−19,800	−10	−380	−5
Core 80% REF	−119,000	−58	−4,180	−55
High–Demand Baseline	43,700	21	1,700	22
High–Demand 80% REF	−106,200	−51	−3,600	−47

Table 7. *80% REF* water use compared to *Baseline* water use (water use reductions are negative).

	Δ Withdrawals		**Δ Consumption**	
	[Mgal/day]	**%**	**[Mgal/day]**	**%**
Low–Demand: 80% REF—Baseline	−99,300	−53	−3,800	−53
High–Demand: 80% REF—Baseline	−149,900	−60	−5,300	−57

5.2 Regional Analysis

One of the features of the WiCTS model is the ability to analyze water use regionally (in this case at the PCA geographic resolution). The geographic resolution capabilities of WiCTS are especially important since some areas in the United States are water rich, while some areas are water stressed. A renewable policy may, in aggregate, produce significant reductions in water use but still require regional increases in water use in water stressed regions.

In our regional analysis, we focus on water consumption in regions with high water stress. Following Waggoner, *et al.* (1990) and Raskin *et al.* (1997), we define a region as water stressed if the mean withdrawal rate exceeds 60% of the mean annual runoff. Based on this definition, **Figure 5** illustrates those regions considered stressed, all of which are located west of the Mississippi River.

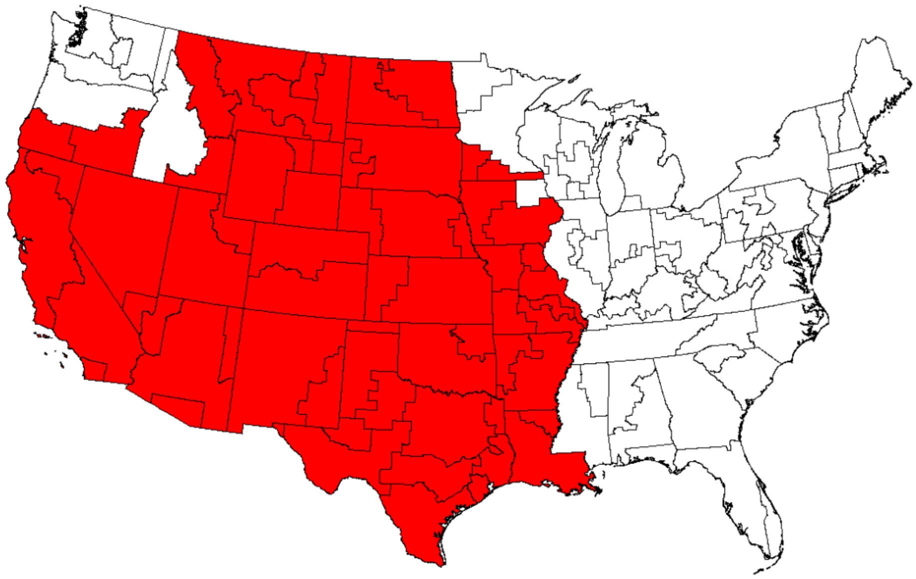

Figure 5. Illustration of water stressed regions (shown in red).

Our regional analysis compares water consumption in the *Core 80% REF* to water consumption in the *Low-Demand Baseline* scenario. The difference in total water consumption is shown in **Figure 6**. Blue shading indicates that the percentage difference is less than 2.5% and therefore represents a *reduction* in water consumption. Red shading indicates that the percentage difference is greater than 2.5% and therefore represents an *increase* in water consumption. Green shading indicates that the percentage difference is between ±2.5% and therefore, for the purposes of our analysis, represents little to no change in water consumption. Those PCA regions classified as water stressed are indicated with the cross-hatch pattern.

Figure 6 shows that with the introduction of the renewable portfolio, water consumption across the country decreases. Much of the decrease in consumption is concentrated in those regions that are not water stressed. Of the 3,809 Mgal/day decrease in water consumption (refer to Table 7), 27% of the decrease occurs in water stressed regions, and the remaining 73% of the decrease occurs in the non-stressed regions.

In stressed regions as a whole, there is a net reduction of 1,016 Mgal/day. There are, however, several stressed regions where water consumption increases. The sum of the increases in water consumption in stressed regions shown in Figure 6 is 131 Mgal/day, whereas the sum of the decreases in stressed regions is 1,147 Mgal/day.

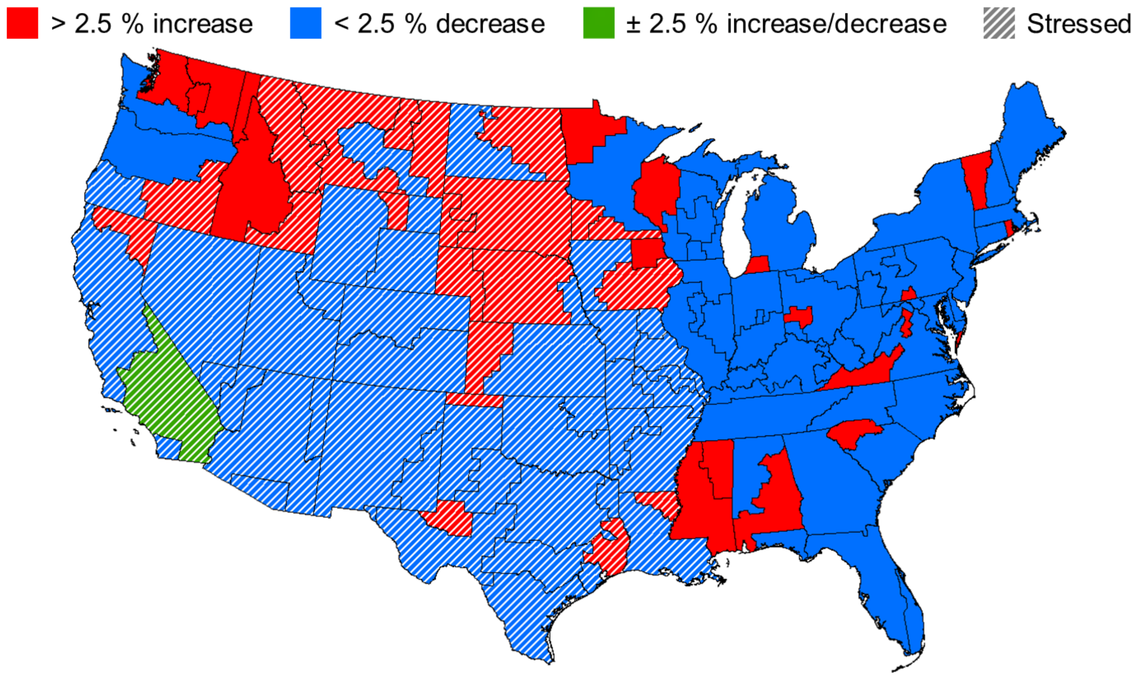

Figure 6. Difference between *Core 80% REF* and *Low-Demand Baseline* total water consumption (Mgal/day).

An important aspect of water consumption that is neglected from the previous analysis is the distinction between fresh and saline water. An analysis of the difference between the *Core 80% REF* and the *Low-Demand Baseline* reveals that there is one water-stressed region in California (PCA 11) where total consumption and withdrawals decrease but fresh water consumption and withdrawals increase[12]. In PCA 11, there are substantial decreases in generation from nuclear and gas-cc[13]. These technologies are assumed to use wet cooling systems. At the same time, there are substantial increases in distributed PV generation and to a lesser extent and onshore wind. Distributed PV and wind power are non-thermal technologies, and since WiCTS assumes that non-thermal technologies consume only fresh water, increases in power generation from these technologies will increase fresh water consumption according to Eq. 4. A similar behavior is observed under the high demand scenarios. This result, therefore, suggests that the expansion of non-thermal renewable technologies in regions that predominantly use saline water could cause an increase in fresh water consumption despite overall reductions in water use due to large decreases in saline water consumption.

[12] The increase, in absolute terms, is small; about 0.25 Mgal/day. Proportional to the Baseline scenario, however, the increase is very large.

[13] For the high demand scenarios, there is an additional substantial decrease in generation from coal-new.

5.3 Alternative Cases: Wet and CCF Policy

The results above suggest that reductions in water withdrawals and consumption are possible by moving to a renewable fuels portfolio. Here we ask whether these results are robust to the two alternative cases posed in Section 4.2 and Section 4.3. **Figure 7** and **Figure 8** illustrate the total water withdrawals and consumption for the *RFNC*, *WET*, *CCF* and *CCF-WET* scenarios. *RFNC* refers to the reference case, where geothermal and CSP are assumed to use dry cooling systems and no CCF policy is assumed. *WET* refers to the scenarios run under the assumption that geothermal and CSP use wet cooling systems. *CCF* refers to the scenarios run under the assumption that all plants use only fresh water in closed cycle systems by 2050. Finally *WET-CCF* is a combination of the *WET* assumption and *CCF* policy case. Figure 7 and Figure 8 illustrate a similar pattern as displayed in Figure 4, suggesting that the renewable portfolio scenarios will still achieve reductions in water use compared to their baseline counterparts.

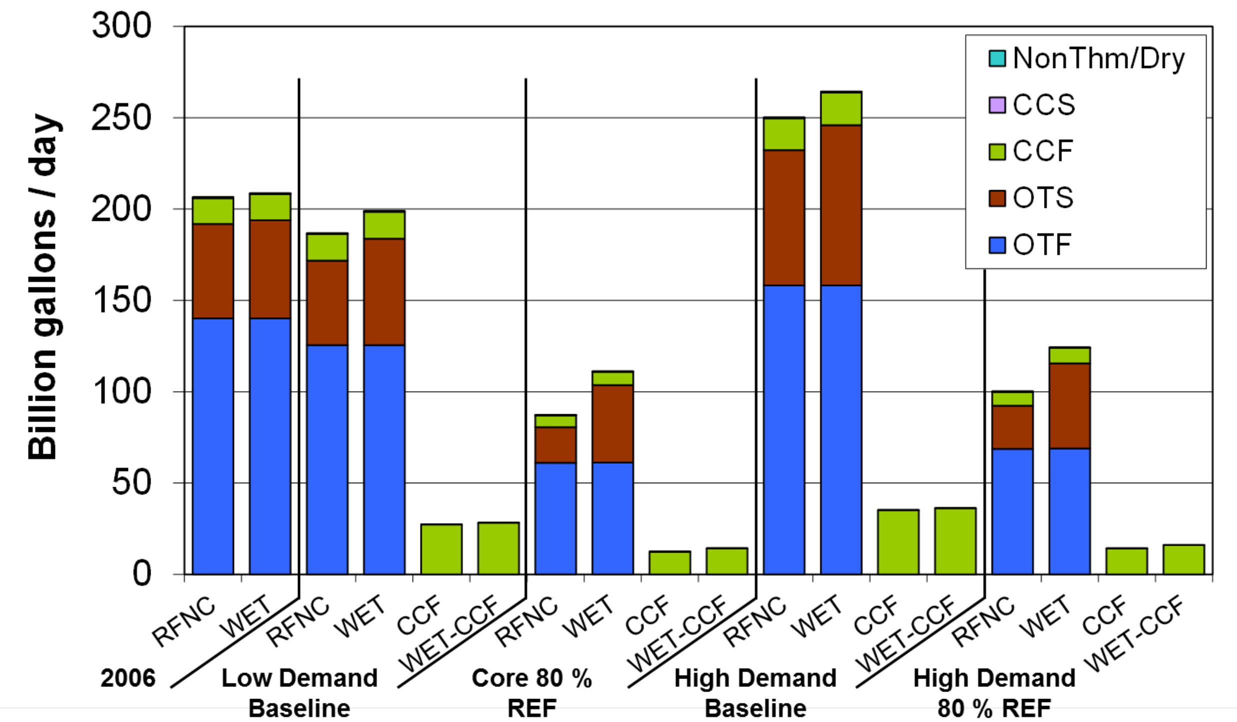

Figure 7. Water Withdrawals: all policies.

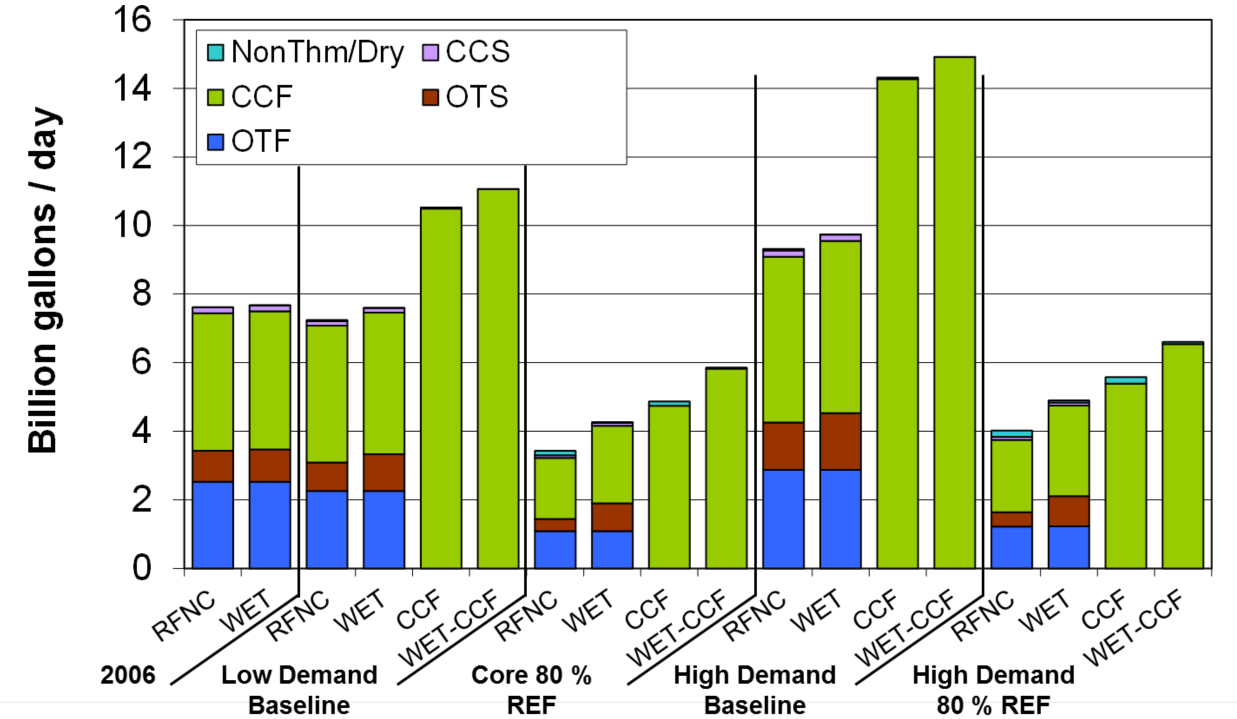

Figure 8. Water Consumption: all policies.

Assuming the renewable fuels portfolio has been deployed, we analyze the impact that the *WET* and *CCF* cases would have on water use. **Table 8** shows the difference between the *80% REF (WET case)* and the *80% REF (RFNC)* under both high and low demand scenarios. Table 8 also shows the difference between the *80% REF (CCF case)* and the *80% REF* (*RFNC*) under both high and low demand scenarios. The third column, '% in Stressed', presents the percentage of the increase or decrease in water use that occurred in the stressed regions illustrated in Figure 4.

Table 8. *80% REF* water use with WET or CCF policy compared to *80% REF* water use under the reference scenario (water use reductions are negative).

	Δ Withdrawals [Mgal/day]	**%**	**% in Stressed**	**Δ Consumption [Mgal/day]**	**%**	**% in Stressed**
			WET Case vs. Reference Scenario			
Low-Demand	23,720	27	99	838	24	99
High-Demand	23,950	24	99	882	22	99
			CCF Policy Case vs. Reference Scenario			
Low-Demand	-74,880	-86	23	1,440	42	*
High-Demand	-85,950	-86	22	1,550	39	2

* There is actually small (< 1%) net decrease in water consumption in stressed regions

Referring to Table 8, consider first the *WET* case (first two rows). Both withdrawals and consumption increase when geothermal and CSP switch from dry-cooling technology to wet-cooling technology. Since technologies employing wet cooling are the primary driver of water use, we would expect water use to increase if the amount of power generation using wet cooling increases. Furthermore, virtually all of the increase in water use occurs in the water stressed regions (refer to the column "% in Stressed" in Table 8). This suggests that despite the increased cost of dry-cooling, if geothermal and CSP must be wet cooled, the appeal of these electricity generation technologies is reduced from the perspective of water use. As indicated by Figure 7 and Figure 8, however, if CSP and geothermal are wet cooled, decreases in water use are still observed, however, these decreases in water use are not as great as the decreases in water use in the case of CSP and geothermal being dry cooled.

If we next consider the *CCF* case, we note that water consumption increases while water withdrawals decrease[14]. Recall that recirculation technology is the primary driver of water consumption, yet once-through technology is the primary driver of withdrawals. If the technology that primarily drives withdrawals is eliminated, we would expect a significant reduction in water withdrawals. Furthermore, if the technology that drives consumption is mandated, then we would expect an increase in total consumption. The increase in consumption may be concerning, but the percentage of this increase that occurs in water stressed regions is very small (1% or less). The increase in consumption, therefore, occurs in those areas that are relatively water abundant. Furthermore, most of the decrease in withdrawals is occurring in the non-stressed regions, where concern is being raised about high withdrawal rates in connection with negative impacts on local ecosystems. These results, therefore, indicate that the shift from once-through technology to recirculation technology would be beneficial.

6. DISCUSSION AND CONCLUSION

A model for estimating cooling water-use for thermo-electric generating systems, WiCTS, is introduced. WiCTS calculates consumption and withdrawals associated with electricity generation based on exogenous power generation scenarios, USGS water withdrawal data and

[14] A similar conclusion is reached by Feeley *et al.*. (2008). They study several cases of possible future cooling scenarios, two of which are akin to this report's CCF Policy scenario. In these two scenarios, Feeley *et al.*. conclude that at the national scale, withdrawals decrease while consumption increases.

coefficients of operational water use. In this analysis, WiCTS is used to investigate the impact of four future scenarios, two of which make significant use of renewable energy technologies.

Water use is dominated by electricity generating technologies that employ wet-cooling. Compared to the non-renewable technology portfolio scenarios, the renewable portfolio scenarios use less water intensive technologies, leading to overall reductions in water use. This is especially important for many of the water stressed regions, all located west of the Mississippi River, where even small reductions in water use can produce a large benefit.

In certain regions, however, the renewable portfolio scenarios showed increases in water consumption with respect to the non-renewable scenarios. This should temper the enthusiasm with which renewable portfolio standards are pursued. Depending upon the relative importance of water consumption compared to competing demand for water, a more careful local or regional analysis should be conducted before implementing a renewable portfolio.

Though renewable technologies tend to play negligible roles in water use, WiCTS demonstrates that the expansion of renewable technology in one coastal region can cause an increase in fresh water consumption, despite a net decrease in water use due to a large decrease in saline water consumption. The implications, though not national in scope, are important for stressed regions that currently withdraw high volumes of saline water for cooling purposes. Such regions should cautiously proceed towards renewable technologies inasmuch as these technologies will require a shift from saline water use to fresh water use, since doing so may actually cause an increase in the consumption of the scarce fresh water resources. From the perspective of water consumption alone, therefore, shutting down plants that withdraw seawater for thermal cooling in favor of fresh-water-using renewable technology may not be the appropriate policy. There are, of course, valid reasons for not discharging large amounts of heated seawater back in to the ocean, such as the disruption of fragile ecosystems.

The model also demonstrated that a shift to recirculation technology across the country would lead to a decrease in withdrawals but an increase in consumption. Much of the increase in water consumption, however, occurs in the relatively water rich eastern half of the U.S. The recirculation policy, therefore, may be a sound policy—at least in the East—if it appears that the environmental benefits of reducing withdrawals outweigh in increase in water consumption. There are increases in water consumption in water stressed regions under the recirculation policy as well, but these increases are relatively small.

Finally, if geothermal and CSP technologies are wet cooled, decreases in water consumption are less than if geothermal and CSP technologies are dry cooled. From the perspective of water consumption, then, dry cooling—at least in the West—is the best policy. There is, however, a trade off, due to the high cost of dry cooling. Depending upon the local limitation of water resources, however, dry cooling may be worthwhile.

There are several areas for further research. One area regards the assumption of static specific water withdrawal coefficients. It is highly unlikely that by 2050, cooling technologies and their associated water use will remain unchanged, especially given the fact that historical records show a decrease in the ratio of water withdrawals per unit power generation from 1950 to 2005 (Kenny *et al.*, 2009). Furthermore, possible future climate change and associated variations in regional temperatures will also have an impact on specific water withdrawal coefficients. Climate change and changes in cooling system technology will also impact consumptive coefficients. Developing a more specific model of consumptive losses is therefore a second area of future work. A third area of future work relates to the treatment of hybrid plants. The USGS data only reports water withdrawals for once-through and closed cycle plants, where closed cycle plants include cooling systems that employ cooling towers or ponds (Kenny *et al.*, 2009; Hutson, 2007). In reality, however, some plants employ both once-through and closed cycle cooling systems depending upon the season and associated water availability and/or policy constraints. Because of the dichotomous nature of the USGS data, WiCTS is not able to explicitly describe such hybrid plants. It is an area of future inquiry to include more plant specific information into the WiCTS modeling framework.

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APPENDIX A: SPECIFIC WATER WITHDRAWAL COEFFICIENT PLOTS

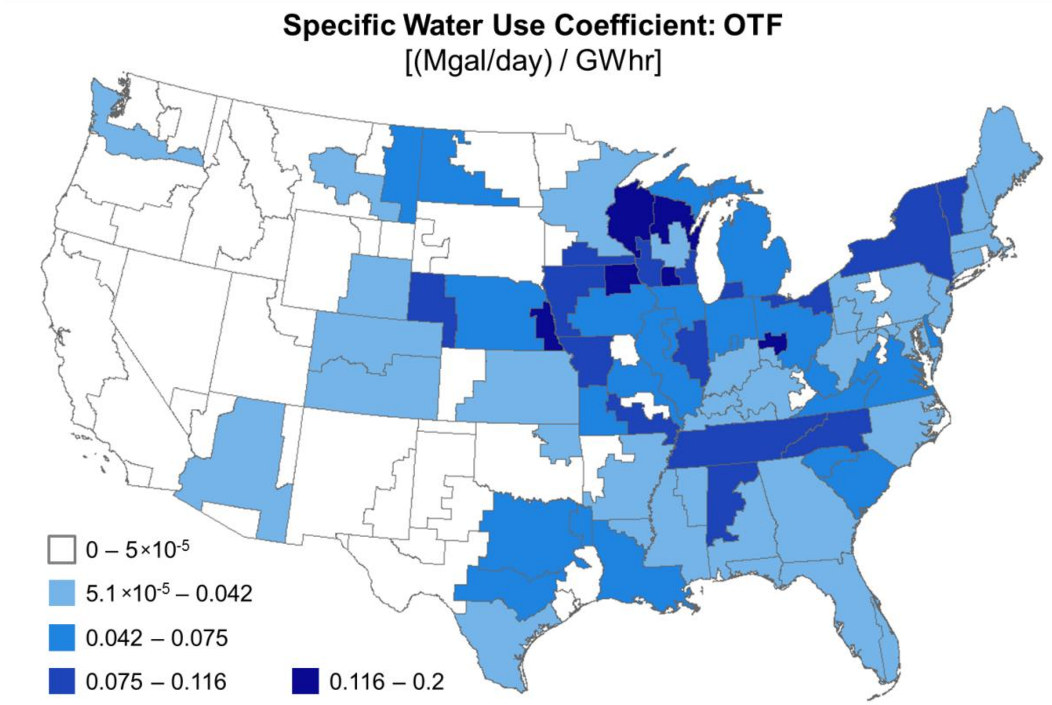

Figure A1. Illustration of OTF specific water withdrawal coefficients by PCA.

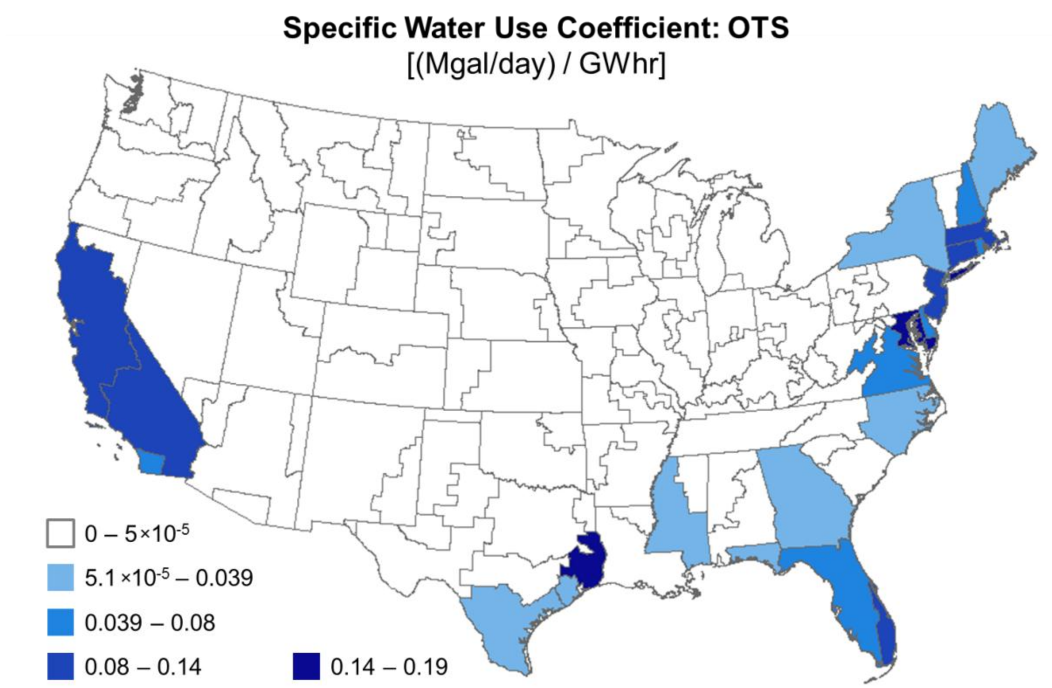

Figure A2. Illustration of OTS specific water withdrawal coefficients by PCA.

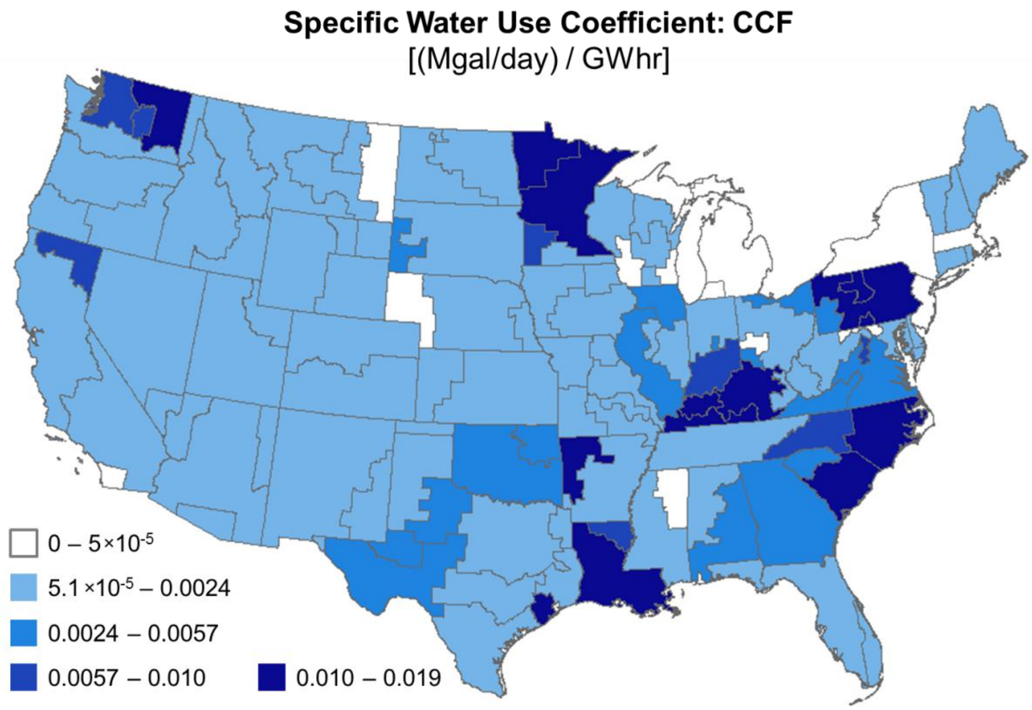

Figure A3. Illustration of CCF specific water withdrawal coefficients by PCA.

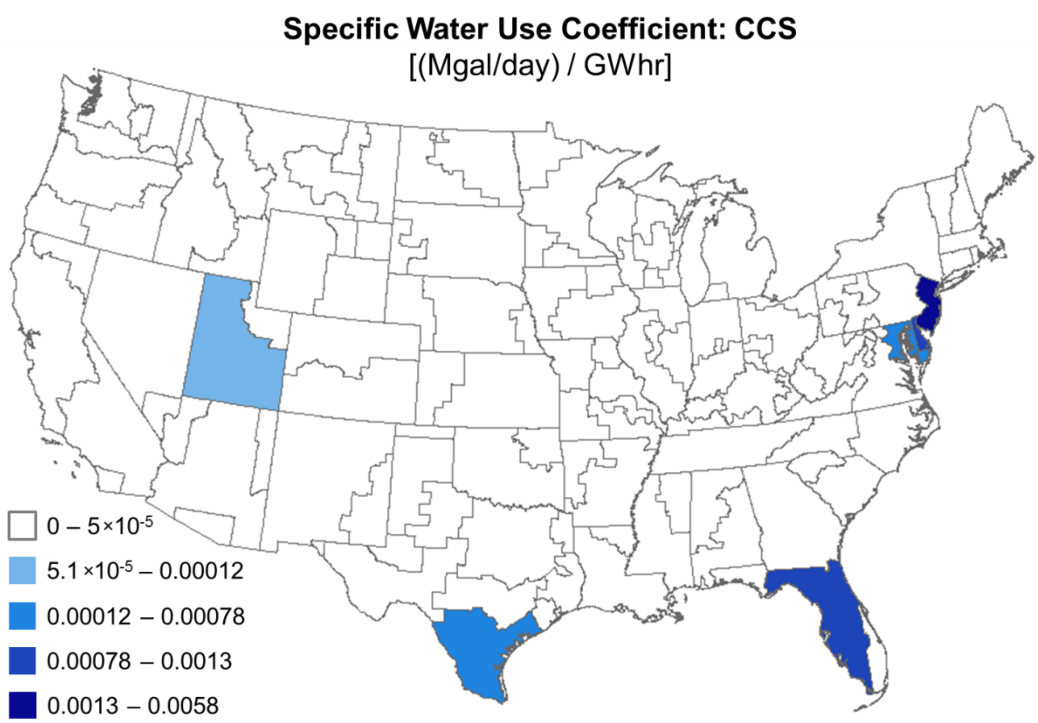

Figure A4. Illustration of CCS specific water withdrawal coefficients by PCA.

APPENDIX B: COEFFICIENT METHODOLOGY

Two input files were generated before running WiCTS. The first file is a data set of the power generation ratios of Eq. 2 for each PCA. The second file is a data set of the specific water withdrawal by power type coefficients of Eq. 2 for each PCA. **Figures B1** through **B5** illustrate the link between PCA numbers and geographic locations.

California: Two authors of the USGS report expressed concern that the power was significantly underestimated in California, compared to EIA data (Refer to **Figure D1**). They suggested that the specific water withdrawal ratios would therefore be too large by approximately a factor of two. To account for this, we manually reduce the initially calculated specific water withdrawal ratios in PCA 9, 10, and 11 by a factor of two. Note that PCA 8 is also part of California. Its value, however, is originally zero, and is therefore not altered.

Rhode Island: The USGS power generation for Rhode Island (refer to **Figure D2**) grossly overestimates the EIA power generation estimate. To develop an appropriate set of power generation and specific water withdrawal ratios, the total power generated in 2005 in Rhode Island is calculated using EIA form-906/920. Power generated from co-generation plants as well as power generated from non-thermals is not considered in this estimate.

The USGS reported value for power generated from recirculation plants appears reasonable. Therefore, to calculate power generated from once-through plants, the power generated from recirculation plants is subtracted from the total power generated in Rhode Island as calculated by the EIA data. Using the USGS water withdrawal data, the new values for total power generated and total power generated from once-through power plants, power generation and specific water withdrawal by power type ratios are re-calculated manually. These new ratios replace those originally calculated.

PCA 106 (Indianapolis): The original water to power ratio for OTF is two orders of magnitude larger than its neighboring values in PCA 105 and 107. An investigation into the cause of this revealed that the USGS reported value of fresh water withdrawn for once-through technology is very large compared to total power generated using once-through technology. Additionally, the reported value of fresh water withdrawn for recirculation is very small. PCA 106 is surrounded by PCA 105 and PCA 107 and in general, the ratios of Eq. 2 should be geographically consistent. For this reason, the power generation and specific water withdrawal by power type ratios for PCA 106 are recalculated based on the average of the respective values for PCA 105 and PCA 107 (which comprise the northern and southern portions of Indiana, respectively).

Power Generation Ratio Input File: A CCF power ratio coefficient value of 1 is assigned for those PCAs whose coefficients are otherwise all zero (i.e. no power is reported in these PCA regions by USGS). This is done to avoid underestimating water use in the case that ReEDS places power in a PCA where USGS reports no power. This would be especially important for the future ReEDS scenarios.

Power Generation Ratio Input File—CCF Policy: To implement a policy whereby all power plants are required to use recirculation technology, a CCF power generation ratio of 1 is assigned to all PCAs and all other coefficients are assigned a value of zero.

Specific Water Withdrawal by Power Type Coefficient Input File: Similar to the Power Generation Ratio Input File, in order to avoid underestimating water use, especially in future scenarios, PCAs that otherwise would have no specific water withdrawal by power type coefficient for any water type (OTF, OTS, CCF, and CCS) are assigned a specific water withdrawal by power type coefficient for CCF. The method for calculating this involves averaging the CCF specific water withdrawal by power type ratios of all surrounding PCAs. The exception is that a surrounding PCA whose original CCF specific water withdrawal by power type ratio is zero is not considered in the average.

PCA 119 and 120 are surrounded primarily by PCA 122 and are within the same state as PCA 122. For this reason, both CCF specific water withdrawal by power type ratios for PCA 119 and 120 take the water to power ratio of PCA 122.

Specific Water Withdrawal by Power Type Coefficient—CCF Policy: For the CCF policy, it is important that all CCF specific water withdrawal by power type ratios are non-zero. The same method that applied to calculating specific water withdrawal by power type ratios in the non-CCF Policy case above is applied to the remaining PCA regions where specific water withdrawal by power type ratios are zero. The exceptions are noted below:

PCA 88: surrounded by PCA 87, PCA 89 and PCA 92. PCA 92's specific water withdrawal by power type ratio is an order of magnitude greater than the specific water withdrawal by power type ratio of PCA 87 and PCA 89. It seems more consistent to average only the values of PCA 87 and PCA 89 especially considering PCA 92 is all of Tennessee.

PCA 103 and PCA 104: PCA 103 is surrounded by PCA 74, PCA 104, PCA 105, PCA 111, and PCA 112; PCA 104 surrounded by PCA 103 and PCA 105. The specific water withdrawal by power type ratio of PCA 111 is applied to both PCA 103 and PCA 104. PCA 74 originally had no CCF coefficient. PCA 111 is Lake Erie, and both PCA 104 and PCA 105 border Lake Michigan. It seems reasonable to give Michigan the same ratio as that applied to Lake Erie (i.e. PCA 111).

PCA 113: surrounded by PCA 112, PCA 114 and PCA 107. PCA 107 is in Indiana, while PCA 112, PCA 113 and PCA 114 are in Ohio. Similar to the reasoning behind the assignment of PCA 88, I think it more appropriate to leave the specific water withdrawal by power type ratio of PCA 107 out of the average.

PCA 121: surrounded by PCA 123, PCA 120, PCA 122 and PCA 116—this is the western tip of Maryland. The specific water withdrawal by power type ratio in PCA 120 is ignored since it was originally zero. It seems most appropriate to leave out PCA 122, since this PCA is most of Pennsylvania and leaving it in would skew the number for western Maryland too high it seems.

PCA 128: This is Long Island. It was assigned the specific water withdrawal by power type ratio of PCA 126 (New Jersey).

Capping the Specific Water Withdrawal by Power Type Coefficients: In order to avoid spikes in the data, CDFs of all specific water withdrawal by power type ratios were constructed at the county resolution. This provided us with significantly more data points than would be available if we developed a CDF of the specific water withdrawal by power type ratio at the PCA resolution.

The specific water withdrawal by power type ratio nearest to the 90% level for OTS, OTF and CCF[16] is set as the cap. In order to appropriately modify the input files, if specific water withdrawal by power type ratio in a PCA exceeds the cap, the specific water withdrawal by power type ratio becomes the cap divided by the power generation ratio (in Eq. 2). This ensures that the specific water withdrawal ratio (the fraction in Eq. 1, or in other words the product of the two ratios in Eq. 2) does not exceed the cap for a given water type.

An alternative would have been to appropriately scale both the power generation ratio and the specific water withdrawal by power type ratio in Eq. 2. We decided not to do this in order to ensure that the sum for power generation ratios in a given PCA remained one.

[16] Very little *CCS* used and as such, it seemed inappropriate to set a cap based on so few data points.

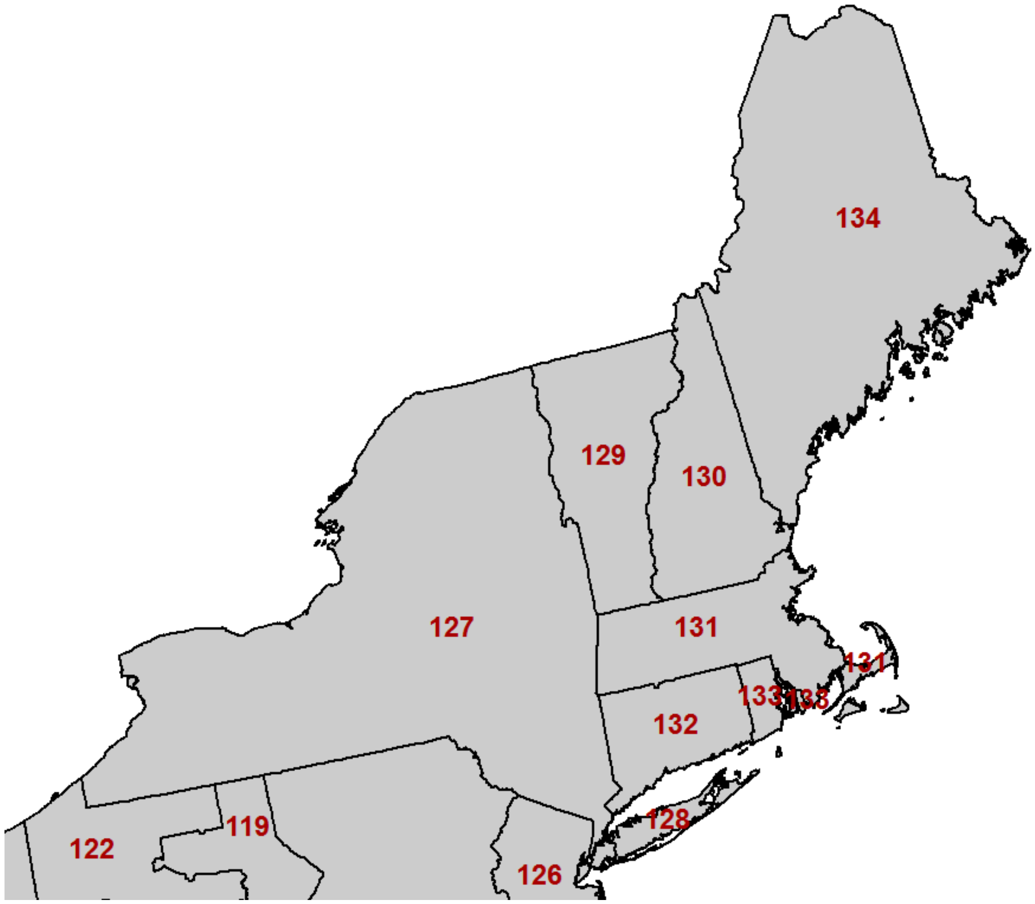

Figure B1. Illustration of PCA identification number; New England states.

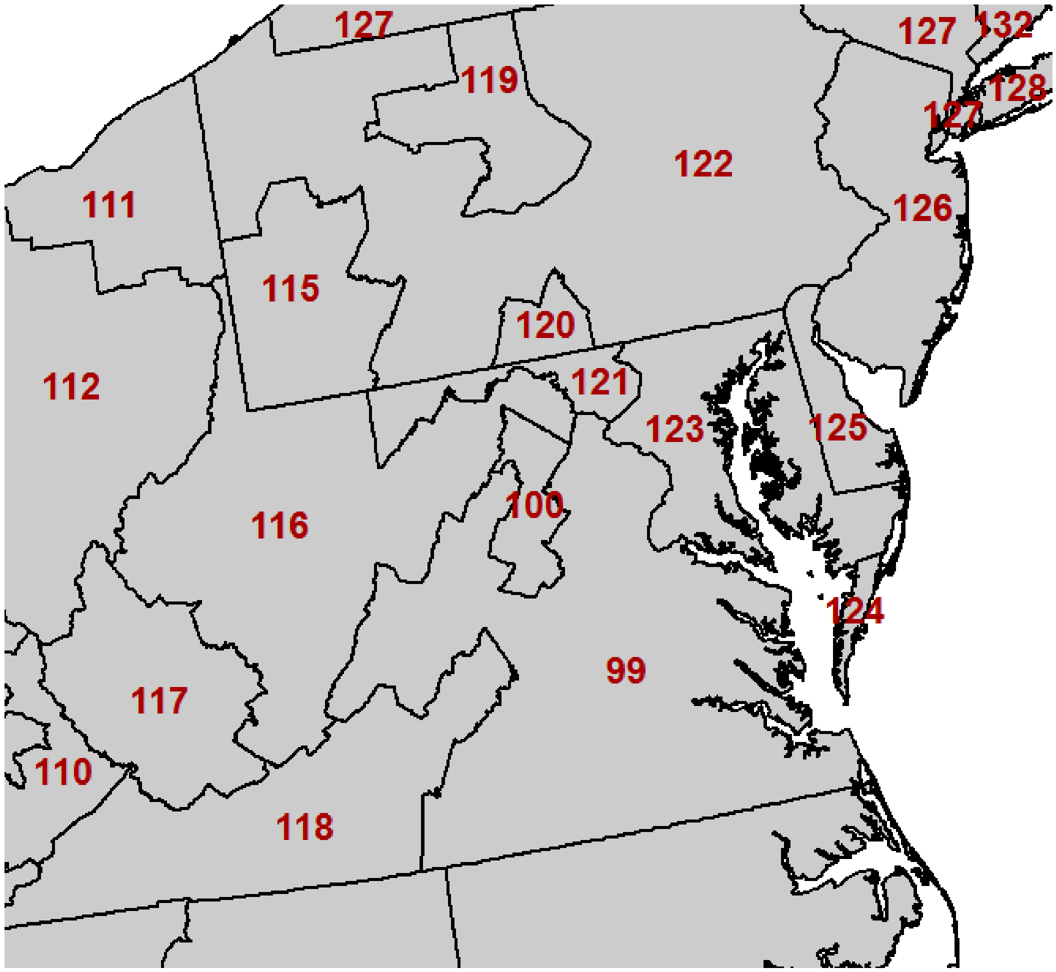

Figure B2. Illustration of PCA identification number; Mid-Atlantic states.

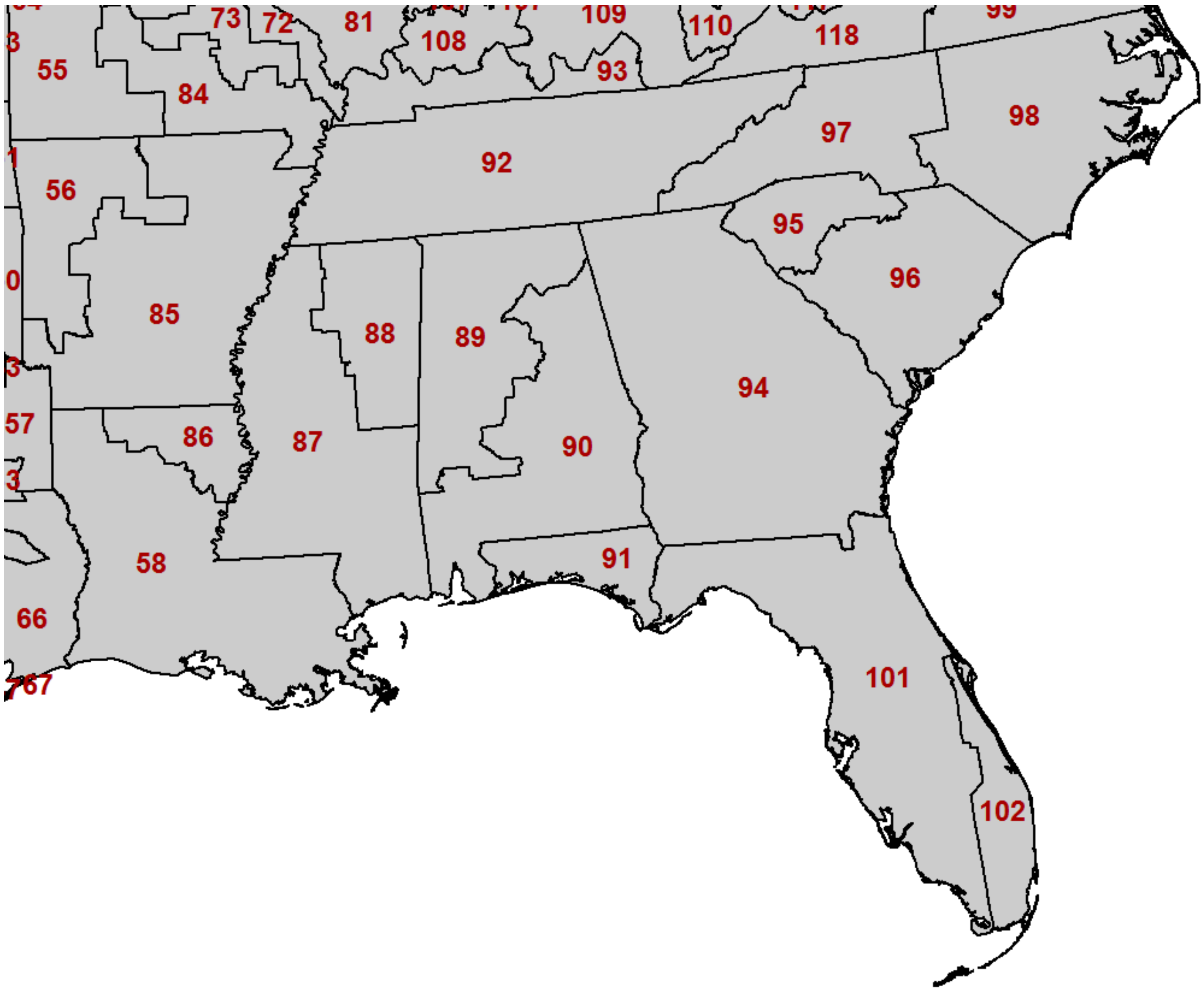

Figure B3. Illustration of PCA identification number; Southeast states.

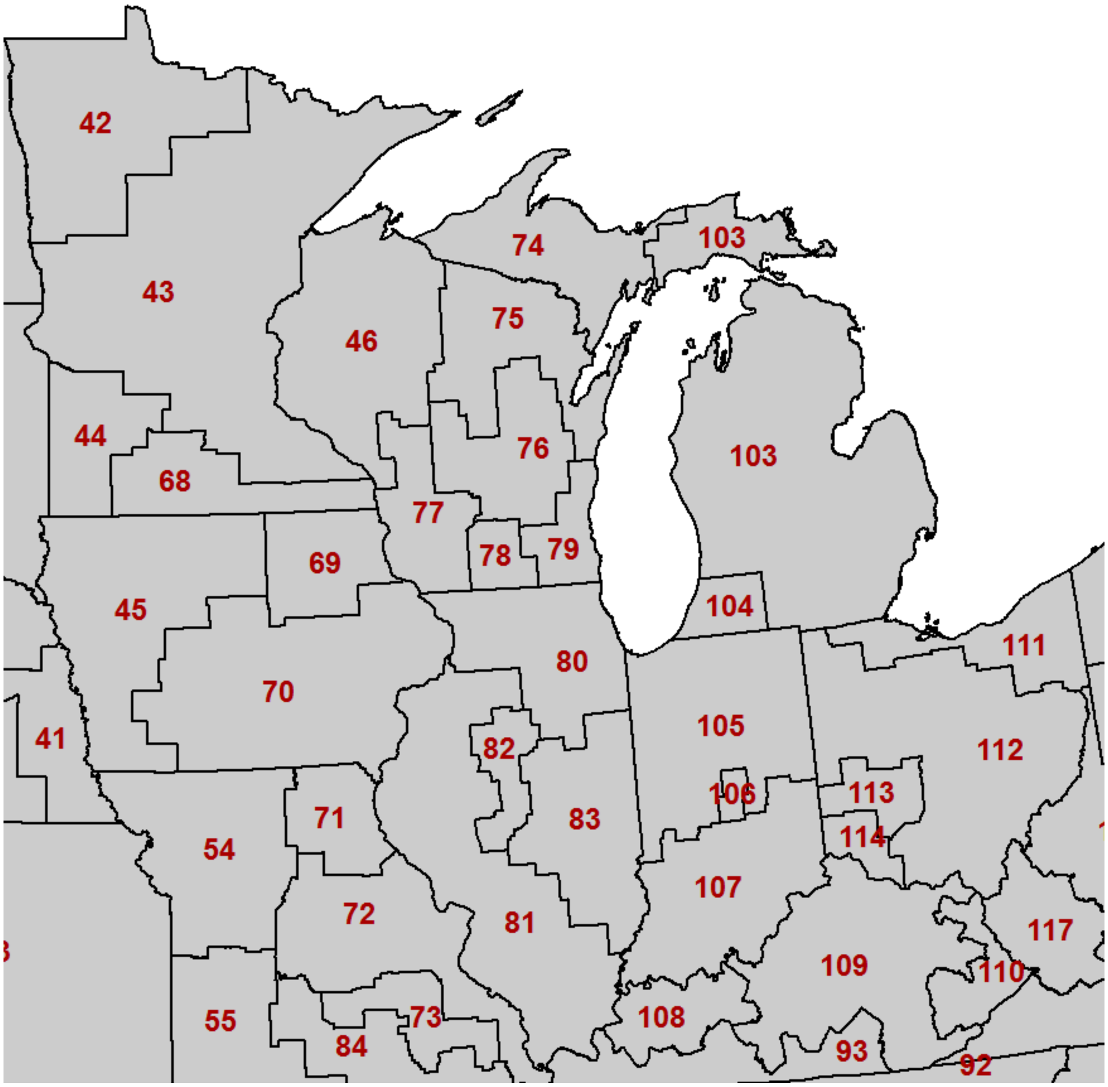

Figure B4. Illustration of PCA identification number; Midwest states.

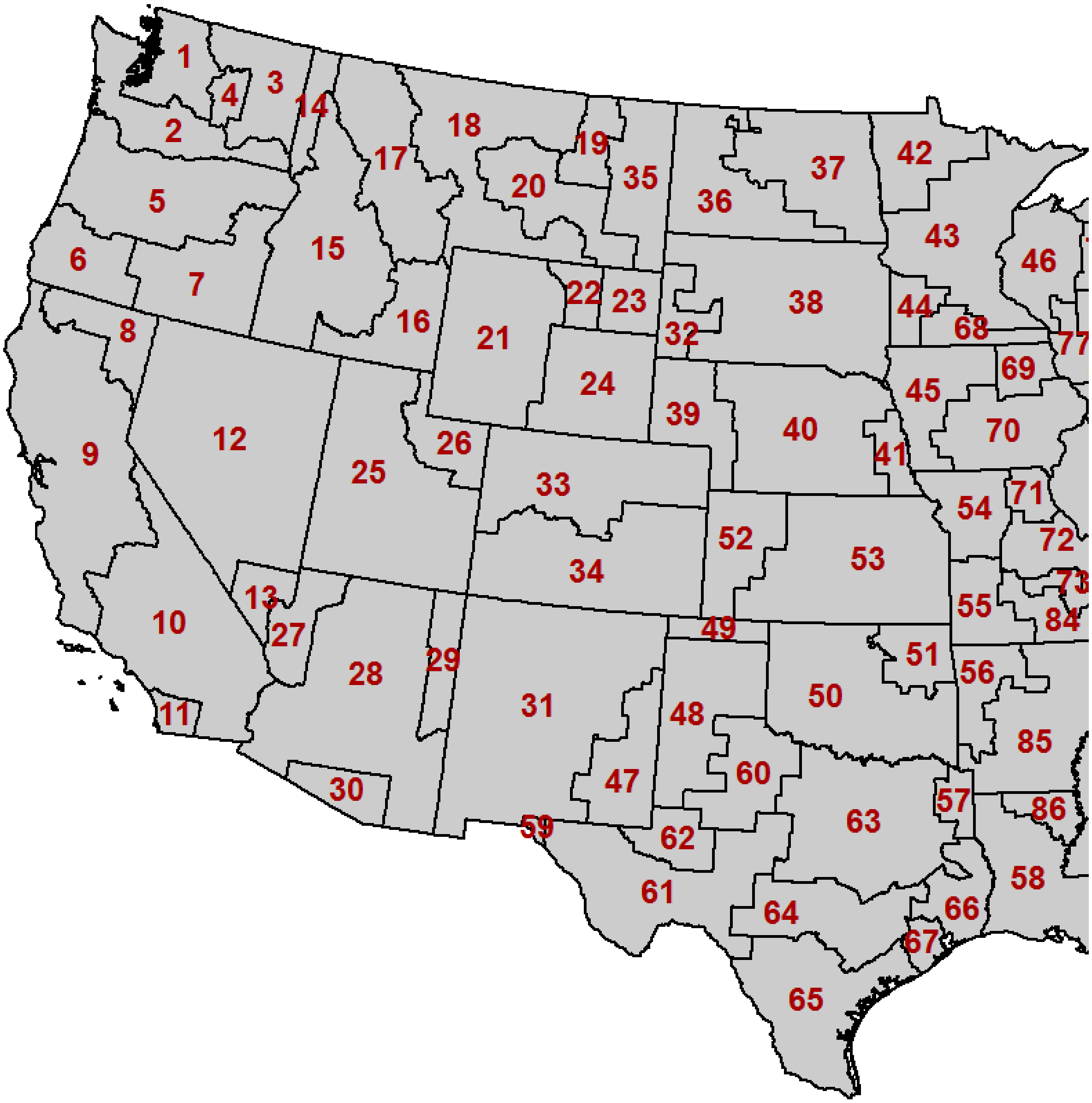

Figure B5. Illustration of PCA identification number; Great Plains and West Coast states.

APPENDIX C: ADJUSTING THE CONSUMPTIVE FACTORS

Initial runs of WiCTS in the current year (2006) produced various regions with very large specific water consumption ratios. Though the most recent USGS water use report by Kenny *et al.* does not report consumption information, a previous USGS water use report by Solley *et al.* (1998) does report values of consumption (but does not report power generation). We use county and state level results from Solley *et al.* to develop an understanding of "typical" specific water consumption ratios. Following our procedure for setting the cap on specific water withdrawal ratios (APPENDIX B), we determine that 1100 gal/MWhr corresponds to the 90% level of the county data. Consumptive factors are adjusted in regions where the specific water consumption is greater than 1100 gal/MWhr.

Adjusting the consumptive factors is a two-step process. We first reduce the consumptive factors for once-through technology in regions where the specific water consumption is greater than 1100 gal/MWhr in 2006. We reason that in these regions, the assumed value of 2% is too high.[17] In regions where the cap of 1100 gal/MWhr is achieved by reducing the consumptive factor below zero, we set that consumptive factor to the average of the consumptive factors for those regions that are reduced, but not below zero.

In the second step, we reduce the recirculation consumptive factor (originally 60%) until the 1100 gal/MWhr specific water consumption value in 2006 is achieved. After running the future scenarios, two regions (PCA 42 and PCA 120) that originally had no consumption in 2006 demonstrated specific water consumption values greater than 1100 gal/MWhr. The recirculation consumptive factor for these two regions was adjusted by assigning to them the consumptive factors for PCA 43 and PCA 119 respectively.

Table C1 indicates PCA regions that were affected by the adjustment as well as the values that resulted from the adjustment. PCA regions not listed in Table C1 were unchanged.

[17] A data set from EIA (EIA form 767) showing water consumption and withdrawal rates for a limited number of power plants suggests that some once-through plants do in fact consume less than 2% of water withdrawn.

Table C1. Adjusted consumptive factors (dashes indicate a consumptive factor left unchanged from the original 2% or 60% assumption).

PCA	OTF	OTS	CCF	CCS
1	–	–	0.33789	–
3	–	–	0.168757	–
4	–	–	0.253323	–
42	–	–	0.133255	–
43	0.014654	–	0.133255	–
56	–	–	0.158616	–
58	0.014654	–	0.10123	–
66	–	0.017675	–	–
67	–	0.014654	0.154905	–
75	0.015001	–	–	–
78	0.017769	–	–	–
81	0.014654	–	0.402448	–
86	0.014654	–	0.469691	–
90	0.012327	–	–	–
92	0.014802	–	–	–
93	0.014654	–	0.150162	–
96	0.014654	–	0.134736	–
97	0.014654	–	0.192302	–
98	0.014654	0.014654	0.132503	–
99	0.013577	0.013577	–	–
107	0.014654	–	0.386011	–
108	0.014654	–	0.147713	–
109	0.014654	–	0.191039	–
111	0.014654	–	0.313142	–
113	0.015096	–	–	–
119	–	–	0.158616	–
120	–	–	0.158616	–
122	0.014654	0.014654	0.174125	–
123	0.012046	0.012046	–	–
125	0.013595	0.013595	–	–
126	0.014654	0.014654	0.205018	0.205018

APPENDIX D: COMPARING USGS POWER DATA TO EIA POWER DATA

The ReEDS power generation data is based on power generation data from the EIA as is the USGS power generation data. As a means of validating these two sets of power generation data, we compare them to raw power generation data from EIA form-906/920 (EIA, 2009).

The EIA data includes generation technologies that are not considered by the USGS, namely co-generation plants, as well as all other plants classified as non-thermal.[18] In order to make a fair comparison between USGS and EIA, all co-generation plants and non-thermal plants must be excluded from EIA form-906/920. The classification of EIA data as thermal or non-thermal is shown in **Table D1**. In addition, all plants classified as co-generation in EIA form 906/920 are excluded.

USGS total power generation is close to that of the EIA estimate, underestimating by 7%. One possible source of this underestimation is nuclear power. USGS does not use EIA form-906/920 in its estimates of power generation, but rather another power generation data set (also published by the EIA) that better suits the purpose of the USGS water use report. This data set, however, does not include nuclear power, requiring USGS to collect nuclear power generation from other sources of information.

Figure D1 and **Figure D2** present a comparison, by state, between the power generation reported by USGS, and power generation reported by EIA form-906/920 with the appropriate power plant technologies excluded. In general, there is relatively close agreement among power generation estimates in each state.

There are, however, two notable discrepancies; California and Rhode Island. The case of these two states, along with other issues related to the ratios in Eq. 2, are discussed in APPENDIX B.

[18] In conversation with two of the authors of the USGS report, we learned that both co-generation power plants and municipal power plants would not be considered by USGS, but would be included in power generation estimates from EIA form-906/920.

Table D1. Classification of EIA generation technologies.

EIA Energy Source Code	Description	Classification
BIT	Anthracite Coal and Bituminous Coal	Thermal
LIG	Lignite Coal	Thermal
SUB	Sub-bituminous Coal	Thermal
WC	Waste/Other Coal (includes anthracite culm, bituminous gob, fine coal, lignite waste, waste coal)	Thermal
SC	Coal-based Synfuel, including briquettes, pellets, or extrusions, which are formed by binding materials or processes that recycle materials	Thermal
DFO	Distillate Fuel Oil (Diesel, No. 1, No. 2, and No. 4 Fuel Oils)	Thermal
JF	Jet Fuel	Non-Thermal
KER	Kerosene	Non-Thermal
PC	Petroleum Coke	Thermal
RFO	Residual Fuel Oil (No. 5, No. 6 Fuel Oils, and Bunker C Fuel Oil)	Thermal
WO	Waste/Other Oil (including Crude Oil, Liquid Butane, Liquid Propane, Oil Waste, Re-Refined Motor Oil, Sludge Oil, Tar Oil, or other petroleum-based liquid wastes)	Thermal
NG	Natural Gas	Thermal
BFG	Blast Furnace Gas	Thermal
OG	Other Gas	Thermal
PG	Gaseous Propane	Thermal
NUC	Nuclear Fission (Uranium, Plutonium, Thorium)	Thermal
AB	Agricultural Crop Byproducts/Straw/Energy Crops	Thermal
MSW	Municipal Solid Waste	Thermal
OBS	Other Biomass Solids	Thermal
TDF	Tire-derived Fuels	Thermal
WDS	Wood/Wood Waste Solids (paper pellets, railroad ties, utility poles, wood chips, bark, an other wood waste solids)	Thermal
OBL	Other Biomass Liquids (specify in Comments)	Thermal
BLQ	Black Liquor	Thermal
SLW	Sludge Waste	Thermal
WDL	Wood Waste Liquids excluding Black Liquor (BLQ) (Includes red liquor, sludge wood, spent sulfite liquor, and other wood-based liquids)	Thermal
LFG	Landfill Gas	Non-Thermal
OBG	Other Biomass Gas(includes digester gas, methane, and other biomass gases)	Thermal
GEO	Geothermal	Non-Thermal
WAT	Water at a Conventional Hydroelectric Turbine	Non-Thermal
SUN	Solar	Non-Thermal
WND	Wind	Non-Thermal
WAT	Pumped Storage Hydroelectric	Non-Thermal

PUR	Purchased Steam	Non-Thermal
WH	Waste heat not directly attributed to a fuel source. Note that WH should only be reported where the fuel source for the waste heat is undetermined, and for combined cycle steam turbines that are not supplementary fired	Non-Thermal
OTH	Other	Non-Thermal

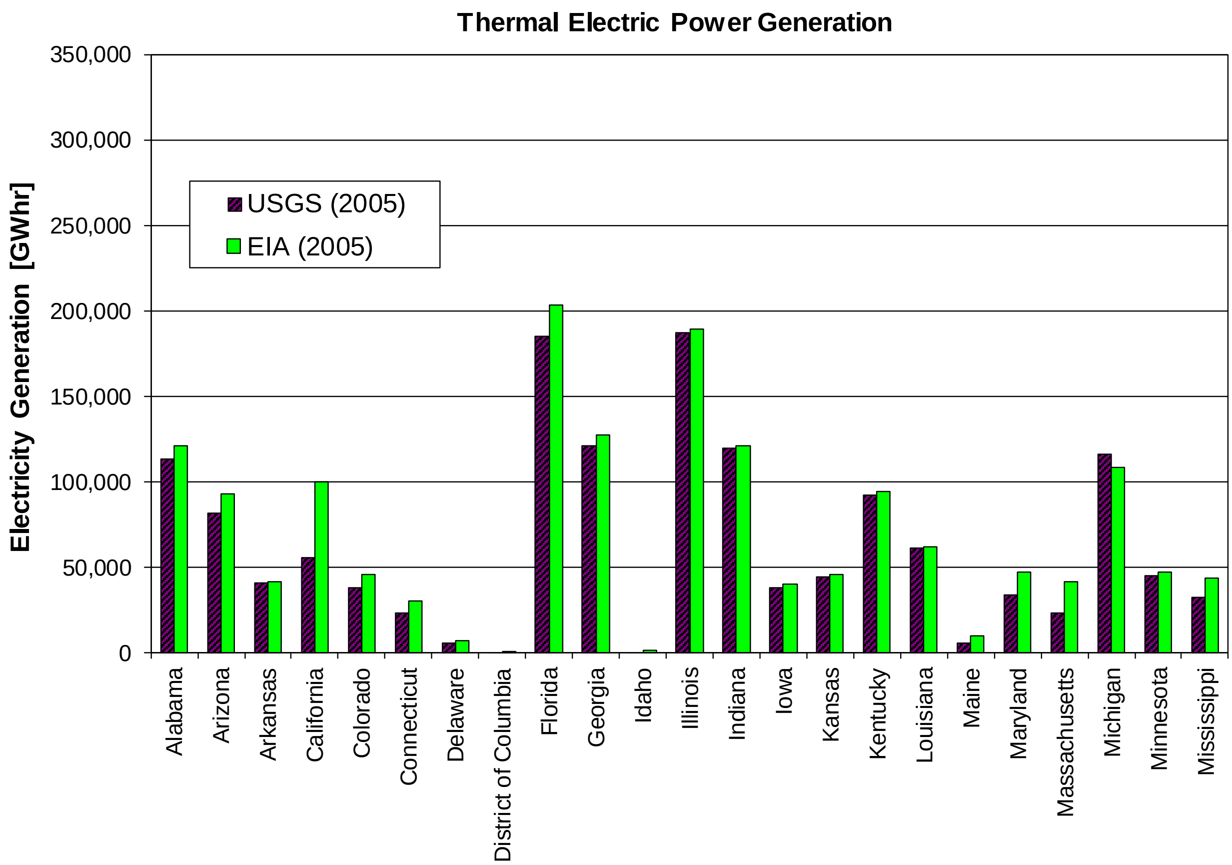

Figure D1. Thermal electric power generation comparison between the USGS data, and EIA form 906/920.

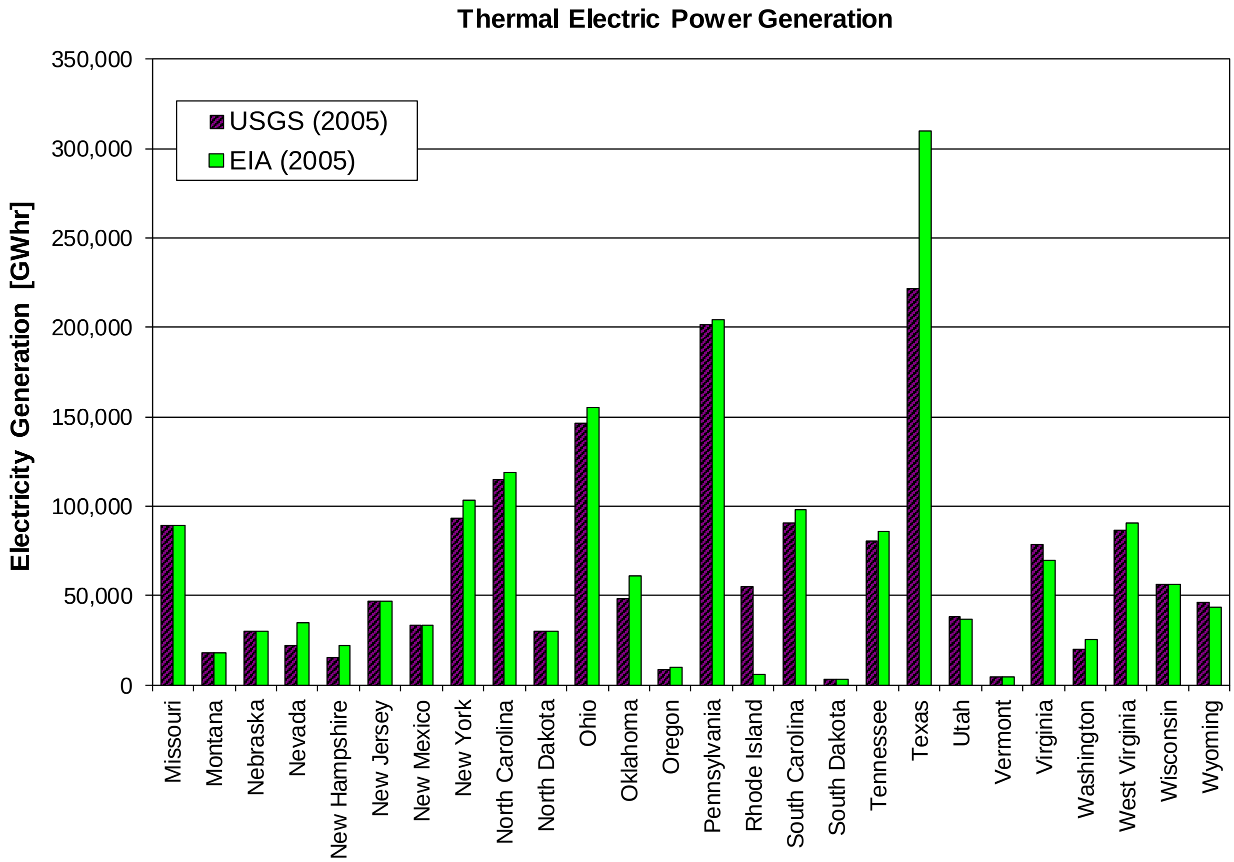

Figure D2. Thermal electric power generation comparison between the USGS data, and EIA form 906/920.

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