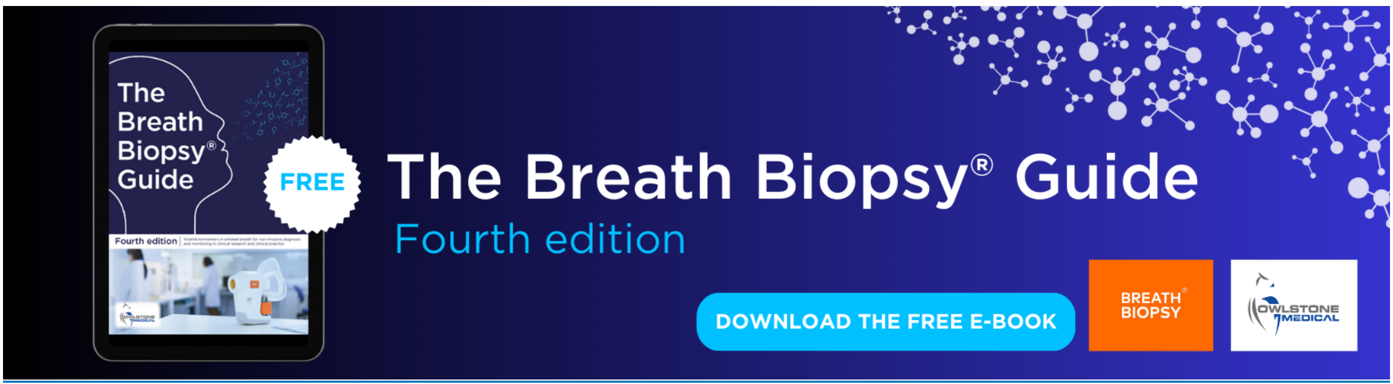
ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

The water implications of generating electricity: water use across the United States based on different electricity pathways through 2050

To cite this article: J Macknick *et al* 2012 *Environ. Res. Lett.* **7** 045803



OPEN ACCESS
IOP PUBLISHING ENVIRONMENTAL RESEARCH LETTERS
Environ. Res. Lett. **7** (2012) 045803 (10pp) doi:10.1088/1748-9326/7/4/045803

The water implications of generating electricity: water use across the United States based on different electricity pathways through 2050

J Macknick[1], S Sattler[2], K Averyt[3], S Clemmer[2] and J Rogers[2]

[1] National Renewable Energy Laboratory, Golden, CO 80401-3305, USA
[2] Union of Concerned Scientists, Cambridge, MA 02238-3780, USA
[3] Cooperative Institute for Research in Environmental Sciences, Boulder, CO 80309-0216, USA

E-mail: jordan.macknick@nrel.gov, ssattler@ucsusa.org, kristen.averyt@colorado.edu, sclemmer@ucsusa.org and jrogers@ucsusa.org

Received 28 August 2012
Accepted for publication 26 November 2012
Published 20 December 2012
Online at stacks.iop.org/ERL/7/045803

Abstract
The power sector withdraws more freshwater annually than any other sector in the US. The current portfolio of electricity generating technologies in the US has highly regionalized and technology-specific requirements for water. Water availability differs widely throughout the nation. As a result, assessments of water impacts from the power sector must have a high geographic resolution and consider regional, basin-level differences. The US electricity portfolio is expected to evolve in coming years, shaped by various policy and economic drivers on the international, national and regional level; that evolution will impact power sector water demands. Analysis of future electricity scenarios that incorporate technology options and constraints can provide useful insights about water impacts related to changes to the technology mix. Utilizing outputs from the regional energy deployment system (ReEDS) model, a national electricity sector capacity expansion model with high geographical resolution, we explore potential changes in water use by the US electric sector over the next four decades under various low carbon energy scenarios, nationally and regionally.

Keywords: energy water nexus, electricity, freshwater demands

1. Introduction

The electricity sector in the United States has a significant impact on national and regional water resources and is highly dependent on water. The United States Geological Survey (USGS) has estimated that 41% of all freshwater withdrawals in the United States in 2005 were for the electricity sector, primarily for thermoelectric cooling needs (Kenny *et al* 2009). Although water consumption for electricity generation accounts for a much small portion of total water consumption (3%) (Solley *et al* 1998), it can have impacts in places with low water availability or high water temperatures (Averyt *et al* 2012). The future development of the power sector will have important impacts on regional water resources, while the availability of water resources can impact the types of power plants and cooling systems that are built. Consequently, the power sector may also be vulnerable to variability in water quantities (e.g. drought), especially those that may result from potential climatic changes (Dai 2010, Van Vliet *et al* 2012, Averyt *et al* 2012). The 2007 drought in the southeast exposed many thermal generators, including Browns Ferry nuclear plant, to water-related shut downs and curtailments due to high discharge temperatures and shallow or exposed cooling water inlet locations (NETL 2009b).

Power plants can impact the quality and quantity of local water resources. For this study, we consider two quantity-related impacts on water resources: withdrawal and consumption. According to the USGS, 'withdrawal' is defined as the amount of water removed from the ground or diverted from a water source for use, while 'consumption' refers to the amount of water that is evaporated, transpired, incorporated into products or crops, or otherwise removed from the immediate water environment (Kenny *et al* 2009). Both water withdrawal and consumption values are important indicators for water managers and other stakeholders determining power plant impacts and vulnerabilities associated with water resources. Once-through cooled facilities withdraw large amounts of water, increase the temperature of the water when it is returned, and can impact aquatic ecosystems, depending on local water availability (Reynolds 1980, EPA 2011). Recirculating cooling systems (or closed-loop) withdraw less, but consume more water per unit of generation than once-through systems on similar power plants, which could have important consequences in times of low water availability (Macknick *et al* 2011).

Low carbon energy technology choices can have different impacts on water resources, depending on energy source and cooling system decisions (Cooper and Sehlke 2012). Renewable energy sources, including non-thermal renewables (e.g., solar photovoltaics and wind) and thermal renewables (e.g., geothermal and concentrating solar power), along with non-renewables (e.g., nuclear, fossil technologies with carbon capture and storage, or CCS) have a wide range of water impacts (Macknick *et al* 2011). Some state agencies, as well as the Environmental Protection Agency, have recognized the connections between energy and water and have proposed policy actions to address the impacts of power plants' water use and the environmental impacts of their cooling systems (CSLC 2006, Kyl 2010, NYSDEC 2010, EPA 2011).

Prior efforts have examined water-related impacts of future electricity production on national and North American Electric Reliability Corporation (NERC) regions. This study goes beyond these efforts through consideration of highly detailed regional analysis of water impacts based on a regionalized electricity model. EPRI (2011) and Roy *et al* (2012) consider regional impacts of water withdrawal in the electricity sector, but the regional electricity demand is developed at the NERC level and disaggregated according to existing generation and transmission, not taking into consideration the impacts of new generation and transmission or water consumption (EPRI 2011, Roy *et al* 2012). Other studies that consider electricity generation at the NERC region or sub-region level (NETL 2009a, Elcock 2010, Chandel *et al* 2011, Cooley *et al* 2011) do not have sufficient geographic resolution to adequately evaluate highly localized water impacts. Van Vliet *et al* (2012) assessed the relative vulnerability of existing power plants (select plants in the United States and Europe) to projected changes in cooling water source temperatures and flows, but not on scales that are policy relevant for state water managers (Van Vliet *et al* 2012).

This paper evaluates the water implications of a range of future electricity generation mixes in the United States expected to have appreciably different water profiles and impacts at a regional level that is relevant for policymakers and water managers (Clemmer *et al* 2012). Because of the large role of the power sector in contributing to and potentially mitigating climate change, several of our scenarios incorporate deep cuts in carbon emissions in the electricity sector. Generating diverse electricity mixes allows for an examination of water use at broad scales and of how mixes emphasizing different technologies might fare, particularly during droughts and considering competing uses. The results of this work can be used in conjunction with other estimates of future water availability (EPRI 2011, Harto *et al* 2011, Roy *et al* 2012) to identify areas that may see competition for water resources between the energy sector and other sectors.

2. Methodology

The sections below describe our choice of electricity scenarios and water use assumptions analyzed in this study.

2.1. Electricity scenarios

As described in Clemmer *et al* (2012), we consider four electricity scenarios: one reference scenario and three carbon-constrained scenarios emphasizing different low carbon technologies. The reference scenario (scenario 1) is patterned off of EIA's Annual Energy Outlook 2011 (AEO 2011) reference case. Scenario 2 assumes that the United States meets the electricity sector's share of a cumulative economy-wide carbon budget of 170 gigatons of CO_2eq from 2012 to 2050 through economic competition of low carbon technologies. Scenarios 3 and 4 include the electricity sector's share of the US CO_2eq emissions budget plus additional targets for specific low carbon technologies. For scenario 3, we assume nuclear generation would grow from approximately 20% of the US electricity mix today to 29% in 2035 and 36% in 2050, while coal with CCS would grow to 15% of the generation mix by 2035 and 30% by 2050. For scenario 4, we assume aggressive deployment of energy efficient technologies and buildings would reduce US electricity demand 20% by 2035 and 35% by 2050 versus the reference case, while generation from renewable energy technologies (wind, solar, geothermal, biomass and hydropower) increases from 10% in 2010 to 50% in 2035 and 80% by 2050.

The national electricity capacity expansion model used to analyze these scenarios, the regional electricity deployment system (ReEDS), forecasts the deployment of supply side generation and transmission capacity for the power sector in the contiguous United States in two year increments to the year 2050 (Short *et al* 2009). ReEDS is a long-term capacity expansion and dispatch model that represents all major generation technologies, including coal, natural gas combined cycle, natural gas combustion turbines, fossil fuels with carbon capture and storage (CCS), nuclear, hydropower, wind, solar, geothermal, biopower and storage. It is unique among capacity expansion models for its highly discretized regional structure and statistical treatment of the impact of variability of wind and solar resources on capacity planning and dispatch. Further details of the electricity scenarios and modeling assumptions can be found in Clemmer *et al* (2012).

2.2. Application of water use factors

Water withdrawal and consumption coefficients are applied in a consistent functional unit of gallons per MWh of electricity generated and are adapted from Macknick *et al* (2012) as utilized in Averyt *et al* (2011). Only operational freshwater uses are analyzed by region, but use of saline water is also tracked. Water use rates are assumed to be constant over the duration of the analysis, though any changes in technologies' thermal efficiencies could alter those rates. We aggregate fuel and cooling type technologies from existing plants to match ReEDS technologies along with fuel and cooling system categories discussed in Macknick *et al* (2012). Median withdrawal and consumption factors are utilized for all technologies.

All existing coal and nuclear plants are matched with the generic category in Macknick *et al* (2012) which includes estimates of water usage for a variety of different types and vintages of plants. For concentrating solar power (CSP) technologies, which include both parabolic trough and power tower systems in ReEDS, we use dry-cooled parabolic trough systems water use rates for this analysis, with exception of the cooling system sensitivity analysis, where we considered wet-cooled parabolic trough systems. Geothermal technologies have large ranges of water use values, depending on the specific technology and whether they use externally sourced freshwater or the on-site geothermal fluids for cooling. For purposes of this study, we assume all new geothermal technologies are dry-cooled binary systems that required additional freshwater for makeup due to operational geofluid loss, per assumptions in Clark *et al* (2011). For the cooling system sensitivity analysis we consider wet/dry hybrid-cooled binary systems, which use more freshwater as part of their cooling systems. Due to data constraints, we use dedicated biopower plant values for plants that co-fire biomass with coal.

ReEDS does not consider combined heat and power (CHP) systems. Water use from CHP technologies are thus omitted, though CHP could play an important role in meeting energy efficiency reductions such as those envisioned under Scenario 4. Whereas substantial evaporation can occur from reservoirs that produce hydroelectricity, we have elected to not consider this water usage (withdrawal or consumption) due to the complexities in attributing water use to particular demands on these reservoirs, such as drinking water supply, recreation and flood control (Gleick 1992, Torcellini *et al* 2003, Pasqualetti and Kelley 2008).

Water use coefficients were applied to technology-specific generation output from each ReEDS power control area (PCA) region, based on 2008 generation data by technologies with specific cooling systems, as compiled and described in Averyt *et al* (2012). We consider only volumes of inland freshwater resources and existing wastewater utilization for regional analysis. Saline water volumes utilized in electricity production are tracked but excluded from the regional analysis. In cases where EIA does not report cooling systems for certain fuel types within a particular PCA region, the cooling system makeup for the fuel type with most generation is applied. If there is no existing generation in a PCA, new thermoelectric generation (with the exception of geothermal and CSP technologies) is assumed to be cooled with recirculating cooling systems. In addition, reflecting Environmental Protection Agency guidelines (EPA 2011), all new thermal generation is assumed to be equipped with recirculating cooling towers or dry-cooled systems, depending on existing structures in each PCA. For retirements of thermal generation, once-through cooled thermal plants within a PCA are assumed to retire prior to plants with recirculating cooling technologies. In coastal areas, retiring once-through cooled facilities utilizing saline water are assumed to be replaced by power plants utilizing freshwater in recirculating cooling systems.

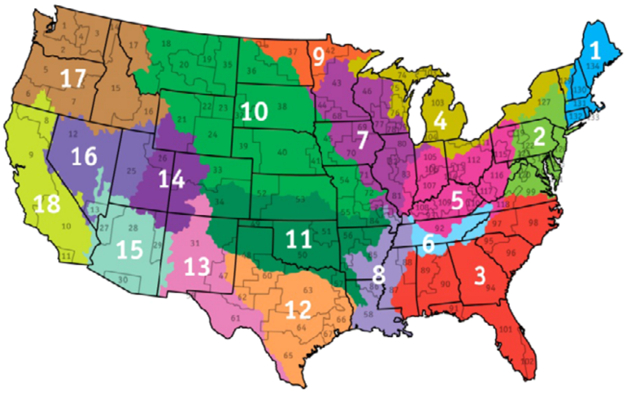


Figure 1. Mapping of ReEDS PCA regions (gray outlines) to USGS HUC-2 regions (shaded regions).

2.3. Aggregation of results by hydrologic unit code 2 (HUC-2) levels

Water withdrawal and consumption values are displayed according to USGS hydrologic unit code 2 levels (HUC-2) (Seaber *et al* 1987). Water values are calculated based on electricity generation by PCA region as calculated by ReEDS and then distributed to HUC-2 regions on a land area basis. Figure 1 shows the mapping of ReEDS PCA regions to USGS HUC-2 regions. For a PCA entirely within a HUC-2 region, all generation and water use in the PCA is attributed to the HUC-2. For a PCA that overlaps with multiple HUC-2 regions, generation and water use from the PCA are apportioned to overlapping HUC-2 regions based on the per cent of the HUC-2 region inside each PCA region. No attempts are made to project water demands from other sectors or any metrics of water availability.

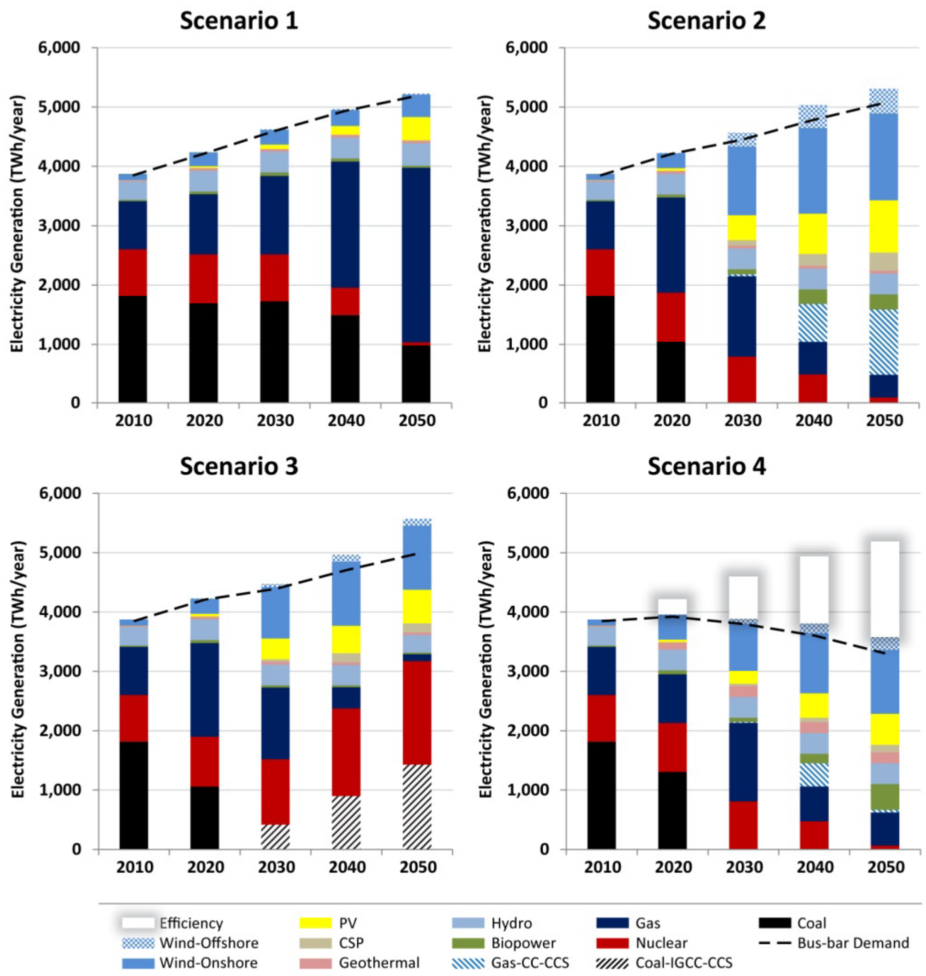


Figure 2. National electricity generation by scenario. Results from the ReEDS model indicate a variety in total electricity generation values and deployed electricity generation technologies in 2030 and 2050. Scenario 1, reference case; scenario 2, carbon budget, no technology targets; scenario 3, carbon budget with coal with CCS and nuclear targets; scenario 4, carbon budget with efficiency and renewable energy targets.

3. Results

Using the ReEDS model to explore the four electricity scenarios, we compare national- and regional-level water withdrawal and consumption impacts.

3.1. Electricity generation

Results from the ReEDS modeling show a range of electricity generation technologies deployed between 2010 and 2050 under the four scenarios (figure 2). Under the reference case (scenario 1), natural gas becomes the dominant fuel for generating electricity, while renewable energy experiences more modest growth, to meet the projected increase in electricity demand and replace coal and nuclear plants retired in the ReEDS model analysis. Under the carbon budget scenarios (scenarios 2–4), conventional coal generation is largely phased-out by 2030. Under scenario 2, conventional natural gas generation increases in the early years to replace coal and reduce power plant carbon emissions, while renewable generation (particularly wind and solar) and natural gas with CCS make significant contributions in the last half of the forecast. Under scenario 3, coal with CCS and nuclear steadily increase after 2020, providing approximately two-thirds of total US generation by 2050, while renewable energy technologies provide most of the remaining generation. Under scenario 4, energy efficiency more than eliminates the projected growth in electricity demand, while wind and solar increase to meet a large share of the renewable energy target of 80% by 2050.

3.2. Electricity sector water withdrawals

Based on the results of the ReEDS model analysis, national-level water withdrawals steadily decrease from 2010 values under all scenarios (figure 3). Compared with 2010 withdrawals, 2030 annual withdrawals decrease by 10.6 trillion gallons (26.6%), 27.6 trillion gallons (69.2%), 26.7 trillion gallons (67.0%) and 27.7 trillion gallons (69.5%) for scenarios 1–4, respectively. By 2050, these scenarios have reduced water withdrawals from 2010 by 32.2 trillion gallons (80.7%), 37.9 trillion gallons (95.1%), 29.9 trillion gallons (75.2%) and 38.7 trillion gallons (97.0%), respectively.

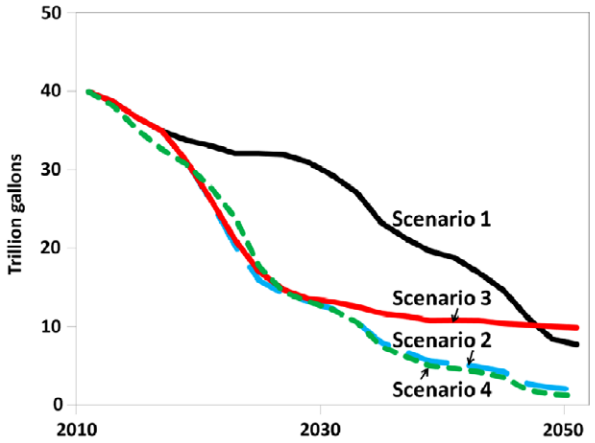


Figure 3. National-level water withdrawal results for four electricity scenarios. Scenario 1, reference case; scenario 2, carbon budget, no technology targets; scenario 3, carbon budget with coal with CCS and nuclear targets; scenario 4, carbon budget with efficiency and renewable energy targets.

The universal reduction in withdrawals is largely due to the retirement of once-through cooled thermal generation and the construction of new facilities utilizing recirculating cooling technologies. In addition, high penetration of renewable technologies with minimal water requirements and energy efficiency reduce water withdrawals. Specifically, scenario 1 reductions are primarily due to retirements of some coal and nuclear plants, including those that utilize once-through cooling, along with the construction of new natural gas combined cycle facilities, which have a lower water withdrawal requirement than coal and nuclear facilities. Scenario 2 reductions are primarily due to the gradual phase-out of coal power plants and the increase in new natural gas combined cycle facilities between 2010 and 2030, and further coal and nuclear retirements along with high renewable penetration between 2030 and 2050. Scenario 3 reductions are a result of existing once-through cooled coal and nuclear facilities being replaced by newer coal and nuclear facilities that utilize recirculating cooling technologies, which have lower withdrawal rates. As coal and nuclear technologies still have higher withdrawal rates than natural gas combined cycle plants, however, by 2050 scenario 3 withdrawals are higher than those of scenario 1. Scenario 4 reductions are driven by a combination of energy efficiency, which reduces overall electricity demand and associated water requirements, and the high penetration of renewable technologies, which generally require less water than non-renewable technologies.

Despite substantial national-level reductions in withdrawals, regional withdrawal impacts vary greatly by scenario (figure 4).

Certain HUC-2 regions in the northeast (1, 2), southeast (6) and northwest (17) mirror national trends and show substantial reductions in withdrawals under all scenarios for both 2030 and 2050. Other HUC-2 regions in the southeast (3, 8), Midwest (4, 5, 7, 9) and central (10) parts of the nation show only modest reductions in withdrawals by 2030 for scenario 1, with more substantial reductions by 2050. The southwest (13, 14, 15) and south central (11, 12) regions of the nation show only modest reductions in withdrawals by 2030 and 2050 under scenario 1. Two HUC-2 regions in the west (16, 18) show increases in freshwater withdrawals in both 2030 and 2050. These western regions (including parts of California, Nevada and Utah) show increases in water withdrawals in scenario 1 largely due to new electricity demands in the region. In addition, California shows increases in freshwater withdrawals largely due to once-through coastal facilities (which withdraw saline water) retiring and being replaced by inland (freshwater-cooled) energy generating sources. Regions 12 and 15 (parts of Texas and Arizona, respectively), show decreases in withdrawals by 2030 for scenario 3, but substantial increases in withdrawals by 2050 as more coal with CCS and nuclear technologies are adopted in these regions. Under scenario 2, withdrawals increase from 2030 to 2050 for region 18, but the 2050 value is only 57.1% of the 2010 freshwater withdrawals. Scenario 4 shows substantial reductions in withdrawals for all regions in 2030 and 2050.

3.3. Electricity sector water consumption

National-level water consumption trajectories vary widely depending on energy scenario (figure 5). Compared with 2010, scenario 1 shows an increase in national water consumption of 8.5 billion gallons (0.6%) by 2030, but a decrease of 460 billion gallons (34.2%) by 2050. Scenario 3 leads to a 470 billion gallon (35.0%) reduction by 2030, though subsequent increases in consumptive uses lead to a net increase of 190 billion gallons (21.7%) from 2010 values. Scenarios 2 and 4 follow a similar decreasing trajectory until 2030, reducing consumptive uses by 810 (60.0%) billion gallons by 2030, yet diverge from 2030 to 2050. In 2050, total reductions in consumption for scenario 2 are 750 billion gallons (55.4%), whereas scenario 4 leads to reductions of 1.1 trillion gallons (85.2%) from 2010 values.

National consumption trends are slightly different than withdrawal trends due to different relative withdrawal and consumption factors for the energy technologies and cooling systems deployed. Under scenario 1, consumption in 2030 increases from 2010 as a result of increased electricity demand being met by primarily natural gas combined cycle plants, with no substantial reduction in coal and nuclear generation. By 2050, coal and nuclear generation is substantially reduced and replaced with natural gas combined cycle generation, which has a lower consumption rate than coal and nuclear generation. Scenario 2 consumption decreases greatly from 2010 to 2030 due to coal plant retirements, and then increases from 2030 to 2050 as a result of building new natural gas combined cycle plants with CCS. Scenario 3 consumption declines sharply from 2010 to 2030 due to the retirement of conventional coal facilities and additional natural gas combined cycle generation. From 2030 to 2050, consumption increases due to increased deployment of coal with CCS and nuclear facilities utilizing recirculating cooling technologies, which have higher water consumption rates than

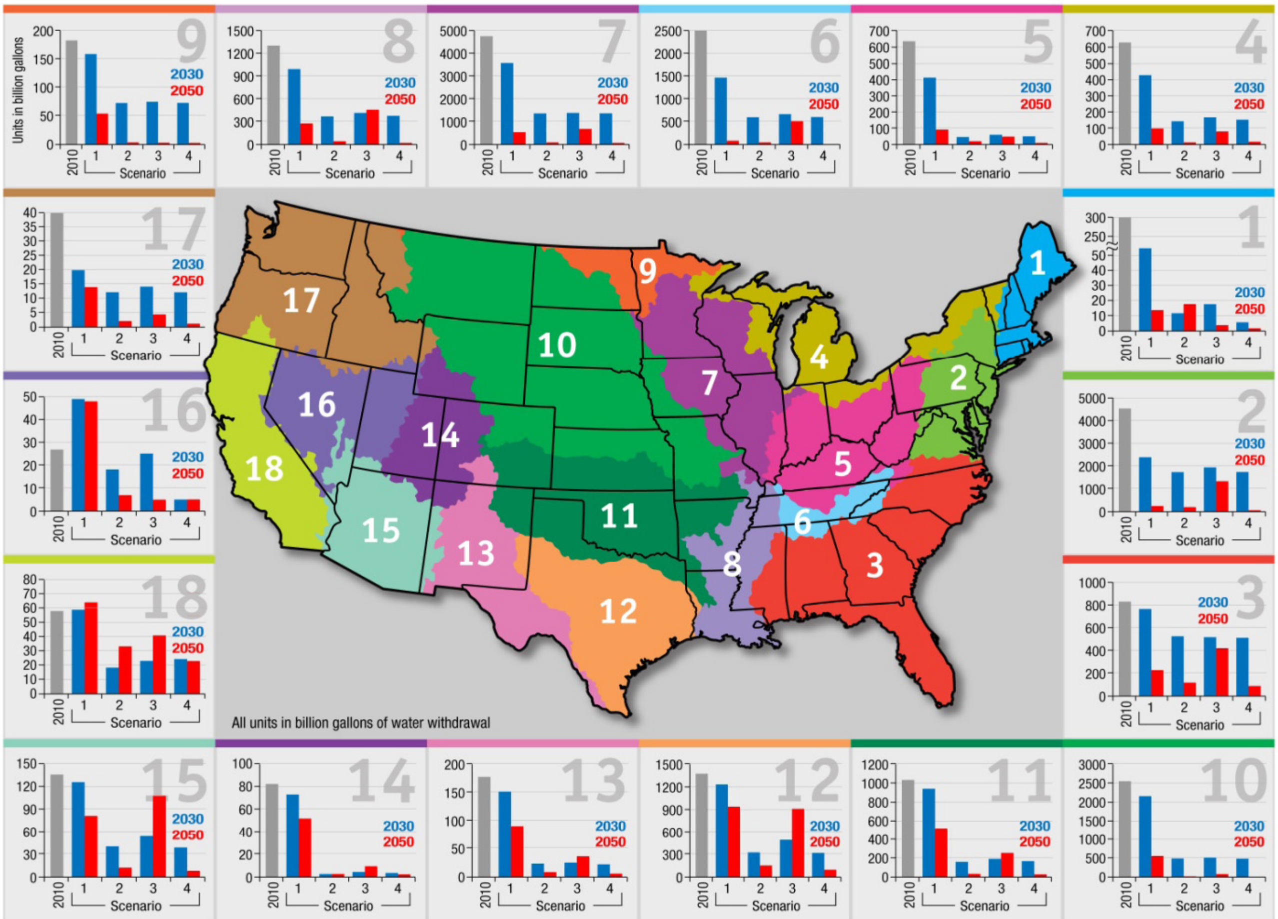


Figure 4. Water withdrawal results (in billion gallons per year) for 2030 (blue bars) and 2050 (red bars) by HUC-2 region for electricity Scenarios 1–4; scenario 1, reference case; scenario 2, carbon budget, no technology targets; scenario 3, carbon budget with coal with CCS and nuclear targets; scenario 4, carbon budget with efficiency and renewable energy targets; *y*-axes have different scales and are for intra-region comparison purposes.

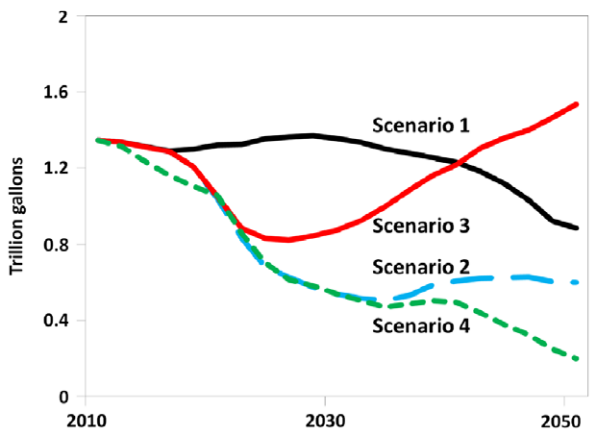


Figure 5. National-level water consumption results for four electricity scenarios. Scenario 1, reference case; scenario 2, carbon budget, no technology targets; scenario 3, carbon budget with coal with CCS and nuclear targets; scenario 4, carbon budget with efficiency and renewable energy targets.

other technologies. Scenario 4 national water consumption declines steadily due to a reduction in total energy demand and increased penetration of renewable technologies.

Similar to withdrawal impacts, regional changes in consumptive uses vary greatly by energy scenario and may differ from national trends (figure 6).

In particular, scenarios 1 and 3 lead to changes in water consumption in many regions (figure 6) that may differ from national trends (figure 5). Compared with 2010 values, scenario 1 leads to a slight increase in consumptive uses in 2030; this national-level increase is a result of increases in consumption for certain HUC-2 regions representing the southeast (3, 8), southwest (16, 18), northwest (17) and central (10, 11, 12) parts of the nation. The majority of regions in the US show reductions in expected consumptive use. By 2050, although national levels of consumptive uses decrease, HUC-2 regions in the northeast (1) and the southwest (16, 18) show increases in consumptive uses. Increases in consumption in the southeast (3, 8) and central (10, 11, 12) regions are largely due to the retirement of once-through coal and nuclear facilities, which are replaced by new power plants operating with recirculating cooling systems. The switch from technologies utilizing once-through systems to technologies utilizing recirculating systems contributes to the decrease in withdrawals in the southeast (3, 8) and central (10, 11, 12) regions, yet increased consumption levels. Increases in

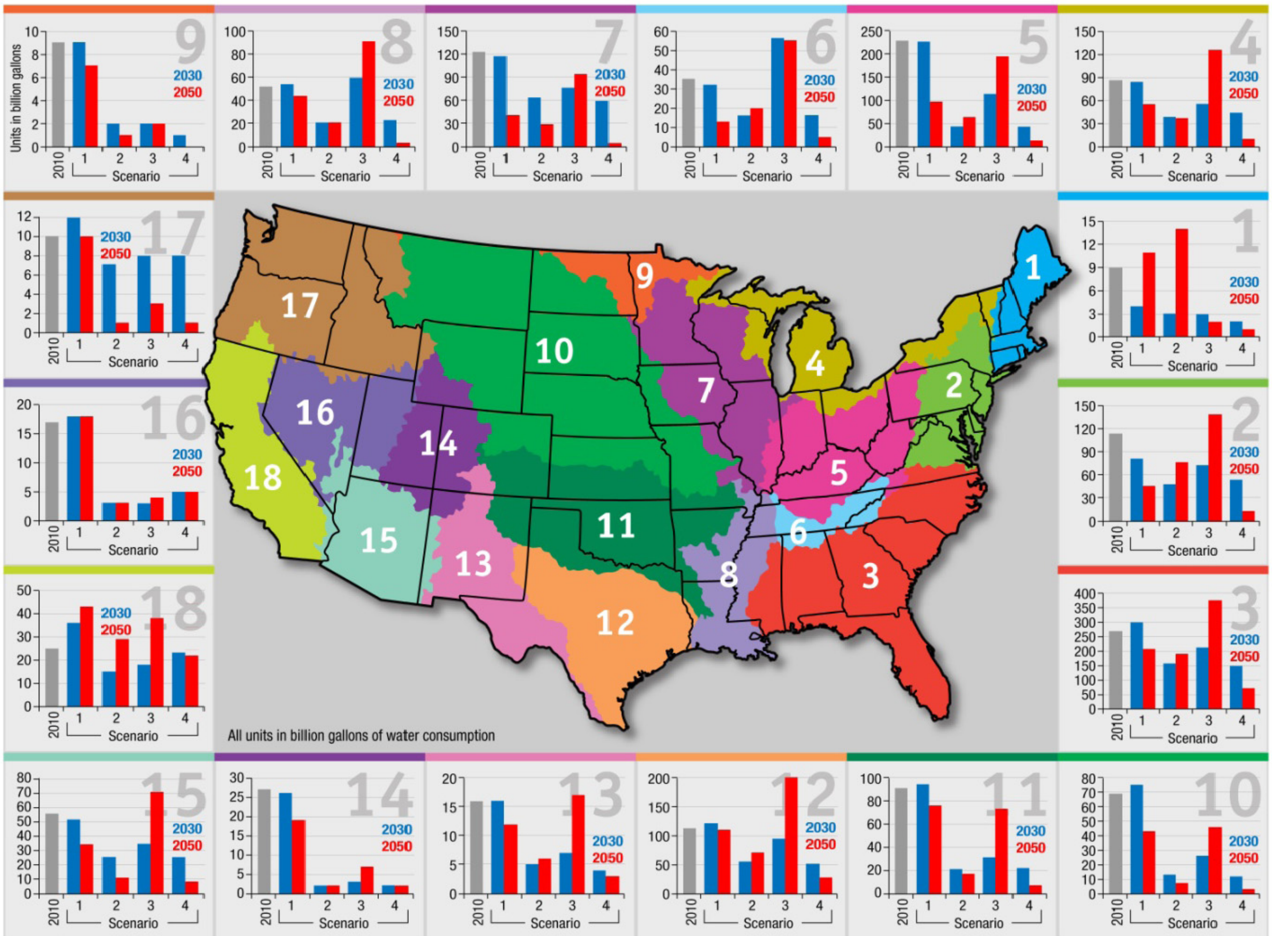


Figure 6. Water consumption results (in billion gallons per year) for 2030 (blue bars) and 2050 (red bars) by HUC-2 region for electricity Scenarios 1–4; scenario 1, reference case; scenario 2, carbon budget, no technology targets; scenario 3, carbon budget with coal with CCS and nuclear targets; scenario 4, carbon budget with efficiency and renewable energy targets; *y*-axes have different scales and are for intra-region comparison purposes.

consumption in the southwest (16, 18) and the northwest (17) regions in scenario 1 are largely due to the construction of new recirculating cooling systems in areas that currently have no generation or have predominantly hydropower generation. Under scenario 3, national levels of consumption decrease in 2030 (figure 5), yet HUC-2 regions 6 and 8 in the southeast show increases in consumptive uses (figure 6). By 2050, after substantial increases in nuclear and coal with CCS generation, consumption increases from 2010 values in a variety of regions in the Mid-Atlantic (2), Great Lakes (4), southeastern (3, 6, 8), central (12) and southwestern (13, 15, 18) parts of the country. All other regions (1, 5, 7, 9, 10, 11, 14, 16, 17) show decreases in consumption in 2050 from 2010 values. Scenario 2 shows reductions in consumption for all regions except regions 1 and 18 in 2050. Scenario 4 leads to reductions in consumption for all regions in both 2030 and 2050.

3.4. Renewable technology cooling technology sensitivities

Certain renewable energy technologies (e.g., concentrating solar power and geothermal) deployed in arid regions can have higher water consumption rates than non-renewable energy technologies (Macknick *et al* 2011). We conducted sensitivity analyses associated with the choice of cooling systems for geothermal and concentrating solar power technologies in scenario 4 in 2050, which achieves the highest level of penetration for these technologies in the ReEDS model analysis. Due to resource availability, deployment of these technologies only occurs in western states. Under a wet/hybrid-cooled variation of scenario 4, where all concentrating solar power systems are wet-cooled and all geothermal systems are cooled utilizing wet/dry hybrid-cooling systems, national-level water consumption in 2050 increases by 80 billion gallons (41.5%) from scenario 4 with the dry-cooling assumption. Regionally, water consumption changes depending on the level of geothermal and concentrating solar power penetration in each region, with regions experiencing more concentrating solar power deployment having higher consumptive impacts (figure 7).

Overall, deploying geothermal and CSP with dry-cooling lead to substantial reductions in water consumption in 2050 from 2010 values. Utilizing wet-cooled systems for these technologies increases water consumption over dry-cooling, but overall water consumption is still reduced from a 2010

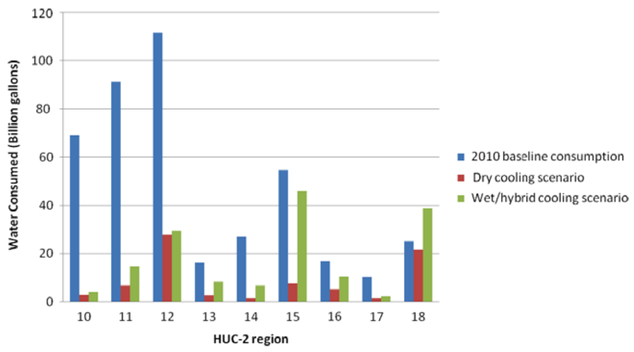


Figure 7. Comparison of water consumption by HUC-2 region in 2050 for scenario 4 employing different cooling system assumptions for renewable technologies.

baseline. The only region where the wet/hybrid assumption pushes total consumption over 2010 values in the model is in region 18 (i.e., California), but the likelihood of that occurring is small as California prohibits the use of freshwater for cooling in desert regions (CEC 2009).

4. Discussion

Reductions in national water withdrawals (figure 3) and consumptive uses (figure 5) appear in each electricity scenario, yet higher resolution results provide more insight for water management. Water resources are managed on relatively small spatial scales that may cross state and national political boundaries. Providing projections of future water use from the electric sector on a watershed level (HUC-2 region) may be more useful for water managers than providing estimates at a national-, state- or FERC region level; examining results by region may (as in our cases) provide results that differ importantly from national ones. A watershed-level approach also facilitates analysis with estimates of current and projected water availability metrics.

At the national level, for 2030 and 2050, all electricity scenarios modeled in this analysis lead to reductions in water withdrawals (figure 3). However, two regions in the arid west (16, 18) show increases in withdrawals for both time periods under scenario 1, the reference case (figure 4). In these areas, there may be limited freshwater available for use in the power sector, or it may be required to transfer water rights from other sectors (e.g., agriculture) to the power sector to meet the increased power sector water demand. Withdrawals decline in most regions due to the retirement of once-through cooled facilities that are replaced with recirculating cooled facilities. In areas where there are few existing once-through cooled freshwater facilities, such as in regions 16 and 18, increases in generation can lead to overall increases in freshwater withdrawals. In areas that have plants with once-through cooling, transitioning to recirculating cooling systems, regardless of fuel choice, leads to reductions in water withdrawals. As recent power plant curtailments in the southeast and elsewhere were primarily related to the weather-related impacts on once-through cooled facilities, such as insufficient water supplies to meet high volume withdrawals and increased temperatures of discharged water, reductions in withdrawal requirements may lead to a greater resilience against water-related curtailments for power plants in many regions.

The reductions in withdrawals resulting from switching from once-through cooled systems to recirculating systems is accompanied by an increase in consumption for some regions. Under scenario 1, as national-level withdrawals decline (figure 3), total national-level consumptive uses increase by the year 2030 (figure 5), driven by increases in eight regions (3, 8, 10, 11, 12, 16, 17, 18) in the southeast, central, northwest and southwest parts of the nation (figure 6). Many of these regions have experienced droughts in recent years; increased droughts or other reductions in water availability could affect availability of water for the power sector. As national-level withdrawals continue to decline in scenario 3 from 2030 to 2050 (figure 3), consumption increases in 9 regions (2, 3, 4, 6, 8, 12, 13, 15, 18) in the east, southeast, Midwest and southwest parts of the nation (figure 6), driving increases in national consumption totals (figure 5). In cases where national-level water consumption decreases, many regions may still show increases in consumption. For example, from 2030 to 2050, scenario 1 shows decreases in national levels of water consumption (figure 5), yet during this same period consumptive uses in some northeast and southwest regions (1, 16, 18) rise above 2010 values (figure 6). In addition, from 2010 to 2030, scenario 3 consumptive uses decline on a national level (figure 5), yet increase in two regions (6, 8) in the southeast (figure 6).

High renewable energy penetration scenarios lead to the most substantial reductions in water withdrawals and consumption, with energy efficiency and conservation providing the greatest water savings. Scenarios 2 and 4 both show greater than 50% renewable penetration by 2050 and only two regions (1, 18) in the northeast and California in scenario 2 show increases in consumption in 2050 (figure 6). In contrast, for scenarios 1 and 3, which have non-renewable technologies providing more than 50% of generation in 2030 and 2050, 14 of the 18 regions show an increase in either withdrawals or consumption in 2030 or 2050. In regions 16 and 18 in the west, freshwater consumption in 2030 is greater under scenario 4 (with high renewable penetration) than scenarios 2 and 3 (figure 6). This is largely driven by the deployment of geothermal and solar technologies into these areas in scenario 4. Scenario 4 levels of consumption in 2030 for regions 16 and 18 are, however, lower than scenario 1 and 2010 baseline values (figure 6). By 2050, consumption in region 16 remains higher than that in scenarios 2 and 3 and below that of scenario 1 and the 2010 baseline. For region 18, consumption in 2050 for scenario 4 is the lowest of all scenarios.

A high degree of spatial resolution in this study assists in targeting specific areas for future analysis that may be overlooked when analyzing data on a national or state level. National-level reductions in withdrawals or consumptive uses may be a result of large changes in some regions, while increases may be occurring in other regions, such as in the southwest and southeast. Future, more granular studies could be conducted in the southeastern and southwestern parts of the nation, which historically have seen increasing energy–water competition and which consistently show potential water usage increases under the electricity scenarios considered in this study. Electricity generation and deployment in these areas could be limited by water availability, increasing demands from other sectors, or legal availability related to the water transfers between water rights holders (e.g., agriculture and municipal). In some areas, large increases in water withdrawals or consumptive uses by the power sector or any other sector by 2030, combined with potential climatic changes such as droughts, could prompt policy changes that affect future energy and water management decisions. However, we did not evaluate water availability as a constraint, nor did we evaluate climatic changes and how those could affect decision-making. Future analyses should evaluate these issues.

Freshwater usage associated with many renewable and non-renewable technologies could be reduced by utilizing alternative water resources (e.g., shallow brackish water) or by utilizing dry-cooling technologies, yet these technologies and options incur additional costs and performance penalties and may affect power plant siting decisions.

5. Conclusions

This work provides an initial assessment of the water impacts of various electricity scenarios at a USGS HUC-2 region level. The four scenarios considered show reductions in national-level electricity sector water withdrawals for both 2030 and 2050, largely due to the retirement of once-through cooled facilities and the building of power plants with recirculating cooling systems. National-level electricity sector consumptive uses decline in 2030 for all low carbon scenarios, while the reference case, scenario 1, shows a slight increase. By 2050, all scenarios have lower consumption levels than 2010 except for scenario 3, which includes high penetration of coal with CCS and nuclear technologies.

Regional trends may differ substantially from national-level results. Western regions (including parts of California, Nevada and Utah) show increases in withdrawals under scenario 1 for both 2030 and 2050, and other parts of the south and southwest (including Arizona and Texas) show increases in withdrawals from 2030 to 2050 under scenario 3. Considering consumptive uses, scenario 1 leads to increases in 2030 for areas in the southeast, southwest and central parts of the nation, and scenario 3 leads to increases in Mid-Atlantic, Great Lakes, southeastern, Texas and southwestern states. In general, regional increases in consumption and withdrawals are associated with scenarios 1 and 3, whereas the scenarios 2 and 4 show consistent reductions.

This high-level analysis provides insight to decision-makers on water-relevant spatial scales related to the impacts of future electricity scenarios on water resources. Future research of this nature is recommended, including a more detailed study on the impacts for specific geographic regions that may see increases in withdrawal or consumption, analysis of additional electricity generation scenarios, evaluation of different cooling system policies and technologies, and an assessment of how total projected water usage for power plants and other sectors compares with projected water availability in each region.

Acknowledgments

We gratefully acknowledge the research oversight provided by the EW3 Scientific Advisory Committee—Peter Frumhoff (Union of Concerned Scientists), George Hornberger (Vanderbilt University), Robert Jackson (Duke University), Robin Newmark (NREL), Jonathan Overpeck (University of Arizona), Brad Udall (University of Colorado Boulder, NOAA Western Water Assessment) and Michael Webber (University of Texas at Austin). In addition, we received helpful feedback and assistance from Anthony Lopez, Trieu Mai and Laura Vimmerstedt (NREL), as well as Michelle Schmoker (Union of Concerned Scientists). We also wish to thank Al Hicks and Scott Gossett of NREL for their graphical assistance.

References

Averyt K, Fisher J, Huber-Lee A, Lewis A, Macknick J, Madden N, Rogers J and Tellinghuisen S 2011 *Freshwater Use by US Power Plants: Electricity's Thirst for a Precious Resource* (Cambridge, MA: Union of Concerned Scientists)

Averyt K, Fisher J, Huber-Lee A, Lewis A, Macknick J, Madden N, Rogers J and Tellinghuisen S 2012 Developing a comprehensive database of power plant cooling water use: lessons learned, challenges and opportunities *Environ. Res. Lett.* at press

California Energy Commission (CEC) 2009 *Best Management Practices & Guidance Manual: Desert Renewable Energy Projects* (Sacramento, CA: California Energy Commission)

California State Lands Commission (CSLC) 2006 *Resolution by the California State Lands Commission Regarding Once-Through Cooling in California Power Plants* Proposed 13 April 2006

Chandel M K, Pratson L F and Jackson R B 2011 The potential impacts of climate-change policy on freshwater use in thermoelectric power generation *Energy Policy* **39** 6234–42

Clark C, Harto C, Sullivan J and Wang M 2011 *Water Use in the Development and Operation of Geothermal Power Plants* (Argonne, IL: Argonne National Laboratory)

Clemmer S, Macknick J, Mai T, Rogers J and Sattler S 2012 Modeling low-carbon US electricity futures to explore impacts on national and regional water use *Environ. Res. Lett.* submitted

Cooley H, Fulton J and Gleick P 2011 *Water for Energy: Future Water Needs for Electricity in the Intermountain West* (Oakland, CA: Pacific Institute)

Cooper D C and Sehlke G 2012 Sustainability and energy development: influences of selected options for greenhouse gas emissions reductions on water resources *Environ. Sci. Technol.* **46** 3509–18

Dai A 2010 Drought under global warming: a review *Wiley Interdiscip. Rev. Clim. Change* **2** 45–65

Elcock D 2010 Future US water consumption: the role of energy production *J. Am. Water Resources Assoc.* **46**

Electric Power Research Institute (EPRI) 2011 *Water Use for Electricity Generation and Other Sectors: Recent Changes (1985–2005) and Future Projections (2005–2030)* (Palo Alto, CA: EPRI)

Environmental Protection Agency (EPA) 2011 *Cooling Water Intake Structures—CWA 316(b), Basic Information* (Washington, DC: US EPA)

Gleick P 1992 Environmental consequences of hydroelectric development: the role of facility size and type *Energy* **17** 735–47

Harto C B, Yan Y E, Demissie Y K, Elcock D, Tidwell V C, Hallett K, Macknick J, Wigmosta M S and Tesfa T K 2011 *Analysis of Drought Impacts on Electricity Production in the Western and Texas Interconnections of the United States* (Chicago, IL: Argonne National Laboratory)

Kenny J F, Barber N L, Hutson S S, Linsey K S, Lovelace J K and Maupin M A 2009 *Estimated Use of Water in the United States in 2005* (*US Geological Survey Circular* vol 1344) (Reston, VA: USGS)

Kyl J 2010 *Deploying Solar Power in the State of Arizona: A Brief Overview of the Solar–Water Nexus* (Washington, DC: Office of Senator Jon Kyl)

Macknick J, Newmark R, Heath G and Hallett K C 2011 *A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies* (Golden, CO: National Renewable Energy Laboratory)

Macknick J, Newmark R, Heath G and Hallett K C 2012 Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature *Environ. Res. Lett.* submitted

National Energy Technology Laboratory (NETL) 2009a *Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements* (Pittsburgh, PA: National Energy Technology Laboratory)

National Energy Technology Laboratory (NETL) 2009b *Impact of Drought on US Steam Electric Power Plant Cooling Water Intakes and Related Water Resource Management Issues* (Pittsburgh, PA: National Energy Technology Laboratory)

New York State Department of Environmental Conservation 2010 *Best Technology Available (BTA) for Cooling Water Intake Structures* Proposed 4 March

Pasqualetti M J and Kelley S 2008 *The Water Costs of Electricity in Arizona* (Phoenix, AZ: Arizona Department of Water Resources)

Reynolds J Z 1980 *Science* **207** 367–72

Roy S B, Chen L, Girvetz E H, Maurer E P, Mills W B and Grieb T M 2012 Projecting water withdrawal and supply for future decades in the US under climate change scenarios *Environ. Sci. Technol.* **46** 2545–56

Seaber P R, Kapinos F P and Knapp G L 1987 *Hydrologic Unit Maps* (Denver, CO: United States Geological Survey) (accessed most recent data from ftp://ftp.ftw.nrcs.usda.gov/wbd/)

Short W, Blair N, Sullivan P and Mai T 2009 *ReEDS Model Documentation: Base Case Data and Model Description* (Golden, CO: National Renewable Energy Laboratory)

Solley W B, Pierce R R and Perlman H A 1998 *Estimated Use of Water in the United States in 1995* (*US Geological Survey Circular* vol 1200) (Reston, VA: USGS)

Torcellini P, Long N and Judkoff R 2003 *Consumptive Water Use for US Power Production* (Golden, CO: National Renewable Energy Laboratory)

Van Vliet M T H, Yearsley J R, Ludwig F, Vögele S, Lettenmaier D P and Kabat P 2012 Vulnerability of US and European electricity supply to climate change *Nature Clim. Change* **2** 676–81