Linking electricity and water models to assess electricity choices at water-relevant scales

S Sattler\textsuperscript{1}, J Macknick\textsuperscript{2}, D Yates\textsuperscript{3}, F Flores-Lopez\textsuperscript{4}, A Lopez\textsuperscript{2} and J Rogers\textsuperscript{1}

\textsuperscript{1} Union of Concerned Scientists, Cambridge, MA 02238-3780, USA
\textsuperscript{2} National Renewable Energy Laboratory, Golden, CO 80401-3305, USA
\textsuperscript{3} University Corporation for Atmospheric Research, Boulder, CO 80307-3000, USA
\textsuperscript{4} Stockholm Environment Institute, Davis, CA 95616-4112, USA

E-mail: ssattler@ucsusa.org, Jordan.Macknick@nrel.gov, yates@ucar.edu, Francisco.flores@sei-us.org, anthony.lopez@nrel.gov and jrogers@ucsusa.org

Received 9 August 2012
Accepted for publication 27 November 2012
Published 20 December 2012
Online at stacks.iop.org/ERL/7/045804

Abstract
Hydrology/water management and electricity generation projections have been modeled separately, but there has been little effort in intentionally and explicitly linking the two sides of the water–energy nexus. This paper describes a platform for assessing power plant cooling water withdrawals and consumption under different electricity pathways at geographic and time scales appropriate for both electricity and hydrology/water management. This platform uses estimates of regional electricity generation by the Regional Energy Deployment System (ReEDS) as input to a hydrologic and water management model—the Water Evaluation and Planning (WEAP) system. In WEAP, this electricity use represents thermoelectric cooling water withdrawals and consumption within the broader, regional water resource context. Here we describe linking the electricity and water models, including translating electricity generation results from ReEDS-relevant geographies to the water-relevant geographies of WEAP. The result of this analysis is water use by the electric sector at the regional watershed level, which is used to examine the water resource implications of these electricity pathways.

Keywords: energy–water nexus, thermoelectric water demand, energy modeling, clean energy, renewable energy

1. Introduction

Because water use for cooling power plants is a major component of water use overall in the United States, understanding how electricity-sector choices affect future water use is important. Power plant cooling accounts for over 40\% of freshwater withdrawals in the United States, principally due to thermoelectric plants using once-through cooling (Kenny \textit{et al} 2009). Withdrawals can be substantially reduced by switching to evaporative or recirculating cooling, but the switch may increase overall consumptive use (Macknick \textit{et al} 2011).

While hydrology/water management and electricity generation projections have both been widely modeled, few models link the two. Water-for-energy analyses have been conducted on national and large regional levels. Tidwell \textit{et al} (2004) developed a decision support framework for water planning for the North American Electric Reliability Corporation (NERC) regions based on projections from the US Department of Energy’s Energy Information
Administration (EIA). This analysis aggregated water use/demand at the NERC level and also performed a more detailed analysis of the upper Rio Grande, disaggregating electricity demand from the NERC region level to the watershed level. The 2012 Renewable Energy Futures study from the US National Renewable Energy Laboratory (NREL 2012) also considered future water demand of the electric sector at the sub-NERC region scale for baseline and high renewable energy penetration scenarios. Other studies (EPRI 2011 and Roy et al 2012, e.g.) also considered water use for energy at the regional level but do not take into account areas of new generation.

This paper describes an innovative platform for assessing and comparing water withdrawals and consumption under different electricity pathways at geographic and time scales appropriate for both electricity and hydrology/water management. A key component of this work is linking electricity modeling with water modeling to make it possible to analyze the water implications of various energy futures. This paper details one component of a multi-year research project to consider the water impacts of different future electricity generation scenarios in the United States (UCS 2012). This platform uses the National Renewable Energy Laboratory’s (NREL’s) Regional Energy Deployment System (ReEDS) model, which provides a high level of geographic resolution for examining different US electricity generation scenarios, and the Water Evaluation and Planning (WEAP) system, which is unique in its ability to combine hydrologic simulation with a representation of place-specific water management decisions (Yates et al 2005). For this work, we draw on a set of future electricity generation and capacity mixes developed under the broader research project and the analyses of current power plant water use by Clemmer et al (2012) and Averyt et al (2012). We also make use of the work of Macknick et al (2011), who performed a meta-analysis of published studies of cooling water use based on fuel type and cooling technology, to provide water withdrawal and consumption coefficients to calculate water use under each electricity generation scenario.

The linking of the electricity and water models is described here, and includes translating the electricity modeling results at their relevant geographies (in this case, sub-state electricity balancing areas known as power control authorities, or PCAs) to water-relevant geographies (water sub-basins). We describe our experiences in connecting these models in one of two regions of the United States where water demands associated with electricity production are particularly relevant—the southeast and the southwest. The result of this analysis, water withdrawals and consumption by the electric sector at the regional watershed level, is used by the WEAP model to further examine the water implications of these electricity pathways in the context of the overall water resource system (Yates et al 2013).

2. Methodology

The sections below describe the geographies involved in our electricity and water assessments and the details of the translation or ‘hand-shake’ of results from ReEDS (electricity generation and capacity) to WEAP (water resources). This translation includes the application of the relevant water factors that convert electricity generation into water withdrawals and consumption based on electricity generation and capacity for fossil fuel, nuclear and renewable energy power plants.

2.1. Geographies

Clemmer et al used ReEDS to model multiple electricity scenarios, four of which we included in this work. ReEDS reports the electricity capacity and generation results by type of electric power generation technology at the level of the continental United States’ 134 power control authorities (PCAs) (figure 1). This is done for a series of two-year periods between 2010 and 2050 (Short et al 2011). The PCA is the regional level at which demand requirements must be satisfied (available electricity both generated within that PCA or imported from a surrounding PCA must meet electricity demand) and at which the model represents the national transmission grid. PCA boundaries reflect electrical grid-related boundaries, political and jurisdictional boundaries, and demographic distributions.

To consider the water withdrawals and consumptive use of each electricity scenario, and the implications of that water use, we used WEAP, a computer-based decision support system for integrated water resources management and policy analysis. WEAP is a model-building tool, used to create simulations of water demand, supply, storage, water quality and other aspects of importance to allow for consideration of varying policy, hydrology, climate, land use, technology and other factors.

For the water evaluation, we create models for select basins in the southwest and southeast, figure 2. Integrating the electricity results into the WEAP-based models requires translating PCA-level electric capacity and generation results to water-relevant geographies for integration with all other water uses (e.g., municipal, industrial, and irrigated agriculture). For our analysis, the models are based on WEAP’s ‘catchment objects’ derived from a customized version of the 8-digit Watershed Boundary Dataset or HUC-8.

Figure 1. Map of the 134 power control authorities (PCAs) within the continental United States.

![Figure 1. Map of the 134 power control authorities (PCAs) within the continental United States.](image-url)
Figure 2. HUC-8 regions in the southwest and southeast. Red outlined regions represent PCAs and colored regions represent HUC-8s (89 regions in the southwest, left, and 28 regions in the southeast, right) that are being considered in this analysis.

Figure 3. Example of how catchment objects are defined in WEAP.

(Seaber et al 1987, data downloaded 2 February 2012), as described in Yates et al (2013). Catchment objects in both models represent specific geographic areas in which the intersection of land cover, elevation and management points defined by diversions, reservoirs, return flows, etc—are used to define contributing catchment areas (figure 3). The management or ‘pour’ points define locations in the system where water is stored in reservoirs, or diverted to meet demands (e.g. municipal, industrial, irrigated agriculture, thermoelectric cooling, etc). These catchments are first defined by their contribution to specific riverine systems and then further divided into sub-catchments according to 500 m elevation bands and general land use, including forested, non-forested, urban and irrigated agriculture. Sub-catchments are defined by the intersection of the land use and elevation to estimate fractional areas for each land use and elevation combination in each catchment.

This delineation result in more than 300 catchment objects associated with 30 river systems in the southwest, and 39 catchment objects and 7 rivers in the southeast. Elevation
bands are delineated for every 500 m, with the lowest level at 500 m asl, going up to the crest of the highest mountain range at 4000 m asl. Of course, the elevation range is not as dramatic in the southeast model. This level of elevation discretization is chosen in order to provide resolution in the elevation ranges where snow accumulation, and subsequent runoff generation to the riverine system, is critical.

2.2. Translation of electricity capacity and generation from PCA to HUC-8

Our translation of generation and capacity data at the PCA level to the HUC-8 level for assessing HUC-level water use involves different approaches for fossil fuel and nuclear plants and renewable energy facilities.

2.2.1. Translating fossil fuel and nuclear generation and capacity from PCA to HUC-8. Each PCA has generation and capacity data by technology as output from each ReEDS scenario for each time slice and year. The amount of new capacity is tracked for each two-year period over the course of the projection from 2010 to 2050. For each thermoelectric fossil fuel/nuclear generating technology represented in the model (Short et al. 2011), we apportion the generation and capacity data for each PCA to the HUC-8 regions within each PCA proportional to the amount of capacity and generation of the previous two-year period. For the first analysis year (2010) we determine and incorporate thermoelectric plant location data as described in Averyt et al. (2012). We plot these plant latitudes in ArcView using GCS_North_American_1983 as the datum. We then project plant locations onto the Watershed Boundary Dataset (NRCS 2011) to determine the watershed locations of individual plants at the HUC-8 level. These ratios for the HUC-8s within each PCA remain static throughout the length of the projection with the exception that we do not allow capacity increases at plants that utilize saline water for cooling.

We assume that no new once-through cooled plants will be built, given that almost no large once-through cooled plants have been built in more than two decades (UCS 2012). Similarly, we also do not consider saline water for cooling, given that almost no large saline plants have been built in that time period as well (UCS 2012). New capacity that would have been apportioned to a HUC-8 region with saline capacity we instead apply proportionally to the other HUC-8 regions within that PCA based on the previous analysis period’s ratio excluding the saline capacity portion.

2.2.2. Translating renewable energy generation and capacity from PCA to HUC-8. As with fossil fuel and nuclear technologies, each PCA has generation and capacity data by renewable energy technology as output from the ReEDS scenarios for each time slice and year. For each such technology represented in the model, we apportion generation and capacity data for each PCA to the HUC-8 regions within each PCA proportional to the resource availability and total land area available within each HUC-8 region, or, in the case of biomass co-firing (using biomass to displace coal directly), to existing coal plants.

| Table 1. Associated average capacity factors for wind classes utilized in this analysis. |
|-----------------|-----------------|
| Wind class      | Capacity factor (%) |
| 1               | 36.8             |
| 2               | 47.0             |
| 3               | 51.6             |
| 4               | 54.0             |
| 5               | 56.0             |

| Table 2. Associated average capacity factors for CSP classes utilized in this analysis. |
|-----------------|-----------------|
| CSP class       | Capacity factor (%) |
| 1               | 36.8             |
| 2               | 44.9             |
| 3               | 42.7             |
| 4               | 44.9             |
| 5               | 46.0             |

- **Wind and concentrating solar power.** The ReEDS model utilizes 356 resource quality regions for wind and concentrating solar power (CSP) with thermal storage technologies (Short et al. 2011). Data is applied from this dataset for this analysis through distributing generation to HUCs proportionally based on resource quality within each HUC in a PCA. HUC regions are overlaid onto PCAs to produce distinct combinations of the two layers. The distribution of generation and capacity is determined by the ratio of generation potential within each HUC/PCA combination and the full associated PCA generation potential. Potential generation estimates are calculated using the wind speed frequency distribution (resource class), system power density (wind: 5 MW km$^{-2}$; CSP: 31 MW km$^{-2}$), and average resource class capacity factor (tables 1 and 2).

- **Geothermal.** Geothermal generation is translated similarly to CSP and wind, but instead of varying capacity factors for each resource class, geothermal has various power densities determined by resource quality.

- **Utility-scale photovoltaics (PV).** For utility-scale PV technologies, distribution from PCAs to HUCs is determined based on the total land area of the resource within each HUC for each PCA.

- **Biomass.** Generation and capacity for biomass technologies are translated from county level total biopower resource estimates (see Clemmer et al. 2012) to the 134 PCA regions, which are in turn translated into HUCs via an area-weighted analysis.

- **Biomass co-firing.** Distribution is based on existing coal generation and capacity within each HUC in a PCA, on the assumption that co-firing would take place only where coal generation already exists.

For PCA regions entirely within the scope of analysis (i.e., the HUCs of interest cover the entire PCA region), we apply all generation to those HUCs for analysis and consider the full amount of that generation in this study. For PCA
regions not entirely within the scope of analysis, we consider only the generation for the land area that falls within the HUC regions. Distribution of new generation and capacity is independent of existing capacity and generation within a region.

2.3. Calculating power plant water use by HUC-8

Once we have HUC-8 capacity and generation data, we then assign cooling technology types and apply water withdrawal and consumption coefficients to project water use.

2.3.1. Assigning cooling technology types to HUC-8 generation and capacity data for fossil fuel and nuclear plants. We assign the generation and capacity of each technology in a particular HUC-8 to one of four cooling types: once-through, recirculating, dry cooling and pond cooling (or ‘none’ for technologies that do not require cooling systems, i.e., natural gas combustion turbines). For each HUC-8 region, we apportion the generation and capacity data of a technology to the cooling system types according to the amount of capacity and generation of cooling system types used in the previous analysis year. Again, we know the location of plants and the per cent of the capacity and generation that occurs from technologies and cooling types within each HUC-8 region for the initial analysis year 2010 from the research discussed in Averyt et al. (2012). We hold these ratios static throughout the duration of the projection with the exception that we do not allow once-through cooling values to increase. As described above, we assume for this analysis that there will be no new once-through cooled power plants, that all new plants will be cooled with recirculating, dry or pond cooling technologies. We assign cooling technologies to any new capacity and generation in a given HUC-8 region based on the previous analysis year’s ratios excluding the once-through cooling portion.

While the ReEDS model gives both electric generation and capacity data by technology as output, ReEDS identifies only newly built capacity, not generation produced from new plants. Because water use coefficients are applied to generation, not capacity, analysis of water use requires apportioning generation between new and old plants. Our platform divides generation data proportionally based on the ratio of capacity for new and old plants. If ReEDS builds new capacity in a PCA of a particular technology (i.e. new natural gas builds), we distribute this new capacity and generation to the HUC-8 regions based on the amount of existing thermoelectric fossil fuel and nuclear capacity in general.

We use similar logic for plant retirements. For a given PCA, we distribute the reduction of coal capacity and generation, for example, proportionally to the coal technologies in each HUC-8 region. We treat retirements of non-coal thermoelectric plants similarly to other changes in generation and capacity; for a given PCA, the reduction in capacity and generation of a technology is distributed proportionally to the existing types in each HUC-8 region. We also included an additional 22.2 GW of announced coal plant retirements in these model runs (Clemmer et al. 2012), retiring these plants according to their scheduled retirement dates.

2.3.2. Applying water withdrawal and consumption coefficients to electric generation based on cooling technology. Cooling plant consumption and withdrawal coefficients are largely adapted from Macknick et al (2011), Clark et al (2011) and DOE (2012), as utilized in Averyt et al. (2012). The coefficients are described in Macknick et al (2011) and are determined based on annual changes in capacity and generation. These coefficients are applied to the generation values for each HUC-8 region for each time slice for each analysis year for all four energy scenarios. This water use data then is positioned to serve as input to the WEAP model for further analysis of the water implications of these different energy pathways.

3. Example

This section describes a specific example of implementing the approach described above, breaking out model data from an individual PCA into its corresponding HUC-8s. Here we PCA 34, located in southern Colorado (figure 4). We will focus on the summer of 2020 of scenario 1 from Clemmer et al (2012). We will also focus only on the 10 HUC-8 regions that will be considered in PCA 34 in the subsequent WEAP analysis (Yates et al 2013). For this scenario, PCA, and season, the ReEDS model reports the generation data given in table 3 (select technologies, in MW h).

3.1. Translation of fossil fuel and nuclear capacity and generation from PCA To HUC-8

PCA 34 contains 7 HUC-8 regions that contain fossil fuel and nuclear capacity in 2018. The first step in the breakout process is to track the incremental generation changes made to fossil fuel and nuclear technologies over the previous two years. In this example, there is a slight decrease in natural gas combined-cycle generation and no other changes in other fossil fuel or nuclear generation from 2018 to 2020 (figure 5).
Figure 5. Fossil-fuel generation in 2018 (upper) and 2020 (lower) for PCA 34 by HUC-8 and cooling technology. Highlighting shows values that have changed between 2018 and 2020.

Table 3. Generation data for select technologies (in MWh) for summer 2020 in PCA 34.

| Hydro | Gas combustion turbine (CT) | Gas combined-cycle (CC) | Coal | Utility-scale PV | Distributed PV | Wind |
|-------|-----------------------------|-------------------------|------|-----------------|----------------|------|
| 250614| 67503                       | 739703                  | 2541474| 201049          | 63391          | 48942 |

We then apportion the generation data to the HUC-8 regions and to cooling types based on the previous analysis year’s distribution, as shown in the tables below.

3.2. Translation of renewable generation and capacity from PCA to HUC-8

As described above, we break out renewable energy generation into the HUC-8 regions by the resource and land availability within each region. This example shows utility-scale PV, distributed PV, hydroelectric and wind generation in PCA 34 (table 4). Because wind, hydro and distributed PV do not require water for cooling, we will focus only on operational water use for utility-scale PV for the purposes of this example. The following table shows the HUC-8 regions considered in this study, the utility-scale PV ratio applied to this HUC for this PCA, and the calculated generation data. Note that for this example the 10 HUC-8 regions below occupy only 60% of the total land area within PCA 34.

Table 4. Distribution of utility-scale PV generation in 2020 for select HUC-8 regions in PCA 34.

| HUC-8    | Utility-scale PV % (%) | Generation (MWh) |
|----------|-------------------------|-------------------|
| 11020001 | 10.3                    | 20708             |
| 11020002 | 1.9                     | 3781              |
| 11020003 | 7.6                     | 15280             |
| 11020005 | 8.0                     | 16019             |
| 11020009 | 13.9                    | 27859             |
| 11020011 | 12.7                    | 25333             |
| 14020006 | 1.3                     | 2590              |
| 14030003 | 1.3                     | 2671              |
| 14080101 | 0.5                     | 1095              |
| 14080104 | 0.4                     | 889               |

Figure 6 shows the total consumptive water use for these 10 HUC-8 regions within PCA 34. These values can now be used as input to the southwest WEAP model. The WEAP model uses power plant water use data along with other water basin-scale information such as municipal water demand and reservoir storage to simulate local hydrology.

4. Conclusions

Robust analysis of the water impacts of electricity-sector choices depends on producing results according to water-relevant geographies, and developing plausible strategies for assigning cooling types to both retiring and new power plants. Our research demonstrates a replicable approach to translate...
electricity modeling results from the electricity-relevant geographies (PCAs) produced in Clemmer et al (2012) to water-relevant geographies (HUC-8s). These results serve as inputs for hydrologic simulations that require representation of place-specific water demands. Drawing on existing capacity and generation ratios for select technologies and resource ratios for renewable energy technologies for that translation distributes projected power plants and plant use in ways that reflect the tendency of new capacity to be built at or near existing facilities and new renewable energy capacity to follow available renewable energy resources. Our approach also reasonably assumes that certain cooling types will become more or less prevalent as the power sector evolves, and assigns appropriate cooling water use values. The next step for assessing the regional and local water impacts of different electricity pathways is to use the output from this process as input into water modeling of select regions, as described in Yates et al (2013).

Additional opportunities for this work could include expanding its use to other basins or automating more of this work. Providing water use output for other basins would require identifying the relevant PCAs (as described above) and the corresponding water basins. The translation or ‘hand-shake’ work described here could also be incorporated into either the electricity or water models, obviating the need for the separate analyses described here. Much of the disaggregation performed on the ReEDS output could occur within ReEDS itself if the functions were to be incorporated into the model. That integration would allow the model to produce water results by PCA. Given that ReEDS contains the renewable energy resource information and generates the power plant capacity and generation figures on which the allocations are based, ReEDS could produce results (electricity or electricity and water) based on different geographies, including HUC-8s. Similarly, the WEAP modeling platform could accept as input ReEDS’s PCA-based electricity results directly, along with the distribution factors for the various power plant outputs (capacity and generation, or resource potential), and itself apply the relevant water factors.

Acknowledgments

We gratefully acknowledge funding for this research from The Kresge Foundation, Wallace Research Foundation, and Roger and Vicki Sant, and 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).

We also are indebted to various others for their inputs and reviews of this research at key junctures, including Easan Drury and Trieu Mai (National Renewable Energy Laboratory); Steve Clemmer, Ethan Davis and Nadia Madden (Union of Concerned Scientists); Mike Hightower and Vincent Tidwell (Sandia National Laboratories); Claudio Martinez; and Phillip Wu.

References

Averyt K, Fisher J, Huber-Lee A, Lewis A, Macknick J, Madden N, Rogers J and Tellenghusen 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 Tellenghusen S 2012 Developing a comprehensive database of power plant cooling water use: lessons learned, challenges and opportunities Environ. Res. Lett. at press
Clark C E, Harto C B, Sullivan J L and Wang M Q 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 Environm. Res. Lett. submitted
DOE (Department of Energy) 2012 SunShot Vision Study Energy (Washington, DC: US Department of Energy)
Electric Power Research Institute 2011 Water Use for Electricity Generation and Other Sectors: Recent Changes (1985–2005) and Future Projections (2005–2030) (Palo Alto, CA: EPRI)
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)
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)
National Renewable Energy Laboratory 2012 Renewable Electricity Futures Study ed M M Hand, S Baldwin, E DeMeo, J M Reilly, T Mai, D Arent, G Porro, M Meshek and D Sandor (Washington, DC: US Department of Energy)
Natural Resources Conservation Service 2011 Watershed Boundary Dataset (Washington, DC: United States Department of Agriculture) (accessed most recent data from http://datagateway.nrcs.usda.gov)

Figure 6. Power plant cooling and operational water use in summer 2020 for HUC-8 regions in PCA 34.
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, Sullivan P, Mai T, Mowers M, Uriarte C, Blair N, Heimiller D and Martinez A 2011 Regional Energy Deployment System (ReEDS) (Golden, CO: National Renewable Energy Laboratory)

Tidwell V C, Passell H D, Conrad S H and Thomas R P 2004 System dynamics modeling for community-based water planning: an application to the Middle Rio Grande J. Aquat. Sci. 66 357–72

UCS 2012 The Energy and Water in a Warming World Initiative: About EW3 (www.ucsusa.org/ew3)

Yates D, Sieber J, Purkey D, Flores F and Averyt K 2013 Modeling the hydrology of the US southwest for assessment of electricity pathways: the Colorado River Basin, the California water system, and the power sector Environ. Res. Lett. submitted

Yates D, Sieber J, Purkey D and Huber-Lee A 2005 WEAP21: A demand, priority, and preference driven planning model Water Int. 30 487–500