Freshwater Use by U.S. Power Plants: Electricity's Thirst for a Precious Resource

Appendix A: Key EW3 Methods and Assumptions

The UCS EW3 energy-water database is a compilation of information from various sources, and analyses based on those data. This appendix outlines different aspects of the compilation and analysis.

EIA Data

The core of the UCS EW3 database is information collected by the Energy Information Agency (EIA) in 2008 on forms 860 and 923. In 2008, the EIA required reports only from operators of organic-fueled (coal, natural gas, oil, and biomass) steam electric plants with capacities greater than 100 MW.

Form 860 is the "Annual Electric Generator Report," a 60-page questionnaire on the characteristics of 19,558 generators (at approximately 5,928 plants) for that year. Form 860 collects information separately about generators (capacity, ownership, age, major fuel use, and cogeneration), boilers (design firing rate, compliance with various air regulations, and what generators and emissions controls they were connected with), and cooling systems (cooling type, cooling tower type if applicable, cooling pond size, and design parameters for pumps). Of 19,558 generators covered by reports in 2008, owners reported that 15,694 were in operation that year.

Operational information at the plant, generator, and cooling system scale is reported on EIA form 923, the "Power Plant Operations Report." The 2008 EIA dataset includes reported and estimated monthly power generation at 5,242 electrical plants (nearly the entire set of operational plants in 2008).

Form 923 also supports detailed schedules, including Schedule 8, Part D, a database of 1,531 cooling systems. This information includes water withdrawal and consumption rates (in cubic feet per second) that are either estimated or measured. Of the more than 19,000 generators for which EIA received data in 2008, 4,545 were of a type ("prime mover") that we determined required cooling. Of these, only 3,583 generators at 1,748 plants were operational in 2008.

We tagged generators as requiring cooling if they included steam-driven turbines, heat-recovery steam generators on combined-cycle units, single-shaft combined-cycle units, or binary-cycle geothermal turbines. Our analysis assumes that combustion turbines, combustion turbine components of combined-cycle generators, internal combustion engines, and wind, photovoltaic, and hydroelectric generators do not require cooling.

Net Breakdown to Generating Unit Level, and Assumptions

Of 3,583 water-cooled operational units identified, only 2,757 reported electrical output at the generator level on Form 923 Schedule 5A. We had to estimate net output at the generator scale at the remaining units, as only plant information was available. If a generator was the only unit at the plant, then we attributed the plant's electrical output from EIA Form 923 to that generator; this applied to a single generator in this analysis.

For the remaining 1,872 generators, we applied a simple algorithm. If a plant had any units for which operators submitted Schedule 5A, we deducted the electrical output from those units from overall plant output as reported on the primary Form 923. We then distributed the remaining electricity output from the plant among all remaining generators in proportion to nameplate capacity. This approach assumes that all generators at a plant have the same capacity factor (utilization). We found no additional information by which to improve the parsing of generation. We did not include plants where generators were retired or on standby, or for which operators reported no electrical output, in our analyses.

In some instances, total electrical output reported for the plant on Form 923 or the generator-level production on Schedule 5A was negative, or the algorithm above returned a negative value for the residual output. These values may be legitimate for units that run at spinning reserve only, or that provide peaking capacity but have a higher parasitic load than electrical output in most operational hours. Only 649 of the 19,558 generators in the database reported negative output, usually at a very low capacity factor. Of the 3,583 units in this water-use analysis, we estimated only 29 to have negative electricity output (at very small values), and of those, all but 3 reported the negative output directly on Form 923 Schedule 5A. We did not include those facilities in the EW3 analysis.

Reported Water Consumption and Withdrawals

To associate cooling water data with specific generators, we scaled the reported water withdrawals and consumption of each cooling system back to the generator that used that system. Cooling systems are associated with boilers, and boilers are associated with generators. However, at any connection, there may be multiple stages that merge or divide (that is, a single cooling system used by multiple boilers, which feed multiple generators). Although information that allows for characterization of those linkages is available, information that accurately diagrams the complex connections is not readily available.

To best estimate water use at the generator scale, we assumed that each generator passed electrical output down to each boiler associated with it in equal parts, and that those boilers passed that output down to their associated cooling systems in equal parts. If a boiler served more than one generator, we summed the output (or partial output) from all served generators to the boiler.

We applied the same approach at the cooling system level relative to the boiler, passing water use (withdrawals and consumption) to all boilers served by the cooling system, prorated by the amount of generation served by each boiler. We then passed this water use to the generator

served by those boilers, again prorated by the electrical output of the generator served by those boilers.

Of the 3,583 units requiring water for cooling, 21 percent (769) did not have a boiler association (and therefore no recorded water use available), 50 percent (1,788) had a single boiler association, and the remaining 28 percent (1,026) recorded more than one boiler. The units associated with more than one boiler represented only 8 percent of the electrical output in this analysis. However, not all boilers recorded a cooling system association, and of those that did, not all reported cooling water use (either withdrawals or consumption). Operators reported only 1,526 cooling structures at 729 plants on Form 923 Schedule 8D. Of these, operators reported both withdrawals and discharges for only 74 percent (1,133).

After passing this information through the boiler level and back to the generator level, we had estimated withdrawals for 39 percent of the generators (1,410), and estimated consumption for 27 percent (991).

Cooling System and Tower Type

Each power plant operator self-reports the type of cooling structure to the EIA through Form 860. The cooling systems that operators could select in 2008 included once-through systems using freshwater, saline water, or cooling pond(s) or canal(s); recirculating systems with forced, induced, or natural-draft towers; or recirculating systems that relied on a cooling pond or canal. Options for towers included mechanical draft or natural draft, wet- or dry-cooled, or a combination wet-dry process.

To associate specific generators with particular cooling structure "types" and towers, we did a trace-through similar to that for water use described above. However, because the types are discrete values, we associated the first boiler's first cooling structure type with each generator. After tracing cooling structures through to generators, we found that operators of only 1,741 of the 3,583 generators (representing 68 percent of electrical output) reported a cooling structure to the EIA.

We checked reported cooling system data using Google Earth. For each plant identified as requiring cooling and having a capacity greater than 60 megawatts (MW), we checked the cooling type using visual observation via Google Earth, reassigning cooling system types to plants as warranted. We reassigned cooling types by first determining if a plant had a natural-draft or cellular cooling tower structure on site, or if the plant had a dry-cooling system rack. If neither cooling system could be located, we found the closest water body, and located a discharge plume, intake structure, or canal for once-through cooling systems.

For most plants using once-through cooling, both the intakes and discharge structures were clear, and canals or special cooling diversions to local water bodies easily identified. We carefully vetted sites before determining that a plant used a form of once-through cooling. We also used Google Earth to check all plant sites reported by the EIA as having a cooling pond or canal for once-through or recirculating systems. We recategorized most of those as having cooling ponds.

Of the 3,576 generators of interest, we manually corrected 848 units (representing 32 percent of electrical output), or added new information to the database. Only 970 units smaller than 60 MW did not report to the EIA, and those units represented only 1.8 percent of total electrical output. We did not manually correct those plants.

Environmental Compliance Systems

Our visual analyses also uncovered an additional category of cooling strategies, which we captured in the database. Google Earth imagery showed six plants with cooling towers downstream of their boiler condensation loop, with those towers instead attached to discharge canals or streams. The towers, distant enough from plants with explicitly once-through cooling systems, represent what we termed *environmental-compliance cooling*: cooling towers in place solely to reduce the temperature of effluent.

We designated these facilities as once-through in the database, but noted the environmental-compliance systems. Plants with this form of environmental-compliance towers have very different cooling and water-use characteristics from either once-through or tower-cooled plants. We were not in a position to characterize water use by such downstream towers, however, and did not include their water use in the analysis.

Calculated Water Withdrawals and Consumption

To calculate withdrawals and consumption by generator and power plant, we incorporated into the database a series of water coefficients based on a meta-analysis of published estimates of water use by various fuels and cooling technologies from the National Renewable Energy Laboratory (NREL) (Macknick et al. 2011). The one exception was geothermal plants. To more accurately reflect freshwater use by such plants, given that they use geothermal fluids in place of freshwater, we used geothermal water-use coefficients from Argonne National Laboratory (Clark et al. 2011) in place of data from NREL.

We applied the median, minimum, and maximum water coefficients (gallons per megawatt-hour, or MWh) to the best estimate of electrical output at the generator scale to calculate the range of possible water withdrawals and consumption. To harmonize plant characteristics with the results of the NREL meta-analysis, we made selected assumptions in applying the coefficients. We assumed, for example, that all coal units were generic rather than super and subcritical, as we had insufficient information on plant types to distinguish them. We also assumed that oil- and natural gas–fired steam plants using cooling ponds—plants without a designation in the NREL coefficients—had the same water-use habits as coal-fired steam plants with cooling ponds.

Water Source Categories

To adequately characterize water use for electricity generation, we needed to identify sources of water for cooling. We collected names of such sources from EIA Form 860, Schedule 2, for 2008, which provided plant-reported data. Because this dataset did not provide information on water sources for nuclear plants, we obtained additional names of water sources from EIA Form

767 from 1996 to 2000. We coded the reported names according to these water source categories:

- **Air cooled:** All water source data that indicated air cooling.
- **Ocean:** All data with "channel," "ocean," "bay," "harbor," or "sea" in the name of the water source.
- **Surface water:** All water source data with "river" or "lake," "pond," "creek," "reservoir," or "stream," or similar signifiers.
- **Groundwater:** All water source data with "aquifer," "well," or "groundwater."
- **Municipal water:** All water source data with "agency," "city," "municipal," or "authority," where a surface, groundwater, or municipal wastewater resource was not explicitly designated.
- **Wastewater:** All water source data with "reuse," "waste," "WWTP" (wastewater treatment plant), or "treatment." We included municipal sources that explicitly noted wastewater here.
- **Groundwater/surface water /municipal/wastewater hybrids:** As indicated by the source names, which we coded accordingly.
- **Unknown ocean:** All plants with no name for the water source located within one mile of shoreline, according to geolocational data.
- **Unknown freshwater:** All plants with no name for the water source located more than one mile inland, according to geolocational data.

Temperature

We compiled datasets for maximum temperatures of intake and outflow water for power plant cooling units from EIA Form 923, "Power Plant Operations Report," in 2008.

Carbon Emissions

To assess carbon emissions and intensity, we incorporated CO_2 data reported to the U.S. Environmental Protection Agency by operators of power plants with continuous emissions monitoring systems (CEMS), and compiled by SNL Energy. The CO_2 data covered emissions from approximately 1,200 plants, which together were responsible for 92 percent of electrical output from carbon-emitting plants. The plants without associated carbon data were non-emitting plants, such as hydroelectric, wind, solar, and geothermal, or non-reporting CO_2-producing plants.

Reporting Gaps

Comparisons with Other Datasets

We compared our calculations of water withdrawals based on the database outlined above with withdrawals reported by the EIA for 2008, along with withdrawals from thermoelectric power plants reported by the U.S. Geological Survey (USGS) in 2005 (USGS 2009), the most recent five-year water census from USGS. Because USGS water use data are reported by county, we used a dataset resampled at the eight-digit hydrologic unit code (HUC-8) level, provided by the Raleigh Eastern Forest Environmental Threat Assessment Center of the U.S. Forest Service for use in its water stress assessment model (Sun et al. 2008).

Identification of Nonreporting Plants

To characterize nonreporting plants, we identified all plants reporting no water use, and differentiated between those that did not have to report to the EIA in 2008 and those that did. We used EIA requirements for 2008, which mandated reporting only by operators of organic-fueled (coal, natural gas, oil, and biomass) steam electric plants with capacities greater than 100 MW, to filter out nonreporters. For plants using both reported and nonreported fuels (e.g., coal/nuclear or biomass/solar), we assumed that operators divided reported water use correctly between generators. We filtered out the electrical output and water use for nonreported fuels (such as nuclear and solar), including it only as part of nameplate capacity.

Spatial Analyses

Plant Locations

We acquired the latitudes and longitudes reported by operators of 6,600 plants (unpublished) to the EIA and compiled by the Civil Society Institute. The accuracy of these locational data varied, but they allowed manual identification using Google Earth of the plant of interest (based on location, type, and size) within several miles of the geocoded location. In the West (the electricity regions of the Western Electricity Coordinating Council and Texas), we corrected locational data manually. If locational data were determined to be inaccurate, we derived power plant information using traditional Google Internet searches. We then used this information to assign accurate latitudes and longitudes by finding the physical location of the power plants through Google Earth.

HUC Delineation and Assumptions

For components of the EW3 analysis that assessed water use and reporting at the scale of water resource region, we plotted plant latitudes and longitudes in ArcView using GCS_North_American_1983 as the datum. We then assigned each plant to the relevant two-digit hydrologic unit code (HUC-2). To assess the accuracy of the categorization at the HUC-2 level, we checked that the state indicated by each plant's latitude and longitude matched the state that the plant operator reported as its physical address.

We similarly assigned plants to the HUC-8 by latitude and longitude, but noted some problems with this assignment. First, 187 generators mapped outside of HUC-8 areas, in either the ocean or other large water bodies. We assigned these plants to the nearest HUC-8 by distance, and also checked them visually through Google Earth.

Second, as noted, the latitudes and longitudes reported by power plant operators seem to vary in quality, as inspection with Google Earth indicated that some plants might actually be sited several miles from their reported locations. While we corrected locations for every plant in arid electricity regions of the Western Electricity Coordinating Council and Texas, our analysis did not include similarly rigorous corrections of locational data east of these regions. However, a random sample of 120 geolocations in Google Earth indicated that 90 percent of power plants were located within the HUC-8 indicated by their latitudes and longitudes.

Water Stress

WaSSI

Researchers have formulated a number of ways to quantify different aspects of water stress and water vulnerability in both peer-reviewed and gray literature. In considering how to assess water stress as part of the EW3 analysis, we focused primarily on peer-reviewed approaches, including:[1]

- Alcamo, J.; Henrichs, T.; Rösch, T. 2000. World Water in 2025: Global Modeling and Scenario Analysis. In: Rijsberman, F. (ed.) *World Water Scenarios*. Earthscan Publications, 243-281
- Elcock, D., and J.A. Kuiper. Water vulnerabilities for existing coal-fired power plants. 2010. DOE/NETL-2010/1429. Golden, CO: U.S. Department of Energy, National Energy Technology Laboratory.
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- Hurd, B., N. Leary, R. Jones, and J. Smith. 1999. Relative regional vulnerability of water resources to climate change. *Journal of the American Water Resources Association* 35(6).
- Jenicek, E.M., and N.R.D. Myers, D.F. Fournier, K. Miller, M. Hessel, R. Carroll, and R. Holmes. 2009. Army installations water sustainability assessment: An evaluation of vulnerability to water supply. ERDC/CERL TR-09-38. Champaign, IL: U.S. Army Corps of Engineers, U.S. Army Research and Development Center, Construction Engineering Research Laboratory.
- Strzepek, K., G. Yohe, J. Neumann, and B. Boehlert. 2010. Characterizing change in drought risk for the United States from climate change. *Environmental Research Letters* (5):44012.
- Sun, G., S.G. McNulty, J.A. Moore Myers, and E.C. Cohen. 2008. Impacts of multiple stresses on water demand and supply across the southeastern United States. *Journal of American Water Resources Association* 44(6):1441–1457.
- Vorsmarty, C.J., P. Green, J. Salisbury, and R. Lammers. 2000. Global water resources: Vulnerability from climate change and population growth. *Science* (289):284–288.

Of these, we selected the only indicator that captures both demand and available supply at a fine-enough scale to adequately capture water stress: the Water Supply Stress Index, or WaSSI (Sun et al. 2008; 2011). The WaSSI is calculated as the ratio of water demand to water supply. The other measures looked only at supply, or at relatively coarse scales. The exception is the approach taken by the U.S. Army Corps of Engineers (Jenicek et al. 2009). However, that approach is not yet peer-reviewed, so we used the more rigorous peer-reviewed approach of Sun et al. 2008.

For each of the 2,106 eight-digit hydrologic units (HUC-8) nationwide, WaSSI calculates water supply as the sum of a) annual surface water supply, averaged from 2003 to 2007 (Caldwell

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[1] The one non-peer-reviewed approach we considered was developed by the U.S. Army Corps of Engineers (Jenicek et al. 2009).

2011a); b) groundwater supply; and c) return flows from major water users, including cities, agriculture, and power plants. Groundwater supply and return flows are resampled from county to the HUC-8 level from USGS water use data (USGS 2009), except for thermoelectric groundwater withdrawals and return flows, which are from our analysis. Interbasin transfers are not explicitly taken into account in surface water supply, although they are reported implicitly in return flows from water users. This is an important caveat in interpreting the WaSSI analysis, particularly in regions with significant conveyance systems.

WaSSI calculates water demand as withdrawals by seven major users (commercial, domestic, industrial, irrigation, livestock, mining, and thermoelectric). Again, these data are derived from USGS (USGS 2009), except for thermoelectric withdrawals, which are from our analysis.

The higher a basin's WaSSI, the greater its water stress. For our analysis, we considered basins with a WaSSI above 0.4 to be highly stressed (Caldwell 2011b). In basins with a WaSSI exceeding 1.0, more water is consumed than is supplied within the HUC-8 basin, meaning that water is supplied by other regions, surface waters and aquifers are being depleted, or both.

Power Plant Contributions to Water Stress
To identify basins where power plants contribute to the water burden, we calculated the WaSSI for each HUC-8 basin nationwide, both with and without power plant water withdrawals. Mapping the difference between the two highlighted the contribution of electricity generation to local water stress across the country. Those watersheds listed in Appendix B (Table B-8) are the 25 with the highest difference between those two WaSSI scores ("WaSSI anomaly") based on median NREL values

Because WaSSI is a broad indicator of water stress based on *supply*, we removed as hotspots or power-stressed watersheds any that are located directly on one of the Great Lakes and for which power plants in the basin listed one of the lakes as their cooling sources. Those and other basins on the Great Lakes would merit closer attention to determine power plant-induced water stress.

Ecological Effects
We outlined the potential impact of electricity-related activities on aquatic species by comparing power plant peak water discharge temperatures and locations to total counts of aquatic-associated[2] and aquatic-obligate[3] species (NatureServe 2011).

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[2] *Aquatic associated* species are those ranked G1-G2 by NatureServe, or that have federal status under the U.S. Endangered Species Act. *Aquatic associated* is defined as any species known to be associated with—but not necessarily dependent on—aquatic or wetland habitats at some point in its lifecycle, based on NatureServe's habitat data, or on taxonomic group in the absence of habitat data. Such species include aquatic insects, amphibians, and shorebirds, for example.

[3] *Aquatic obligate* species are those ranked G1-G2 by NatureServe, or that have federal status under the U.S. Endangered Species Act. *Aquatic obligate* is defined as any species known to spend all or part of its lifecycle living in the water, based on NatureServe's habitat data, or on taxonomic group in the absence of habitat data. These species include fish, crayfish, mussels, and dragonflies, for example.

Power Plant Water Use Projections

To examine potential water use by power plants over the coming decades, we modeled a base-case electricity development scenario and applied water coefficients to the results. We started with the base case for growth in electricity demand from the EIA (EIA 2011).[4] We used Regional Energy Deployment System (ReEDS), a computer model developed by the NREL that optimizes the build-out of electricity capacity and transmission across the United States through 2050 (NREL 2009).

As inputs and assumptions, we used the EIA's base case for fuel costs, and middle-of-the-road estimates based on our survey of a range of sources of technology costs and performance. Our projections of resource availability were based on the NREL's assessment of renewable energy resources (2009) and EIA 2011 for fuels.

We modeled the mix of power plant generation at biannual time steps to 2036 and beyond for the 134 electricity subregions in the continental United States. The base case assumes growing populations, and existing policies and economics, to project the mix and locations of power plant types to meet demand.

Using electricity generation and capacity figures for each subregion provided in the ReEDS output, we then applied water coefficients derived from Macknick et al. 2011 to compare calculated water use in 2008 with that in 2036. To accommodate the different types of technologies in ReEDS (which has 23, versus more than 60 NREL coefficients), we used weighted water coefficients for each fuel/technology based on the mix of cooling types in 2008.

For 2036:
- In each subregion where capacity for that fuel/technology type was lower than in 2008, we applied the 2008 water coefficient, assuming that capacity of that type was retired proportionally with cooling types. (That is, the mix of once-through and recirculating plants stayed constant, for example.) We also assumed that no new plants were built that would change the water factor.
- In each subregion with a capacity in 2036 greater than in 2008, we applied the 2008 water coefficient to the 2008 capacity level, and a recirculating-cooling water coefficient to all new capacity. Those estimates assumed that 2008 capacity (or the water-factor equivalent) would still be online in 2036, supplemented by more water-efficient (lower-withdrawal) plants.

We then multiplied the water factors for each year by the generation for that year, and assessed changes at the national, Southwest, and Southeast levels.

We also analyzed projected changes in CO_2 emissions in each of those geographic jurisdictions using the CO_2 figures included in the EW3 database.

Water and Carbon Intensities of Electricity Providers

To calculate the water and carbon intensities of the top electricity providers in the United States, we aggregated data by plant owner at the parent company level, based on data available through EIA reporting. We calculated 2008 electricity generation figures and selected the 15 top-producing companies. We then calculated freshwater withdrawal and consumption intensities (total minimum and maximum freshwater values for each company, divided by the company's total generation). We also calculated carbon intensity (reported emissions for each company, divided by the company's total generation).

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