Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature

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Abstract

This report provides estimates of operational water withdrawal and water consumption factors for electricity generating technologies in the United States. Estimates of water factors were collected from published primary literature and were not modified except for unit conversions. The water factors presented may be useful in modeling and policy analyses where reliable power plant level data are not available. Major findings of the report include: water withdrawal and consumption factors vary greatly across and within fuel technologies, and water factors show greater agreement when organized according to cooling technologies as opposed to fuel technologies; a transition to a less carbon-intensive electricity sector could result in either an increase or a decrease in water use, depending on the choice of technologies and cooling systems employed; concentrating solar power technologies and coal facilities with carbon capture and sequestration capabilities have the highest water consumption values when using a recirculating cooling system; and non-thermal renewables, such as photovoltaics and wind, have the lowest water consumption factors. Improved power plant data and further studies into the water requirements of energy technologies in different climatic regions would facilitate greater resolution in analyses of water impacts of future energy and economic scenarios. This report provides the foundation for conducting water use impact assessments of the power sector while also identifying gaps in data that could guide future research.

1. Introduction

Thermoelectric power use has a significant impact on water resources and the power sector is highly dependent on these water resources; the United States Geological Survey (USGS) estimated on a national level that 41% of all freshwater withdrawals in the United States in 2005 were for thermoelectric power operations, primarily for cooling needs (Kenny *et al* 2009). The power sector is thus highly vulnerable to changes in water resources, especially those that are already occurring, and are likely to intensify, as result of climatic changes (Vörösmarty *et al* 2000, Bates *et al* 2008, Dai 2010, NETL 2010d). Increasingly, state agencies, such as those in California and New York, have taken policy actions to address the impacts of power plants' water use and the environmental impacts of their cooling systems (CSLC

2006, NYSDEC 2010). Furthermore, the 2007 drought in the southeast exposed many thermal generators, including Brown's Ferry nuclear plant, to water-related shut downs and curtailments due to unlawfully high discharge temperature and shallow or exposed cooling water inlet locations (NETL 2009c). Effective integrated energy and water policy planning will require identifying the individual and cumulative impacts that power plant configurations have on water resources and the vulnerabilities of specific power plants to changes in water resources (Wilkinson 2007, Scott and Pasqualetti 2010, Stillwell *et al* 2011, Kenney and Wilkinson 2012). Various studies have attempted to consolidate published estimates of water use impacts of electricity generating technologies, resulting in a wide range of technologies and values based on different primary sources of literature (Gleick 1993, Inhaber 2004, DOE 2006, NETL 2007b, 2007c, WRA 2008, Fthenakis and Kim 2010, Mielke *et al* 2010, Macknick *et al* 2011). The goal of this work is to consolidate the most recent and relevant primary literature estimates of water use during the generation of electricity by conventional and renewable electricity generating technologies in the United States to more completely convey the variability and uncertainty associated with current water use in electricity generating technologies. Individual water use factors, reported in terms of the volume of water used per unit of electrical output (gal MW^{-1} h^{-1}), are technology and cooling system specific. These water use factors can be incorporated into energy-economic models to estimate generation-related water use under different projected electricity portfolio scenarios. Although the United States is the focus of this study, results are likely to be applicable to other geographic regions (see Floerke *et al* (2011) and Van Vliet *et al* (2012), for example).

2. Scope and methods

We evaluate two aspects of water usage: 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 determining power plant impacts and vulnerabilities associated with water resources.

We consider water withdrawals and consumption for the operational phase only, thus excluding water usage in the fuel cycle or other aspects of the life cycle. Operational water use in this study includes cleaning, cooling, and other process-related needs that occur during electricity generation, such as flue gas desulfurization (FGD) in coal facilities. For the vast majority of power generation technologies, most of the water used in the life cycle of the plant occurs during the operational phase, with the exception of non-thermal renewable energy technologies that do not require cooling systems (Fthenakis and Kim 2010). In addition, compared to the operational phase, data for the water requirements of other phases (such as the fuel cycle) are scarce, are subject

to greater definitional boundary differences, and have more site-specific differences. Also, although the location of the plant is permanent, the locations of the manufacturing or fuel sources are not permanent. Given this and the continuous local impacts of power plant water use on water resources during the operational phase, we limit this study to a detailed review of only the operational water requirements of electricity generating technologies.

The energy technologies addressed here consist of configurations of concentrating solar power (CSP), solar photovoltaic (PV), wind, biopower, geothermal, hydropower, nuclear, natural gas and coal technologies. Cooling system technologies considered may utilize fresh or saline water resources and include wet recirculating technologies (evaporative cooling towers), once-through cooling systems (open loop cooling), air-cooled condensing (dry cooling), hybrid wet and dry cooling systems (hybrid cooling), and pond cooling systems.

Electricity generating technologies use water for different processes, depending on their configuration. Thermal electricity technologies (e.g., CSP, biopower, coal, nuclear and natural gas technologies) generally require water as the working fluid (and as the cooling medium to condense steam) as part of the Rankine cycle, the thermodynamic process that drives the steam engine (Turchi *et al* 2010). Some technologies have additional operational water needs. Coal facilities may also use water for FGD. Fossil technologies employing carbon capture and storage capabilities will require additional process water requirements (NETL 2007b). CSP facilities have additional water demands for cleaning mirrors or heliostats. Upstream biopower facilities water needs for growing energy crops are not included in this analysis but can be minimal or quite substantial (approximately 100 times greater than operational cooling system needs), varying greatly depending on region, crop and production methods (Berndes 2002, 2008, Stone *et al* 2010).

Geothermal technology configurations (e.g., dry steam, binary and flash) can differ greatly in their use of water due to differences in technology configuration, geology, reservoir characteristics and local climate (Clark *et al* 2011). Enhanced Geothermal Systems (EGS) operate similar to geothermal binary technologies yet also require some additional water for hydraulic stimulation; on a life-cycle basis the amount of water utilized for hydraulic stimulation is orders of magnitude less than the amount of freshwater or other outside water source utilized for cooling (Clark *et al* 2011). A wide variety of estimates have been published on geothermal technologies' operational water usages, as summarized in Macknick *et al* (2011). Published water consumption values may range between 0 and 4000 gal MW^{-1} h^{-1} for a recirculating cooling tower, with the upper end being an order of magnitude greater than natural gas combined cycle water consumption (Layton 1979, Gleick 1993, EPRI and DOE 1997). Many of these studies report water required for cooling system purposes but do not explicitly address whether the water utilized is freshwater or geothermal fluids. Common industry practice is to utilize geothermal fluids as the primary medium for cooling (Clark *et al* 2011). Providing data on the total amount of water

required for cooling may be misleading, as the impacts on freshwater or other outside water sources are substantially less (Kagel *et al* 2007). Freshwater may be used in geothermal facilities to help manage dissolved solids, reduce scaling, meet makeup water losses and replenish the reservoir, as over time some geothermal plant efficiencies may decline and may require outside fresh, brackish or effluent water sources (Bradbury 2009, Clark *et al* 2011). In many cases the outside water does not have to be freshwater, as the high salinity of the geothermal fluids is often greater than many non-freshwater sources. In this report we provide water consumption data for geothermal technologies considering the outside water resources required for operations. Thus we do not consider the use of geothermal fluids as operational water uses, but we do consider the use of water for reservoir enhancement or other ancillary processes.

Considering non-thermal renewable technologies, PV systems may require water for occasional panel washing. Common industry practices indicate that most PV system operators do not wash panels (DOE 2012). Wind systems require very little water, if any, for cleaning. Hydroelectric facilities using reservoirs have evaporative losses resulting from the dammed water (Gleick 1992, Torcellini *et al* 2003).

Estimates of water consumption and withdrawal are displayed irrespective of geographic location, as many published data do not specify the location or climatic conditions of the plant. The location of a plant, and its corresponding climatic conditions, can affect its overall efficiency and thus its water use rate (Giusti and Meyer 1977, Miller *et al* 1992, Dziegielewski and Bik 2006, Yang and Dziegielewski 2007, Rutberg *et al* 2011). Similar fossil plants utilizing cooling towers may have annual water consumption factors that differ by almost 17%, depending on the location in the United States (Huston 1975). Similarly, water consumption factors of CSP plants utilizing cooling towers may differ by as much as 20% (Turchi *et al* 2010). Inter-annual variations in water intensity are also not considered for this review. Withdrawal and consumption factors are often reported in terms of annual averages, yet water intensity of facilities in July may be more than 16% higher than annual values as a result of diurnal and seasonal variations in temperatures, wind speeds and humidity levels (Huston 1975). Other factors that may influence water use intensities of power plants that are not considered here include the age of the plant, the thermal efficiency of the plant, the age of the cooling system and the water source (Dziegielewski and Bik 2006, Yang and Dziegielewski 2007).

Certain aggregations of fuel technology types and cooling system types were made to facilitate analyses. Nuclear technologies include pressurized water reactors and boiling water reactors. Coal technologies make no distinction among different types of FGD processes. For recirculating cooling technologies, no distinction is made between natural draft and mechanical draft cooling tower systems. All pond-cooled systems are treated identically. Pond-cooled systems can be operated in manners that resemble both recirculating systems and once-through systems as well as in hybrids of these technologies (EIA 2011b). Different configurations and

operating practices of pond-cooled systems can lead to widely different reported water withdrawal and consumption values. No distinction is made between water types, which may include freshwater (surface and groundwater), saline water or municipal waste water. In 2005, 71% of thermoelectric water withdrawals were from freshwater sources (Kenny *et al* 2009). Saline withdrawals are primarily concentrated in California, Florida and the coastal northeast, with the rest of the country relying on freshwater.

The estimates provided here are not intended to be precise predictions of specific facilities' water usage characteristics. They represent a summary of published statistics, which have their own limitations.

3. Data availability and limitations

Data sources include published academic literature, state and federal government agency reports, non-governmental organizations' reports and industry submissions to government agencies for permitting procedures. Estimates of national average water use intensity for particular technologies, estimates of existing plant operational water use and estimates derived from laboratory experiments were considered equally. Certain sources report ranges of water consumption and withdrawal factors in place of specific values. If traceable individual case studies form the basis for the range given, the individual values are included as independent estimates within the set of estimates that are statistically analyzed. If a range is given and the underlying data points are not given, then the midpoint of that range is used for calculating a median value, and the high and low extremes are used for determining extreme ranges. This method of addressing ranges may lead to a bias toward data sources reporting explicit cases and may also underestimate actual water use at facilities, as in many cases the midpoint of the range of extremes is less than the median of values reported from individual facilities. This review did not alter (except for unit conversion) or audit for accuracy the estimates of water use published. Because estimates are used as published, considerable methodological inconsistency is inherent, limiting comparability. Certain estimates, such as those addressing water consumption associated with washing PV panels, were omitted due to changes in industry practices that have occurred since those studies were conducted (Meridian 1989, Gleick 1993). We report minimum, maximum and median values for fuel technology and cooling system combinations in tables and additionally show 25th and 75th percentile data in figures, if sufficient data exist. Due to the wide range of values reported from a small number of sources, median values may differ significantly from mean values. Upon request, raw data are available from the authors.

Although the power sector is responsible for the highest withdrawal volumes of water in the nation, national statistics on the consumption and withdrawal rates of individual power plants are characterized by inconsistencies and scarcity (GAO 2009). Power sector water use data on a national level are collected by two federal agencies, the USGS and the US Department of Energy's Energy Information
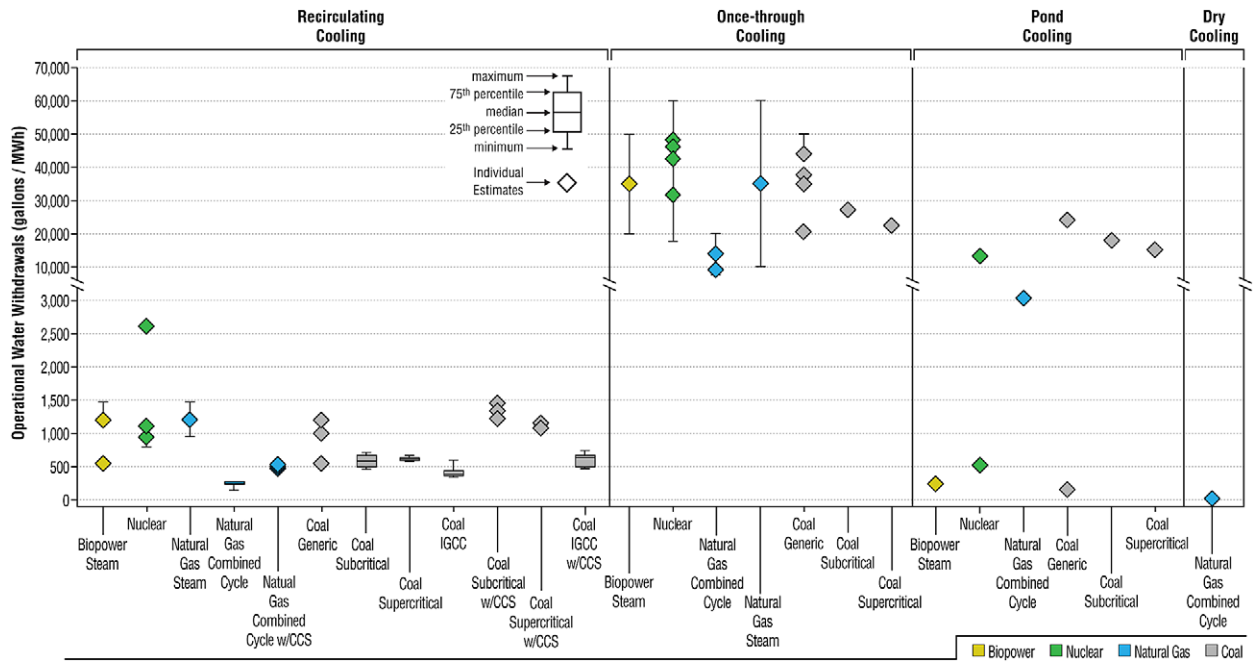
Figure 1. Operational water consumption factors for electricity generating technologies. IGCC: Integrated gasification combined cycle. CCS: Carbon capture and sequestration. CSP: Concentrating solar power. Hydropower values are excluded due to the wide range of estimates.

Administration (EIA). The USGS reports water withdrawals for thermoelectric power production by county and sector every five years; water consumption values for thermoelectric power production were last reported for 1995 (Solley *et al* 1998). These data are collected by state agencies that do not always utilize the same methods or definitions in determining water withdrawals (Kenny *et al* 2009).

EIA provides official energy statistics on an annual basis, and EIA Form 923 reports, among other data, water withdrawal, discharge and consumption rates in Schedule 8D, providing similar definitions of withdrawal and consumption as the USGS (EIA 2011b). However, data are not entirely comprehensive and in the past have omitted nuclear facilities and some natural gas combined cycle technologies (EIA 2011a). Additionally, the quality of data is also of concern with power plants reporting data; many of the power plants report water withdrawal and consumption values that are far below or above the studies of water use in power plants considered in this review. The National Energy Technology Laboratory compiled water use data in their *2007 Coal Power Plant DataBase* (NETL 2007a). However, this database is limited by the data availability and quality of EIA datasets. No similar public database has been developed for natural gas or nuclear generating facilities.

Detailed engineering studies and more general assessments of water use at individual thermoelectric power plants are uneven in their treatment of fuel technologies and cooling systems. For example, water consumption data for coal, natural gas, nuclear and parabolic trough CSP facilities using a wet recirculating cooling system are relatively abundant. Fewer studies are available addressing water withdrawals for all technologies or water consumption for once-through, pond

and dry cooling systems. Very little data exist for dedicated biomass, geothermal and power tower CSP facilities.

Additionally, definitions of withdrawal and consumption, along with operational water use boundary conditions, in water use studies are not always clear or consistent; some sources only report aggregated operational water usage, whereas other reports include water withdrawal and consumption values by individual processes. Even the particular processes included in disaggregated studies may not be equivalent across studies; the inclusion of FGD water requirements in coal facilities is one example where its explicit or implicit consideration is inconsistent. Estimates of evaporation from hydropower reservoirs are complicated by the multiple uses of reservoirs (e.g., water supply, recreation and flood control) and the different methods of allocating evaporation to electricity production (Gleick 1992, Torcellini *et al* 2003, Pasqualetti and Kelley 2008). Hydropower estimates are reported according to the allocation methods utilized in the published reports, which allocate all reservoir evaporation to power production. As the range of values for hydropower consumption range from 0 to 18 000 gal MW^{-1} h^{-1}, we provide tabular data but do not include the large range in the figures, where consumption ranges from 0 to approximately 1200 gal MW^{-1} h^{-1}.

4. Results: water consumption and withdrawal factors

The cooling system employed is often a greater determinant of water usage than the particular technology generating electricity, both in terms of water consumption (figure 1, tables 1 and 2) and water withdrawal (figure 2, table 3).

Figure 2. Operational water withdrawals for fuel-based electricity generating technologies. IGCC: integrated gasification combined cycle. CCS: carbon capture and storage.

Table 1. Water consumption factors for renewable technologies (gal MW^{-1} h^{-1}).

Fuel type	Cooling	Technology	Median	Min	Max	n	Sources
PV	N/A	Utility scale PV	1	0	5	3	(Aspen 2011a, 2011b, DOE 2012)
Wind	N/A	Wind turbine	0	0	0	2	(Inhaber 2004, DOE 2006)
CSP	Tower	Trough	906	725	1109	18	(Gleick 1993, Cohen *et al* 1999, Leitner 2002, Sargent and Lundy 2003, Kelly 2006, Kutscher and Buys 2006, Stoddard *et al* 2006, Viebahn *et al* 2008, WorleyParsons 2009b, 2009a, 2010a, 2010b, Burkhardt *et al* 2011)
		Power tower	786	751	912	4	(Leitner 2002, Sargent and Lundy 2003, Stoddard *et al* 2006, Viebahn *et al* 2008)
		Fresnel	1000	1000	1000	1	(DOE 2009)
	Dry	Trough	78	43	79	11	(Kelly 2006, WorleyParsons 2009b, 2009a, 2010a, Burkhardt *et al* 2011)
		Power tower	26	26	26	1	(Brightsource Energy 2007)
	Hybrid	Trough	338	117	397	3	(DOE 2009, WorleyParsons 2009b)
		Power tower	170	102	302	2	(DOE 2009)
	N/A	Stirling	5	4	6	2	(Leitner 2002, CEC 2008)
Biopower	Tower	Steam	553	480	965	4	(EPRI and DOE 1997, EPRI 2002, CEC 2008)
		Biogas	235	235	235	1	(Mann and Spath 1997)
	Once-through	Steam	300	300	300	1	(EPRI 2002)
	Pond	Steam	390	300	480	1	(EPRI 2002)
	Dry	Biogas	35	35	35	1	(EPRI and DOE 1997)
Geothermal	Tower	Flash	15	5	361	4	(Kagel *et al* 2007, CEC 2008, Adee and Moore 2010, Clark *et al* 2011)
	Dry	Flash	5	5	5	1	(Clark *et al* 2011)
		Binary	270	270	270	1	(Clark *et al* 2011)
		EGS	505	290	720	1	(Clark *et al* 2011)
	Hybrid	Binary	461	221	700	2	(Kutscher and Costenaro 2002, Kozubal and Kutscher 2003)
Hydropower	N/A	In-stream and reservoir	4491	1425	18 000	3	(Gleick 1992, Torcellini *et al* 2003)

Table 2. Water consumption factors for non-renewable technologies (gal MW^{-1} h^{-1}).

Fuel type	Cooling	Technology	Median	Min	Max	*n*	Sources
Nuclear	Tower	Generic	672	581	845	6	(Gleick 1993, EPRI 2002, Dziegielewski and Bik 2006, WRA 2008, NETL 2009a)
	Once-through	Generic	269	100	400	4	(EPRI 2002, Hoffmann *et al* 2004, Dziegielewski and Bik 2006, NETL 2009a)
	Pond	Generic	610	560	720	2	(EPRI 2002, Dziegielewski and Bik 2006)
Natural Gas	Tower	Combined cycle	205	130	300	6	(EPRI 2002, Leitner 2002, NETL 2007c, 2009a, 2010a, 2010c)
		Steam	826	662	1170	4	(Gleick 1993, Feeley *et al* 2005, CEC 2008, WRA 2008)
		Combined cycle with CCS	393	378	407	2	(NETL 2010a, 2010c)
	Once-through	Combined cycle	100	20	100	3	(EPRI 2002, Feeley *et al* 2005, NETL 2009a)
		Steam	240	95	291	2	(Gleick 1993, CEC 2008)
	Pond	Combined cycle	240	240	240	1	(NETL 2009a)
	Dry	Combined cycle	2	0	4	2	(EPRI 2002, NETL 2009a)
Coal	Tower	Generic	687	480	1100	5	(Gleick 1993, EPRI 2002, Hoffmann *et al* 2004, Dziegielewski and Bik 2006, WRA 2008)
		Subcritical	479	394	664	7	(NETL 2007c, 2009a, 2009b, 2010a, 2010b)
		Supercritical	493	445	594	8	(NETL 2007c, 2009a, 2009b, 2010a, 2010c, Zhai *et al* 2011)
		IGCC	380	318	439	8	(NETL 2007c, 2010a, 2010c)
		Subcritical with CCS	921	900	942	2	(NETL 2010a, 2010c)
		Supercritical with CCS	846	815	907	3	(NETL 2010a, 2010c, Zhai *et al* 2011)
		IGCC with CCS	549	522	604	4	(NETL 2010a, 2010c)
	Once-through	Generic	250	100	317	4	(Gleick 1993, EPRI 2002, Hoffmann *et al* 2004, Dziegielewski and Bik 2006)
		Subcritical	113	71	138	3	(NETL 2009a)
		Supercritical	103	64	124	3	(NETL 2009a)
	Pond	Generic	545	300	700	2	(EPRI 2002, Dziegielewski and Bik 2006)
		Subcritical	779	737	804	3	(NETL 2009a)
		Supercritical	42	4	64	3	(NETL 2009a)

Once-through cooling technologies withdraw 10–100 times more water per unit of electric generation than cooling tower technologies, yet cooling tower technologies can consume twice as much water as once-through cooling technologies. Water consumption for dry cooling at CSP, biopower and natural gas combined cycle plants is an order of magnitude less than for recirculating cooling at each of those types of plants.

Water consumption factors for renewable and non-renewable electricity generating technologies vary substantially within and across technology categories. The highest water consumption factors for all technologies result from the use of evaporative cooling towers. With the exception of hydropower, pulverized coal with carbon capture and CSP technologies utilizing a cooling tower represent the upper bound of water consumption, at approximately 1000 gal MW^{-1} h^{-1} of electricity production. The lowest operational water consumption factors result from non-thermal renewable technologies such as wind energy and PV, along with thermal technologies that utilize dry cooling, such as CSP Stirling solar technologies and natural gas combined cycle facilities. Water withdrawal factors for electricity generating technologies show a similar variability within and across technology categories (table 3). The highest water

withdrawal values result from nuclear technologies, whereas the smallest withdrawal values are for non-thermal renewable technologies. Consistent with literature, withdrawal factors for CSP, wind, geothermal, and PV systems are assumed to be equivalent to consumption factors.

5. Discussion

Despite methodological differences in data, general trends can be observed and broad conclusions can be drawn from the breadth of data collected. A transition to a less carbon-intensive electricity sector could result in either an increase or decrease in water consumption per unit of electricity generated, depending on the choice of technologies and cooling systems employed. Non-thermal renewable technologies, such as wind and PV systems, consume minimal amounts of water per unit of generation. However, the highest water consumption factors considered in this study are low-carbon emitting technologies that utilize cooling towers: pulverized coal with carbon capture technologies and CSP systems. Decisions affecting the power sector's impact on the climate may need to include water considerations to avoid negative unintended environmental consequences on water

Table 3. Water withdrawal factors for fuel-based electricity generating technologies (gal MW^{-1} h^{-1}).

Fuel type	Cooling	Technology	Median	Min	Max	*n*	Sources
Nuclear	Tower	Generic	1101	800	2600	3	(EPRI 2002, Dziegielewski and Bik 2006, NETL 2009a)
	Once-through	Generic	44 350	25 000	60 000	4	(EPRI 2002, Hoffmann *et al* 2004, Dziegielewski and Bik 2006, NETL 2009a)
	Pond	Generic	7050	500	13 000	2	(EPRI 2002, Dziegielewski and Bik 2006)
Natural gas	Tower	Combined cycle	255	150	283	7	(EPRI 2002, NETL 2007b, 2007c, 2009a, 2010a, 2010c)
		Steam	1203	950	1460	2	(Feeley *et al* 2005, CEC 2008)
		Combined cycle with CCS	506	487	544	3	(NETL 2007b, 2010a, 2010c)
	Once-through	Combined cycle	11 380	7500	20 000	2	(EPRI 2002, NETL 2009a)
		Steam	35 000	10 000	60 000	1	(CEC 2008)
	Pond	Combined cycle	5950	5950	5950	1	(NETL 2009a)
	Dry	Combined cycle	2	0	4	2	(EPRI 2002, CEC 2008, NETL 2009a)
Coal	Tower	Generic	1005	500	1200	4	(Meridian 1989, EPRI 2002, Hoffmann *et al* 2004, Dziegielewski and Bik 2006)
		Subcritical	587	463	714	8	(NETL 2007b, 2007c, 2009a, 2009b, 2010a, 2010b)
		Supercritical	634	582	670	9	(NETL 2007b, 2007c, 2009a, 2009b, 2010a, 2010c, Zhai *et al* 2011)
		IGCC	393	358	605	12	(Meridian 1989, NETL 2007b, 2007c, 2010a, 2010c)
		Subcritical with CCS	1329	1224	1449	3	(NETL 2007b, 2010a, 2010b)
		Supercritical with CCS	1147	1098	1157	4	(NETL 2007b, 2010a, 2010c, Zhai *et al* 2011)
		IGCC with CCS	642	479	742	7	(NETL 2007b, 2010a, 2010c)
	Once-through	Generic	36 350	20 000	50 000	4	(EPRI 2002, Hoffmann *et al* 2004, Inhaber 2004, Dziegielewski and Bik 2006)
		Subcritical	27 088	27 046	27 113	3	(NETL 2009a)
		Supercritical	22 590	22 551	22 611	3	(NETL 2009a)
	Pond	Generic	12 225	300	24 000	2	(EPRI 2002, Dziegielewski and Bik 2006)
		Subcritical	17 914	17 859	17 927	3	(NETL 2009a)
		Supercritical	15 046	14 996	15 057	3	(NETL 2009a)
Biopower	Tower	Steam	878	500	1460	2	(CEC 2008)
	Once-through	Steam	35 000	20 000	50 000	1	(EPRI 2002)
	Pond	Steam	450	300	600	1	(EPRI 2002)

resources. This can be addressed by integrated energy and water policy planning, as the availability of water in certain jurisdictions may limit the penetration of these technologies and cooling system configurations.

Freshwater use impacts can be reduced by utilizing dry cooling or by using non-freshwater sources as a cooling medium. The reduction in freshwater usage might lead to increased costs or decreased efficiency. Initial work suggests that CSP facilities utilizing dry cooling technologies might have an annual reduction in electricity output of 2%–5% and an increase in the levelized cost of producing energy of 3%–8% compared with wet-cooled facilities, depending on local climatic conditions (Turchi *et al* 2010). Using national averages, the annual performance penalty for switching from wet cooling to dry cooling for nuclear plants is 6.8%, combined cycle plants 1.7%, and other fossil plants (including coal and natural gas steam plants) 6.9% (EPA 2011). Further

efforts are needed to evaluate performance and cost penalties associated with utilizing dry or hybrid cooling systems for fossil fuel facilities using carbon capture technologies. Utilizing reclaimed water, such as municipal wastewater, is another approach that could partially lessen the impact of the power sector on freshwater resources and wastewater treatment facilities. The legal and physical availability of municipal wastewater, especially when it is treated and already utilized downstream, may be a limiting factor to its widespread usage, and the cost and performance penalties of utilizing such sources must be investigated further (EPRI 2003).

The choice of cooling system may play an important role in the development of our future electricity mix. Differences between cooling systems can have substantial environmental impacts on local water resources and on the need to acquire water rights for power generation (Carter

et al 1979, Reynolds 1980, Laws 2000, Scott *et al* 2011). Employing wet cooling technologies (i.e., once-through and cooling tower technologies) imposes an inherent tradeoff between relatively high water consumption and relatively high water withdrawals, which has important implications for regional cooling system policies and regulations. A reduction in withdrawals (but a corresponding increase in consumption) may benefit a watershed, but may lead to concerns in an area that is already lacking water. A shift away from, for example, once-through cooling systems in coastal areas that withdraw saline water, to inland recirculating systems such as cooling towers that primarily consume freshwater, will impact watersheds and water availability differently depending on local conditions. The use of alternative cooling technologies may serve as an energy security benefit for utilities and communities, given uncertainties in future scenarios of water availability and expected vulnerabilities for power plants (Dai 2010, NETL 2010d). Reduced levels in bodies of water, or substantial increases in the temperature of these bodies of water, may require thermal power plants to run at lower capacities or to shut down completely, as was seen in France in 2003 (Poumadère 2005). Utilizing dry cooling or non-freshwater sources avoids some of the risks associated with these drought and climate change scenarios.

Accurate estimates of water use in individual power plants, and the effect of this water use on a regional scale, may be elusive until more studies are conducted for the variety of technologies and cooling systems currently in operation along with those expected to be developed and deployed. Furthermore, calibration of these values on national and regional scales will remain challenging until methods for collecting and evaluating data by federal agencies has improved. Nonetheless, certain conclusions regarding the overall impact power plants have on water resources can be drawn on regional levels from existing water use data.

Further studies with consistent boundary conditions and methods are necessary to develop water consumption and withdrawal estimates for certain technologies and cooling systems to fully understand reasons for variations in data that are not attributable to climatic factors or technology vintages. To better understand how cooling system and technology system decisions will be made in the future, analyses using energy-economic models will require improved data on water availability and regional water use factors. In 2009, the US Government Accountability Office released a report calling for improvements in federal agency water data collection in power plants; EIA is currently working with the USGS and other federal agencies to improve the scope and quality of its data collection (GAO 2009). Such efforts should improve the availability of national and power plant specific data and the ability to calibrate model estimates.

6. Summary

We reviewed primary literature for data on water withdrawal and consumption factors for electricity generation in the United States and have consolidated them in this study. These detailed water consumption and withdrawal factors can be utilized in energy-economic and transmission planning models to better understand the regional and national impacts on water resources for various electricity future scenarios and can inform policy analysis at a national and local level. Improved power plant data gathered on a regional level and further studies into the water requirements of existing and emerging technologies are necessary to assess the water impacts of a developing decarbonizing economy in more detail.

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