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

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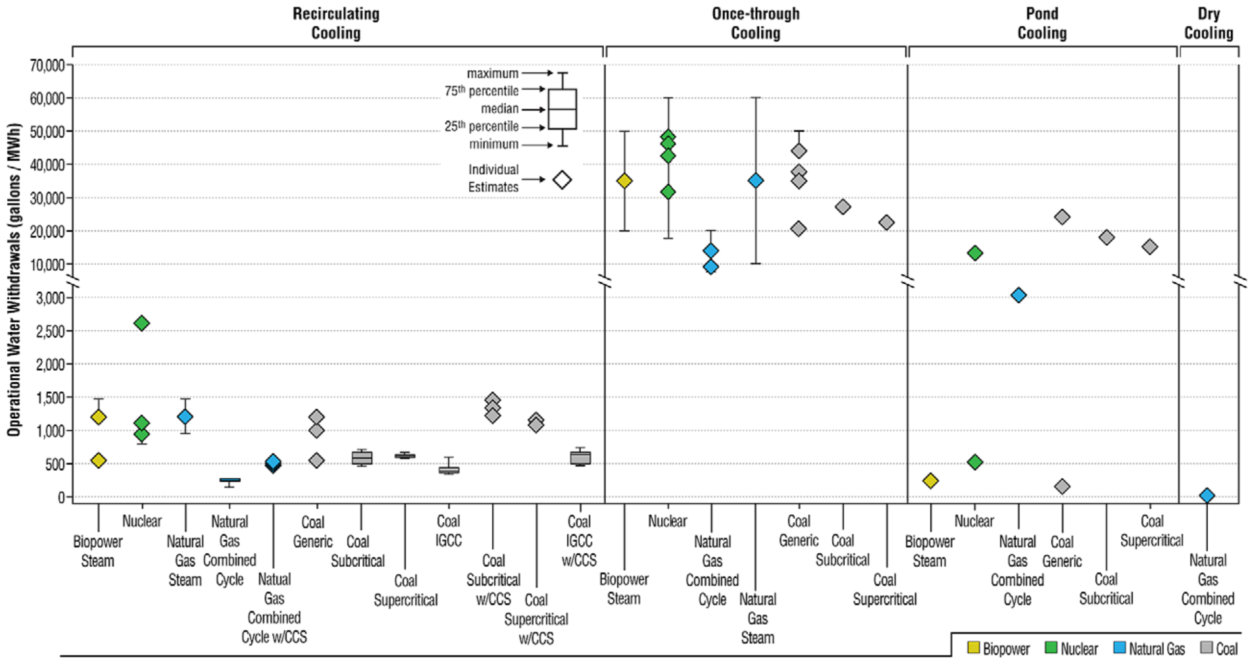

Figure 2. Operational water withdrawals for fuel-based electricity generating technologies. IGCC: integrated gasification combined cycle. CCS: carbon capture and storage.

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