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Life cycle water use for electricity generation: a review and harmonization of literature estimates

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Life cycle water use for electricity generation: a review and harmonization of literature estimates

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Abstract
This article provides consolidated estimates of water withdrawal and water consumption for the full life cycle of selected electricity generating technologies, which includes component manufacturing, fuel acquisition, processing, and transport, and power plant operation and decommissioning. Estimates were gathered through a broad search of publicly available sources, screened for quality and relevance, and harmonized for methodological differences. Published estimates vary substantially, due in part to differences in production pathways, in defined boundaries, and in performance parameters. Despite limitations to available data, we find that: water used for cooling of thermoelectric power plants dominates the life cycle water use in most cases; the coal, natural gas, and nuclear fuel cycles require substantial water per megawatt-hour in most cases; and, a substantial proportion of life cycle water use per megawatt-hour is required for the manufacturing and construction of concentrating solar, geothermal, photovoltaic, and wind power facilities. On the basis of the best available evidence for the evaluated technologies, total life cycle water use appears lowest for electricity generated by photovoltaics and wind, and highest for thermoelectric generation technologies. 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

Water requirements throughout the electricity generation life cycle have important implications for the electricity sector. Although the operations of thermoelectric power plants require substantial water withdrawals (Kenny *et al* 2009, Macknick *et al* 2012), all electricity generation technologies, including those that do not require cooling for steam cycle processes, utilize water throughout their life cycles. This means that the power sector can be vulnerable to constraints caused by drought conditions and other changes in water resources not only directly, due to water required for operations (e.g., Huertas 2007, NETL 2009b), but also indirectly, due to water required throughout fuel supply chains and power plant equipment life cycles. For example, the 2011 drought in Texas not only impacted actual and expected statewide generation (Saathoff 2011) but also led to temporary shutdowns of hydraulic fracturing and other natural gas extraction operations (Carroll 2011, Passwaters 2011). Despite relatively low operational water demands compared to other generation technologies, photovoltaic and wind generation technologies also require water during manufacturing and construction.

The water requirements associated with choices along the life cycle of electricity generation, such as the selection of fuel type or cooling technology, are not well understood.
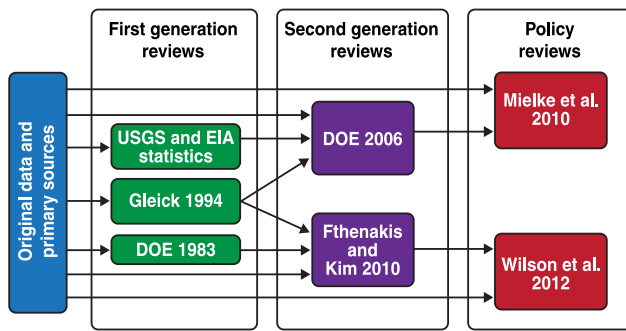
Figure 1. This schematic depicts the main provenance of data for some of the key references addressing the water use of electricity generation technologies. As shown, the sources for most data in even contemporary references are many decades old.

Previous studies address water use across this life cycle to varying degrees (e.g., Gleick 1994, DOE 2006, Fthenakis and Kim 2010, Mielke *et al* 2010, McMahon and Price 2011), but these studies do not provide sufficient information for water and energy managers to quantify the magnitude and duration of expected impacts. Some reviews focus on water consumption and omit withdrawals for many or all processes (e.g., Gleick 1994, Mielke *et al* 2010, McMahon and Price 2011, Grubert *et al* 2012). Most reviews rely on a subset of available data. For example, two representative policy reviews (Mielke *et al* 2010, Wilson *et al* 2012) incorporate small amounts of new data but pull primarily from a few key, decades-old compilations (DOE 1983, Gleick 1994), as reflected in figure 1's schematic of the data provenance. Other reviews cover only specific life cycle stages (e.g., Macknick *et al* (2012) focus only on operations) or geographic contexts (e.g. Grubert *et al* (2012) evaluate life cycle water impacts from switching from coal- to natural gas-fired electricity generation in Texas). In addition, recent research (GAO 2009, Averyt *et al* 2013) questions the reliability of some data in commonly referenced statistics on thermoelectric power plant water use from the United States Geological Survey (USGS) (e.g., Solley *et al* 1998, Hutson *et al* 2004, Kenny *et al* 2009) and from the Energy Information Administration (EIA) (e.g., EIA 2011a, 2011b).

This paper assesses the life cycle water withdrawals and consumptive uses for renewable and non-renewable electricity generation technologies, hereafter referred to as *generation technologies*. It provides concise estimates of water use throughout the life cycle of electricity generation in the United States that are supported by a thorough review of available literature. Where available data differentiate water use among generation technology sub-categories, cooling technologies, or fuel cycle characteristics, we define each collective combination as a *production pathway* and present separate estimates for each. We collect estimates from a broad review of literature across multiple disciplines, publication types, and stages of the life cycle, applying consistent quality and relevance screens and harmonizing methodological differences. This review is intended to support more informed decisions on technological choice, research and development, and water resources management and to identify gaps where

further research could significantly improve understanding of the water requirements for electricity generation.

2. Scope and methods

Following the USGS (Kenny *et al* 2009), this paper classifies water use into water *withdrawals*, referring to 'water removed from the ground or diverted from a surface-water source for use' (p 49), and water *consumption*, referring to the portion of withdrawn water not returned to the 'immediate water environment' (p 47). The generic term water *use* is employed only where both metrics are discussed concurrently. Consistent with these definitions, we only address externally sourced water; therefore, we omit estimates addressing geologically produced and storm water that requires treatment. We focus only on water quantity requirements, although the life cycle of electricity generation may be associated with water quality issues as well (e.g., Lustgarten 2009, Ward 2010, EPA 2011).

This paper reviews the water use throughout the life cycle of each of seven categories of electricity generation technologies: coal, natural gas, nuclear, concentrating solar power (CSP), geothermal, photovoltaics (PV), and wind. It does not address other technologies due to data complexities and uncertainties. For example, a separate literature addresses biopower's water requirements (e.g., Berndes 2008, Gerbens-Leenes *et al* 2009, Stone *et al* 2010), but estimates vary by multiple orders of magnitude across regions, crops, and production methods. Reservoir evaporation complicates hydropower's accounting, leading to estimates ranging from zero to 18 000 gal MWh^{-1} (Gleick 1994, Torcellini *et al* 2003). Co-generation leads to challenges in allocating water use across co-products, and other generation technologies, such as ocean power, lack usable data.

Our broad literature review starts with the more than 2000 references amassed by the National Renewable Energy Laboratory's (NREL) Life Cycle Assessment (LCA) Harmonization project (www.nrel.gov/harmonization). Using keyword database searches, works cited lists, and known reference repositories, we expand this review to also include other peer-reviewed scientific literature, government reports and statistics, and corporate sustainability reports pertaining to life cycle water use or water use in any specific phase of the life cycle of electricity generation for the selected technologies.

We perform a series of three screens, described in more detail in the supplementary data (available at stacks.iop.org/ERL/8/015031/mmedia): two at the reference level and a third at the level of individual estimates. First, we screen this complete body of literature for any written quantification of water use within any electricity generation life cycle stage. Passing references receive a second screen, analogous to the screens for systematic review developed by the LCA Harmonization project (Moomaw *et al* 2011, Heath and Mann 2012), based on methods quality, completeness of reporting, and current technological relevance; this requires sufficient documentation by which the methods for developing results could be trusted and traced. With the exception of
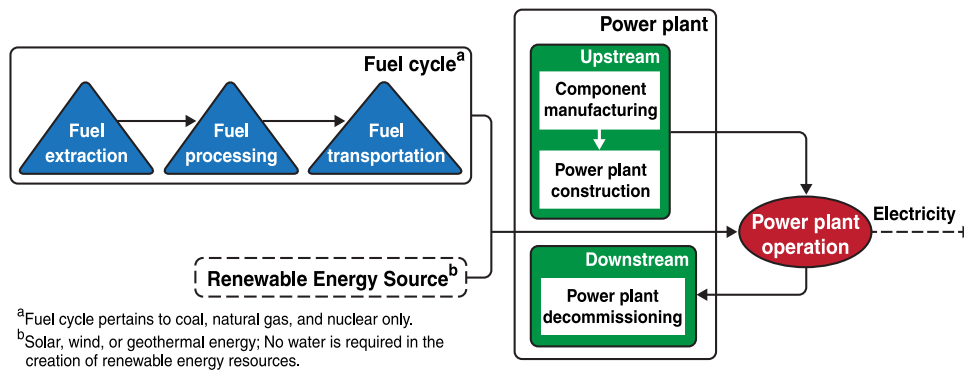
Figure 2. A schematic of the significant life cycle stages for each electricity generation technology demonstrates the additional role of fuel cycle water use in contributing to the life cycle water use for coal, natural gas, and nuclear generation technologies. The power plant life cycle stage consists of an upstream component manufacturing and plant construction phase and a downstream phase when the power plant is decommissioned.

a few frequently cited, older sources (DOE 1983, Tolba 1985, Gleick 1994), which are retained because of both their importance to other literature and difficulties in tracking down many of their sources, we also eliminate references that did not provide primary data.

We gather data from all references passing the first two screens and present all non-duplicate estimates in the supplementary data (available at stacks.iop.org/ERL/8/015031/mmedia). In addition to removing duplicates, the third screen focuses on the reasonableness of individual estimates, considering both engineering principles and the preponderance of evidence. With a bias toward retaining estimates, we subject questionable estimates to further scrutiny, considering the thoroughness of documentation and the age of both the questionable reference and of alternative estimates' sources. We also omit otherwise reasonable estimates that lack sufficient disaggregation along the production pathway. In the results below, we discuss any unique estimates omitted in this third screen and otherwise focus presentation and analysis on data that pass all screens. Of the 138 sources passing the reference-level screens, one (Inhaber 2004) provides quantified water use data for all seven technologies we address, one more (Gleick 1994) addresses all but wind (for which water use is listed as 'negligible'), but the majority cover only one or two technologies each with primary data. A given reference can have multiple estimates, even for the same generation technology.

We categorize gathered data by generation technology and life cycle stage. As shown in figure 2, we separate the life cycle into three main stages: *fuel cycle*, which pertains only to coal, natural gas, and nuclear generation technologies; *power plant*, which represents the life cycle of the physical power plant equipment; and *operations*, which includes cooling for thermal technologies and all other plant operation and maintenance functions. Careful tracking of stage definitions and boundaries, which vary by study, is required to avoid double counting as much as possible when adding estimates across stages. This analysis does not account for electricity transmission, distribution, or end use, neither in terms of resource uses nor electricity losses.

Reflecting the spatial and temporal impacts of water use, most of this analysis focuses on water use disaggregated across life cycle stages. In addition, although the distinction between withdrawal and consumption is essential for understanding these impacts, many references do not specify which type of water use they report. Therefore, we infer this distinction from context and other information where possible and, where not, omit estimates because of insufficient reporting quality. In some cases of insufficient information, noted below, we assume withdrawals equal consumption, seeking balance between underestimating withdrawals when estimates actually report consumption and overestimating consumption when estimates actually report withdrawals.

We define life cycle water use factors (water$_{LC}$) as ratios of life cycle (LC) water use per unit of generated electricity, expressed as gallons per megawatt-hour (gal MWh^{-1}). We calculate factors for the life cycle water consumption and withdrawal associated with each generation technology. These factors represent weighted sums of the water use factors for each of the three major life cycle stages defined in figure 2:

$$\text{water}_{LC} = \text{water}_{FC} * \left(\frac{\text{fuel}_{\text{lifetime}}}{e_{\text{lifetime}}} \right)$$
$$+ \text{water}_{PP} * \left(\frac{1}{e_{\text{lifetime}}} \right) + \text{water}_{OP} \qquad (1)$$

where water$_{FC}$ is the amount of water used in the fuel cycle (FC) per unit of fuel (expressed as gal ton^{-1} for coal, gal MMscf^{-1} for natural gas, and gal kg^{-1} converted, enriched, and fabricated uranium fuel (i.e., UO$_2$) for nuclear); e_{lifetime} is the amount of electricity generated by a power plant over its lifetime (MWh/lifetime); fuel$_{\text{lifetime}}$ is the amount of fuel used by a power plant over its lifetime (ton/lifetime, MMscf/lifetime, or kg/lifetime, as appropriate); water$_{PP}$ is the amount of water used for component manufacturing, power plant construction, and power plant decommissioning (i.e. the power plant equipment life cycle (PP) as defined in figure 2) (gal/lifetime); and water$_{OP}$ is the amount of water used in the operations (OP) of the power plant per unit of generated electricity (gal MWh^{-1}).

In addition to water use estimates, we record parameters relevant to fuel attributes, fuel cycle characteristics, and power plant performance, which can influence the amount of water used in life cycle stages. Where possible with available data,

Table 1. Performance parameters used for harmonization and the life cycle stage in which each is applied.

Parameter[a]	Value[b]	Stages for which parameter applies		
		Fuel cycle	Power plant	Operations
Thermal efficiency				
Coal: PC	35.4% (LHV), 34.3% (HHV)	×[c]	×[c]	×[c]
Coal: SC	39.9% (LHV), 38.4% (HHV)	×[c]	×[c]	×[c]
Coal: IGCC	39.8% (LHV), 38.5% (HHV)	×[c]	×[c]	×[c]
Coal: CFB	38.3% (LHV), 34.8% (HHV)	×[c]	×[c]	×[c]
Natural gas: CC	51.0% (HHV)	×	×	×
Natural gas: CT	33.0% (HHV)	×	×	×
Nuclear: fuel conversion	2.81 kg U_3O_8/kg $UF_{6(natural)}$	×		
Nuclear: fuel enrichment (diffusion)	10.4 kg $UF_{6(natural)}$/kg $UF_{6(enriched)}$	×		
Nuclear: fuel enrichment (centrifugal)	10.8 kg $UF_{6(natural)}$/kg $UF_{6(enriched)}$	×		
Nuclear: fuel fabrication	3.42 kg $UF_{6(enriched)}$/kg UO_2	×		
Nuclear: fuel use	0.004 33 kg UO_2 MWh^{-1}	×		
Fuel heat content				
Coal	21.01 MMBtu/ton (LHV)	×		
Natural gas	1031 Btu/scf (HHV)	×		
Solar-to-electric efficiency				
CSP: trough	15.0%		×	×
CSP: power tower	20.0%		×	×
PV: performance ratio	80%		×	×
PV: m-Si	13.0%		×	×
PV: p-Si	12.3%		×	×
PV: a-Si	6.3%		×	×
PV: CdTe	10.9%		×	×
PV: CIGS	11.5%		×	×
Solar resource				
CSP	2400 kWh m^{-2} yr^{-1}		×	×
PV	1700 kWh m^{-2} yr^{-1}		×	×
Capacity factor				
Coal	85%		×	
Natural gas	85%		×	
Nuclear	92%		×	
Wind: onshore	30%		×	
Wind: offshore	40%		×	
Power plant lifetime				
Coal	30 yr		×	
Geothermal	30 yr		×	
Natural gas	30 yr		×	
Nuclear	40 yr		×	
CSP	30 yr		×	
PV	30 yr		×	
Wind	20 yr		×	

[a] PC = pulverized coal, sub-critical; SC = pulverized coal, super-critical; CFB = circulated fluidized bed; IGCC = integrated gasification combined cycle; CC = combined cycle; CT = combustion turbine; m-Si = mono-crystalline silicon; p-Si = poly-crystalline silicon; a-Si = amorphous silicon; CdTe = cadmium telluride; CIGS = copper indium gallium selenide.

[b] Parameters match those published in LCA harmonization and other benchmark studies on electricity generated by coal (MIT 2007, Whitaker *et al* 2012), natural gas (EIA 2011c, O'Donoughue *et al* 2012), nuclear power (NETL 2012a, Warner and Heath 2012), CSP (Burkhardt *et al* 2012), PV (Hsu *et al* 2012, Kim *et al* 2012), and wind (Dolan and Heath 2012). We base the lifetime of geothermal on the lifetime used for other technologies.

[c] Although LHV is the preferred measure for all life cycle stages of electricity generation by coal, data limitations require the use of HHV for the operations stage.

we harmonize all estimates to the common performance parameters shown in table 1; the goal of harmonization is to reduce analytical variability by adjusting previously published estimates to ones based on a more consistent set of methods and assumptions (Heath and Mann 2012). These parameters are selected to match those published in LCA harmonization

and other benchmark studies on electricity generated by coal (MIT 2007, Whitaker *et al* 2012), natural gas (EIA 2011c, O'Donoughue *et al* 2012), nuclear power (NETL 2012a, Warner and Heath 2012), CSP (Burkhardt *et al* 2012), PV (Hsu *et al* 2012, Kim *et al* 2012), and wind (Dolan and Heath 2012). We assume that, on first order and holding all other aspects of equation (1) constant, each performance parameter affects e_{lifetime} or water_{OP} (as physically appropriate) as:

$$e_{\text{lifetime,h}} = e_{\text{lifetime,o}} * \frac{p_{\text{h}}}{p_{\text{o}}} \qquad (2)$$

or

$$\text{water}_{\text{OP,h}} = \text{water}_{\text{OP,o}} * \frac{p_{\text{o}}}{p_{\text{h}}} \qquad (3)$$

where p is the relevant parameter, the subscript o signifies an original value, and the subscript h signifies a harmonized value. Because e_{lifetime} is increasing in each parameter p, the ratio $(\frac{p_{\text{h}}}{p_{\text{o}}})$ scales $e_{\text{lifetime,o}}$ to the proportional change in parameter value. In contrast, generated electricity is in the implicit denominator of water_{OP}, so the inverse ratio $(\frac{p_{\text{o}}}{p_{\text{h}}})$ scales $\text{water}_{\text{OP,o}}$ to the proportional change in parameter value. The supplementary data (available at stacks.iop.org/ERL/8/015031/mmedia) presents all collected estimates as well as statistics on the availability of information for harmonization; the majority of estimates did not have relevant information and cannot be harmonized.

We develop estimates for each major life cycle stage for each generation technology (where coal, natural gas, and nuclear power have three major stages and all other generation technologies have two, as shown in figure 2). In many cases, such as different fuel extraction methods, cooling technologies, and generation prime movers, distinct production pathways have differentiated water use characteristics. We analyze such choices separately where data provide sufficient detail and aggregate such choices where data are more limited. For each production pathway option, we select the median estimate as reflecting the central tendency of the distribution of available data. Although gathered estimates are not a random sample of actual water use factors from the existing stock of generation facilities, we consider the median to be a reasonable representation across multiple references and technological variability within a category. Finally, we aggregate our selected, harmonized estimates into full life cycle water use estimates and investigate the sensitivity of life cycle water use to different values of the performance parameters shown in table 1.

The broad scope of this analysis necessitates important caveats and assumptions. Studies demonstrate considerable methodological inconsistency, and our attempts to address these through harmonization are limited by available information in the source literature. For example, the majority of thermoelectric operational water use estimates are not accompanied by thermal efficiency data so cannot be harmonized on this parameter. Reported boundaries around life cycle stages, including whether estimates include indirect water use, differ across references, but some references lack clear descriptions of the boundaries applied. As a result, we may overestimate life cycle water use in some cases

where overlap leads to double counting and underestimate it in other cases where gaps in our estimate arise from processes being excluded from source data. Because available information suggests that most, but not all, reported estimates exclude indirect water use, we likely underestimate total attributable water use but overestimate on-site water use throughout the life cycle stages of electricity generation technologies. Although the magnitude of these errors is unknown, one expects it to correlate with an electricity generation technology's energy return on energy invested. In addition, although recycling and the use of degraded water both can dramatically reduce the amount of water used in multiple life cycle stages, particularly for withdrawals, we do not explicitly address these technological advances. Water use can vary substantially owing to site-specific differences such as local climate conditions, the age of equipment, and characteristics of the water source (Yang and Dziegielewski 2007) and the application of different environmental compliance technologies; the gross level of analysis presented here necessarily neglects such considerations. The assumption that performance parameters act proportionally upon water use factors does not account for non-linear effects; for example, higher irradiation increases CSP output directly but also may reduce the efficiency if operating temperatures are also raised (Turchi *et al* 2010). Finally, the estimates provided are neither predictions nor meant to exactly characterize all potential examples of deployment of a certain technology.

3. Results: water use across individual life cycle stages

Tables 2–12 present summary statistics of harmonized estimates of water consumption and withdrawal for major life cycle stages and production pathways for each generation technology, using the performance parameters shown in table 1. The full data these statistics summarize are available in the supplementary data (available at stacks.iop.org/ERL/8/015031/mmedia). Although median estimates are selected to represent each category, ranges reflect not only variability in the analytical reliability of collected estimates but also the aggregation of many potential sub-categories within technologies and life cycle stages. However, the minimum and maximum in the available literature may not represent the true minimum or maximum considering all deployment conditions, technological permutations, etc. Reflecting both the variability and uncertainty in the estimates for broad technology categories, reported results are limited to two significant digits.

3.1. Coal

Coal fuel cycle water factors, shown in table 2, are differentiated between surface and underground mining. Based on available data, we estimate that the fuel cycle uses approximately 22 gal MWh^{-1} with surface mining or 56 gal MWh^{-1} with underground mining, based primarily on US mining data and with estimates constructed from the individual process stages shown in table 3. Most water during

Table 2. Summary statistics of selected, harmonized estimates of water consumption and withdrawal for major life cycle stages and production pathways for coal-fired electricity generation.

	Sub-category[a]	Consumption (gal MWh^{-1})[b]				Withdrawal (gal MWh^{-1})[b]			
		Median	Min	Max	n[c]	Median	Min	Max	n[c]
Fuel cycle[d,e,f]	Surface mining	22	6	58	7	22	6	60	7
	Underground mining	56	17	230	7	57	17	230	7
Power plant[f]	Upstream and downstream[g]	1	<1[h]	25	8	1	<1[h]	12	8
Operations	PC: cooling tower	530	200	1300	20	660	460	1 200	21
	PC: open loop cooling	140	71	350	11	35 000	15 000	57 000	16
	PC: pond cooling	740	300	1000	11	10 000	300	26 000	10
	PC + CCS: cooling tower	940	900	940	3	1 300	1 200	1 400	3
	SC: cooling tower	500	460	590	7	600	580	670	7
	SC: open loop cooling	100	64	120	3	23 000	23 000	23 000	3
	SC: pond cooling	42	4	64	3	15 000	15 000	15 000	3
	SC + CCS: cooling tower	880	850	910	2	1 100	1 100	1 100	3
	CFB: cooling tower	560	560	560	1	1 000	1 000	1 000	1
	CFB: open loop cooling	210	210	210	1	20 000	20 000	20 000	1
	IGCC: cooling tower	320	35	440	14	390	160	6 700	16
	IGCC + CCS: cooling tower	550	520	600	4	640	480	740	7

[a] PC = pulverized coal, sub-critical; SC = pulverized coal, super-critical; CFB = circulated fluidized bed; IGCC = integrated gasification combined cycle; CCS = carbon capture and sequestration.

[b] Statistics based on harmonized estimates, with respect to life cycle stage boundaries as well as relevant parameters shown in table 1.

[c] For estimates constructed from multiple disaggregated stages or processes (reported in table 3), 'n' reports the average number of estimates over each of the stages, plus any included estimates that are not disaggregated. For categories with exactly 2 estimates, the median is defined as the arithmetic mean.

[d] Fuel cycle estimates include estimates constructed from estimates for individual stages reported in table 3 in addition to estimates only for aggregated fuel cycle water use.

[e] All fuel cycle estimates assume train transportation; mine-mouth conversion to electricity would decrease estimates negligibly and slurry pipeline transport would increase estimates substantially.

[f] Fuel cycle and power plant estimates are harmonized to the thermal efficiency of a sub-critical pulverized coal power plant.

[g] Power plant includes both upstream water use estimates (primarily for dust suppression during plant construction but also for manufacturing power plant raw materials) and downstream water use estimates (for decommissioning power plants). The latter contributes negligibly to the total for this life cycle stage.

[h] <1 designates a value between 0.1 and 0.5 (due to rounding), and ≪1 designates a value less than 0.1.

Table 3. Summary statistics of selected, harmonized estimates of water consumption and withdrawal for major production pathways in the coal fuel cycle.

	Consumption (gal MWh^{-1})[a]				Withdrawal (gal MWh^{-1})[a]			
	Median	Min	Max	n	Median	Min	Max	n
Extraction (surface)[b]	3	<1[c]	13	9	3	<1[c]	13	9
Extraction (underground)[b]	27	8	180	8	27	8	180	8
Extraction (type not specified)[b]	45	12	120	4	45	12	120	4
Processing[b]	18	9	1000	8	18	9	1000	8
Transport (train)	<1[c]	≪1[c]	1	3	1	<1[c]	2	3
Transport (slurry)[b]	110	100	410	6	110	100	410	6

[a] Statistics based on harmonized estimates, with respect to life cycle stage boundaries as well as relevant parameters shown on table 1; estimates are harmonized to the thermal efficiency of a sub-critical pulverized coal power plant. This table does not include estimates that are reported only for the entire fuel cycle.

[b] Reflecting data limitations and the nature of water use, we assume withdrawal and consumption are equal for all estimates in this category.

[c] <1 designates a value between 0.1 and 0.5 (due to rounding), and ≪1 designates a value less than 0.1.

extraction is used for dust suppression in mines and on roads, and higher surface mining estimates include water used for land reclamation whereas lower ones do not. We assume consumption equals withdrawals because consumption is often difficult to measure for mines; for example, NETL (2010a) reports that 'no specific data were located on the wa-ter consumed during mine operations…(consumption data) could not be separated from the storm water output' (p 33).

We omit older estimates of withdrawals up to 17 000 gal MWh^{-1} for coal cleaning (Tolba 1985) in favor of newer, better documented estimates and therefore estimate that processing, which may or may not occur at the mine,

Table 4. Estimated effect of carbon capture and sequestration (CCS) on life cycle water use for coal- and natural gas-fired electricity generation.

		Pulverized coal (sub-critical)	Pulverized coal (super-critical)	Circulating fluidized bed	Integrated gasification combined cycle	Natural gas combined cycle
Thermal efficiency (HHV)[a]	w/o CCS	34.3%	38.5%	34.8%	38.4%	51.0%
	w/ CCS	25.1%	29.3%	25.5%	31.2%	43.9%
	Change	−27%	−24%	−27%	−19%	−14%
Power plant, consumption (gal MWh^{-1})[b]	w/o CCS	0.9	0.8	0.8	0.8	0.4
	w/ CCS	1.2	1.0	1.1	1.0	0.8
	Change	37%	31%	36%	23%	100%
Power plant, withdrawal (gal MWh^{-1})[b]	w/o CCS	1.3	1.2	1.2	1.2	0.6
	w/ CCS	1.8	1.5	1.6	1.5	1.0
	Change	37%	31%	36%	23%	67%
Fuel cycle, consumption (gal MWh^{-1})[c]	w/o CCS	22	19	20	20	4
	w/ CCS	30	25	27	24	5
	Change	37%	31%	36%	23%	16%
Fuel cycle, withdrawal (gal MWh^{-1})[c]	w/o CCS	22	19	20	20	5
	w/ CCS	31	25	27	24	6
	Change	37%	31%	36%	23%	16%
Operations, consumption (gal MWh^{-1})[d]	w/o CCS	530	500	560	320	210
	w/ CCS	940	880	980[f]	550	380
	Change	77%	76%	75%[f]	72%	81%
	n[e]	3	2	0[f]	4	2
Operations, withdrawal (gal MWh^{-1})[d]	w/o CCS	660	600	1000	390	250
	w/ CCS	1300	1100	1800[f]	640	510
	Change	97%	83%	81%[f]	64%	104%
	n[e]	3	3	0[f]	7	3

[a] As reported in MIT (2007) for coal technologies and NETL (2010b) for natural gas technology.
[b] We estimate power plant water use for different coal-fired generation technologies with and without CCS by adjusting the parameter for thermal efficiency from our base case (for sub-critical pulverized coal without CCS) to the reported thermal efficiencies. For natural gas-fired generation with CCS, we use the estimate reported by NETL (2010b).
[c] We estimate fuel cycle water use for different generation technologies with and without CCS by adjusting the parameter for thermal efficiency from our base cases for coal- and natural gas-fired generation to the reported thermal efficiencies.
[d] Estimated using median reported values as reported in tables 2 and 5.
[e] 'n' reports the number of operations water use estimates for each prime mover technology with CCS, as reported in tables 2 and 5.
[f] We estimate water use during operations of a circulated fluidized bed power plant equipped with CCS based on the weighted average of the other generation technology's estimates, due to a lack of reported estimates.

contributes a median of 18 gal MWh^{-1} to the fuel cycle total. In the final fuel cycle stage of coal transportation, although slurry pipelines consume 110 gal MWh^{-1} of water, train transport is more common currently, with the median water use reported in table 2 corresponding to a 205 mile transport distance (NETL 2010c).

When amortized to the power plant's lifetime generation, upstream and downstream water use for the coal power plant's equipment is negligible. In contrast, coal power plant cooling requires hundreds to thousands of gallons withdrawn and consumed per MWh. Water use factors vary substantially by cooling technology, with open loop cooling (also known as once-through cooling) requiring much greater withdrawals and recirculating cooling towers consuming relatively more water, as shown in table 2 and described in more detail elsewhere (Macknick *et al* 2012). Estimates for pond-cooled systems vary widely, because they can be operated similarly to either once-through or recirculating tower systems.

Generally, more efficient combustion technologies (e.g., integrated gasification combined cycle (IGCC)) require less water per unit generation for cooling than less efficient ones (e.g., sub-critical pulverized coal). Variation in reported estimates arises from variation in specific operating conditions as well as whether estimates include non-cooling water uses. For example, additional operational needs, such as pollution controls specific to coal, can be substantial; one study reports 155 gal MWh^{-1} for coal–ash handling, 12 gal MWh^{-1} for NO$_x$ control, and 60 gal MWh^{-1} for SO$_x$ scrubbing (TWDB 2003). Flue gas desulfurization increases water use by about 40 gal MWh^{-1} using dry technology and about 70 gal MWh^{-1} using wet technology (NETL 2009a).

As shown in table 4, collected data suggest that carbon capture and sequestration (CCS) can increase operations water consumption by about 75% and water withdrawal by between 64% and 97%, due to a combination of lower efficiencies

Table 5. Summary statistics of selected, harmonized estimates of water consumption and withdrawal for major life cycle stages and production pathways for natural gas-fired electricity generation.

	Sub-category[a]	Consumption (gal MWh^{-1})[b]				Withdrawal (gal MWh^{-1})[b]			
		Median	Min	Max	*n*[c]	Median	Min	Max	*n*[c]
Fuel cycle[d,e]	Conventional natural gas[f]	4	1	26	9	5	4	34	8
	Shale gas	16	3	210	20	17	5	220	18
Power plant[e]	Upstream and downstream[g]	1	<1[h]	1	2	<1[h]	<1[h]	1	3
Operations	CC: cooling tower	210	47	300	19	250	150	760	16
	CC: dry cooling	4	4	120	4	4	≪1[h]	4	2
	CC: open loop cooling	100	20	230	8	9 000	7 200	21 000	7
	CC: pond cooling	240	240	240	2	6 000	6 000	6 000	2
	CC + CCS: cooling tower	380	380	380	2	510	490	510	3
	CT	50	50	340	3	430	430	430	1
	Steam: cooling tower	730	560	1100	8	1 200	1 200	1 200	2
	Steam: open loop cooling	290	190	410	6	36 000	35 000	37 000	2
	Steam: pond cooling[i]	270	270	270	1	270	270	270	1

[a] CC = combined cycle; CT = combustion turbine; CCS = carbon capture and sequestration.

[b] Statistics based on harmonized estimates, with respect to life cycle stage boundaries as well as relevant parameters shown in table 1.

[c] For estimates constructed from multiple disaggregated stages or processes (reported in table 6), '*n*' reports the average number of estimates over each of the stages. For categories with exactly 2 estimates, the median is defined as the arithmetic mean.

[d] Fuel cycle estimates consists of estimates constructed from estimates for the individual stages within the fuel cycle (reported in table 6). All fuel cycle estimates assume pipeline transportation; estimates for water use in the fuel cycle of liquid natural gas (LNG) range widely and could potentially increase estimates substantially.

[e] Fuel cycle and power plant estimates are harmonized to the thermal efficiency of a combined cycle plant.

[f] We define conventional natural gas as that not requiring fracture stimulation.

[g] Power plant includes both upstream water use estimates (primarily for dust suppression during construction but also for the water use for manufacturing power plant raw materials) and downstream water use estimates (for water used in decommissioning power plants). The latter contributes negligibly to the total for this life cycle stage.

[h] <1 designates a value between 0.1 and 0.5 (due to rounding), and ≪1 designates a value less than 0.1.

[i] Reflecting data limitations and the nature of water use, we assume withdrawal and consumption are equal for all estimates in this category.

and additional process demands for certain CCS technologies. Efficiency penalties also increase the fuel cycle and power plant equipment life cycle water use per generated MWh. However, the water use of all CCS technologies has not been characterized in the literature, and technologies with different efficiency and operational characteristics would lead to different relative water impacts.

3.2. Natural gas

The natural gas-fired electricity life cycle also includes a fuel cycle, with the key water-relevant fuel cycle distinction being the use of hydraulic fracturing for shale gas extraction versus other conventional methods of extracting gas sources, as shown in tables 5 and 6. For hydraulic fracturing in shale, reported water use ranges from 300 000 gallons per well (Noble Energy Inc. and CSU 2012) to nearly 9 million gallons per well (TWDB 2012), with 50% of collected data reporting between 2 and 5 million gallons per well. Amortized by play-specific estimated ultimate recovery (EUR) of a well as reported in EIA (2011c), this corresponds to a median of 16 gal MWh^{-1} for shale gas hydraulic fracturing. Reflecting recent interest on the topic (e.g., GAO 2012, JISEA 2012, TWDB 2012), we found many estimates for water use in shale gas hydraulic fracturing and display these in figure 3. The variation in estimates corresponds to the range

of water volumes associated with technological differences; to variations in EUR, which can vary by as much as a factor of 10 across wells even within the same formation (GAO 2012); and to variation in other factors such as well length.

After extraction, natural gas is processed to bring it to pipeline quality. Although three older references (DOE 1983, Tolba 1985, Gleick 1994) agree upon a relatively high water usage of 11 gal MWh^{-1} for this processing, we defer to the more recent NETL (2010d) assessment that processing requires an equivalent of only 0.1 gal MWh^{-1}. Although this estimate is only for natural gas sweetening, it is unclear that any other stages of the natural gas processing stage use water; note that Grubert *et al* (2012) estimate no water use for natural gas processing. In all, our analysis suggests 4 gal MWh^{-1} consumed and 5 gal MWh^{-1} withdrawn in the fuel cycle of conventional natural gas, and 16 gal MWh^{-1} and 17 gal MWh^{-1} in that of shale gas.

As with most other thermoelectric technologies, we estimate water use in the power plant equipment's life cycle as negligible (1 gal MWh^{-1} or less), and operational water use far exceeds that for other life cycle stages in most cases, with important differences among cooling technologies. Reflecting the high thermal efficiencies of combined cycle natural gas plants relative to coal combustion, water used in natural gas operations is approximately one-half to one-third that for coal for a given cooling technology. Less efficient gas combustion

Table 6. Summary statistics of selected, harmonized estimates of water consumption and withdrawal for major production pathways in the natural gas fuel cycle.

	Consumption (gal MWh^{-1})[a]				Withdrawal (gal MWh^{-1})[a]			
	Median	Min	Max	n[b]	Median	Min	Max	n
Drilling[c]	1	≪1[e]	19	29	1	≪1[e]	19	29
Fracturing (other fracture stimulated gas)[c,d]	<1[e]	≪1[e]	2	4	<1[e]	≪1[e]	2	4
Fracturing (shale gas)[c]	12	1	186	49	12	1	186	49
Processing[c]	<1[e]	<1[e]	<1[e]	1	<1[e]	<1[e]	<1[e]	1
Transport (pipeline)	3	1	6	2	4	4	13	3
Transport (liquefied natural gas)	1	1	1	1	8	8	8	1

[a] Statistics based on harmonized estimates, with respect to life cycle stage boundaries as well as relevant parameters shown in table 1; estimates are harmonized to the thermal efficiency of a combined cycle natural gas power plant.

[b] For categories with exactly 2 estimates, the median is defined as the arithmetic mean.

[c] Reflecting data limitations and the nature of water use, we assume withdrawal and consumption are equal for all estimates in this category.

[d] The 'other fracture stimulated gas' category includes two estimates for tight gas and two reported for 'conventional gas with fracture stimulation' (all from IEA (2012)).

[e] <1 designates a value between 0.1 and 0.5 (due to rounding), and ≪1 designates a value less than 0.1.
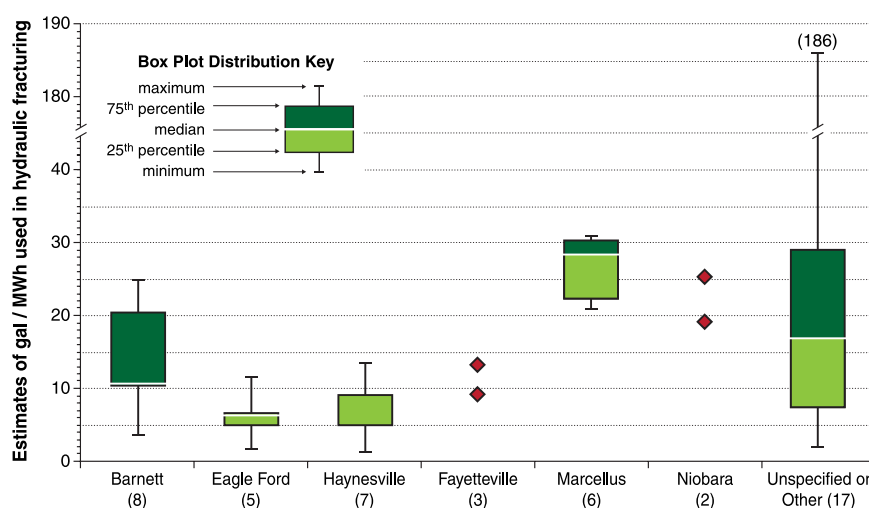

Figure 3. Distributions of estimates of water use for hydraulic fracture stimulation for shale gas extraction, expressed as a function of generated electricity, demonstrate variability both within and across different shale plays. Estimates do not include water used for drilling. The number of estimates for each play is presented in parentheses. The broken *y*-axis accommodates one outlier estimate reported as the upper limit of water use by IEA (2012). This figure is based on author analysis of collected estimates from 17 references; all fracturing (shale) estimates provided in the Natural Gas–Fuel Cycle–consumption table in the supplemental data (available at stacks.iop.org/ERL/8/015031/mmedia) are represented in this figure.

technologies have higher operational water use estimates, and as shown in table 4, CCS technology can increase operational water use by as much as a factor of two.

3.3. Nuclear

The uranium fuel cycle includes extraction, numerous processing steps, and greater end-of-life considerations than other fuels. As shown in table 7, our analysis suggests that the nuclear power fuel cycle typically withdraws 56 gal MWh^{-1} water with centrifugal enrichment and 140 gal MWh^{-1} (87 gal MWh^{-1} of which is consumed) for gaseous diffusion enrichment. Due to data limitations, including consumption estimates that often exceed estimates reported for withdrawal, we assume that withdrawal equals consumption for all fuel cycle stages except gaseous diffusion enrichment. Consistent

with other technologies, we consider only externally sourced water; estimates including produced water for *in situ* leaching exceed those shown here by approximately 70 times (e.g., Mudd and Diesendorf 2009). We do not distinguish between extraction methods; as table 8 shows, external water use estimates are not significantly differentiated by extraction method. End-of-life water use for nuclear power is uncertain; currently implemented fuel management options are at the low end of estimates (e.g., 1 gal MWh^{-1} withdrawal (Schneider *et al* 2010)), whereas potential fuel recycling is estimated at 720 gal MWh^{-1} withdrawal (NETL 2012a).

The large lifetime output of nuclear power plants leads to negligible estimates for the power plant equipment life cycle. Estimated operational water requirements, however, are around one or more orders of magnitude higher than fuel cycle

Table 7. Summary statistics of selected, harmonized estimates of water consumption and withdrawal for major life cycle stages and production pathways for nuclear power.

		Consumption (gal MWh^{-1})[a]				Withdrawal (gal MWh^{-1})[a]			
	Sub-category	Median	Min	Max	n[b]	Median	Min	Max	n[b]
Fuel cycle[c]	Centrifugal enrichment	56	13	300	5	56	13	300	5
	Diffusion enrichment	87	42	330	5	140	62	410	5
Power plant	Upstream and downstream[d]	<1[e]	<1[e]	<1[e]	2	<1[e]	<1[e]	<1[e]	2
Operations	Cooling tower	720	580	890	9	1 100	800	2 600	7
	Open loop cooling	400	100	400	5	47 000	23 000	60 000	12
	Pond cooling	610	400	720	4	1 100	500	13 000	4

[a] Statistics based on harmonized estimates, with respect to life cycle stage boundaries as well as relevant parameters shown in table 1.

[b] For estimates constructed from multiple disaggregated stages or processes (reported in table 8), 'n' reports the average number of estimates over each of the stages. For categories with exactly 2 estimates, the median is defined as the arithmetic mean.

[c] Fuel cycle estimates consists of estimates constructed from the individual stage estimates. All fuel cycle estimates represent a combined estimate for different extraction types and storage and disposal for spent fuel; reprocessing and recycling of spent fuel is not currently practiced in the United States but would increase estimates substantially.

[d] Due to limited information, upstream water use includes estimates only for manufacturing power plant raw materials. In addition, although the stage is expected to be negligible, no estimates for downstream water use were found.

[e] <1 designates a value between 0.1 and 0.5 (due to rounding), and ≪1 designates a value less than 0.1.

Table 8. Summary statistics of selected, harmonized estimates of water consumption and withdrawal for major production pathways in the nuclear fuel cycle.

	Consumption (gal MWh^{-1})[a]				Withdrawal (gal MWh^{-1})[a]			
	Median	Min	Max	n[b]	Median	Min	Max	n[b]
Extraction (*in situ* leaching)[c,d]	18	13	23	2	18	13	23	2
Extraction (surface)[c]	32	4	92	6	32	5	92	6
Extraction (underground)[c]	30	<1[g]	240	4	30	<1[g]	240	4
Extraction (type not specified)[c]	15	15	15	1	15	15	15	1
Processing (milling)[c]	11	3	29	6	11	3	29	6
Processing (conversion)[c]	10	4	13	3	10	4	13	3
Processing (centrifugal enrichment)[c]	4	3	6	3	4	3	6	3
Processing (diffusion enrichment)	35	32	37	2	83	51	120	2
Processing (fuel fabrication)[c]	1	1	3	4	1	1	3	4
End-of-life (storage and disposal)[c,e]	3	1	5	3	3	1	5	3
End-of-life (reprocessing spent fuel)[f]	7	7	7	1	720	720	720	1

[a] Statistics based on harmonized estimates, with respect to life cycle stage boundaries as well as relevant parameters shown in table 1.

[b] For categories with exactly 2 estimates, the median is defined as the arithmetic mean.

[c] Reflecting data limitations and the nature of water use, we assume withdrawal and consumption are equal for all estimates in this category.

[d] For *in situ* leaching, only external water use is considered. The inclusion of produced water can lead to estimates on the order of 70 times higher.

[e] Storage and disposal includes estimates both of 'temporary' storage on site and also the hypothetical Yucca Mountain storage facility.

[f] Reprocessing of fuel is based on a hypothetical facility (NETL 2012a).

[g] <1 designates a value between 0.1 and 0.5 (due to rounding), and ≪1 designates a value less than 0.1.

estimates. As for other generation technologies, we estimate that the proportion of withdrawn water that is consumed is higher for cooling towers than it is for open loop cooling, and the proportion of consumption for pond cooling is in between the two.

3.4. Concentrating solar power (CSP)

CSP has no fuel cycle, but CSP power plant life cycle estimates (in gal MWh^{-1}) are higher than for the non-renewable thermoelectric technologies. This likely reflects the lower lifetime output over which upstream use is amortized

and the use of specialty chemicals requiring more water than commodities used in typical thermoelectric technologies. Although Inhaber (2004) estimates about 1 gal MWh^{-1} for the power plant equipment life cycle based on material volumes, other references estimate water consumption just for construction between 1 and 80 gal MWh^{-1}. We omit these estimates and instead base our median water use estimate of 160 gal MWh^{-1} only on references reporting more comprehensively for the power plant life cycle (Burkhardt *et al* 2011, NETL 2012b). As a thermoelectric generation technology, CSP withdraws similar amounts of operational water to pulverized coal technology, with

Table 9. Summary statistics of selected, harmonized estimates of water consumption and withdrawal for major life cycle stages and production pathways for CSP-generated electricity.

	Sub-category	Consumption (gal MWh^{-1})[a]				Withdrawal (gal MWh^{-1})[a]			
		Median	Min	Max	n[b]	Median	Min	Max	n[b]
Power plant	Upstream and downstream[c]	160	80	170	3	160	99	170	3
Operations	Dish stirling[d]	5	5	5	2	5	5	5	2
	Fresnel[d]	1000	1000	1000	1	1000	1000	1000	1
	Power tower: cooling tower	810	740	860	5	740	740	740	1
	Power tower: dry cooling[d]	26	26	26	1	26	26	26	1
	Power tower: hybrid cooling[d]	170	90	250	2	170	90	250	2
	Trough: cooling tower	890	560	1900	26	960	870	1100	2
	Trough: dry cooling	78	32	140	20	78	33	79	11
	Trough: hybrid cooling	340	110	350	3	340	340	340	1

[a] Statistics based on harmonized estimates, with respect to life cycle stage boundaries as well as relevant parameters shown in table 1.

[b] For estimates constructed from multiple disaggregated stages or processes, 'n' reports the average number of estimates over each of the stages. For categories with exactly 2 estimates, the median is defined as the arithmetic mean.

[c] Power plant includes both upstream water use estimates (using only those that include manufacturing in addition to construction) and downstream water use estimates (for water used in dismantling and disposal of power plants). The latter contributes negligibly to the total for this life cycle stage. Estimates are harmonized to the solar-to-electric efficiency of a trough power plant. We include consumption estimates from Burkhardt *et al* (2011) in the withdrawal category due to lack of available data on withdrawals; therefore, withdrawals might be underestimated.

[d] Reflecting data limitations and the nature of water use, we assume withdrawal and consumption are equal for all estimates in this category.

important differences by cooling technology. However, because CSP systems commonly are located in remote areas and use evaporation ponds for water disposal, consumption volumes typically equal withdrawals regardless of technology (Solar Millennium LLC 2008).

3.5. Geothermal

Usable data on geothermal power's water use are limited, as shown in table 10. From available data, we estimate that 3 gal MWh^{-1} of water are withdrawn and 2 gal MWh^{-1} are consumed in the power plant equipment life cycle, with water use dominated by drilling and cementation in plant construction. As described in more detail elsewhere (Clark *et al* 2011, Macknick *et al* 2012), operational water use varies by more than an order of magnitude corresponding both to technology configurations (e.g., dry steam, binary, and flash) and to local contexts. Consistent with Macknick *et al* (2012) and our treatment of other technologies, we screened out many published estimates of geothermal operations water use that included geothermal fluids in operational water requirements and focus only on estimates of external water required for operations. Estimates of water use that include geothermal fluids in operational water requirements report water consumption values between roughly 2000 gal MWh^{-1} to 4000 gal MWh^{-1}, with estimates of EGS even higher (Macknick *et al* 2011). In addition, because the limited data led to results conflicting with physical laws, we include an estimate for a tower-cooled binary power plant that normally would be excluded by our screens because the value (700 gal MWh^{-1}) is estimated from a graphic in the original source (Kozubal and Kustcher 2003).

3.6. Photovoltaics (PV)

As shown in table 11, estimates of water withdrawal for PV's power plant equipment life cycle vary widely, from 1 to 1600 gal MWh^{-1}, with the majority near the median estimate of 94 gal MWh^{-1} for crystalline silicone (C-Si). Of the few consumption estimates available, those matched to withdrawal estimates suggest approximately 30% of withdrawn water is consumed (Genesee County Economic Development Center 2011). Because the water use for the PV power plant potentially dominates that for other PV life cycle stages, this variation argues for further study; processing silicon into PV equipment involves numerous stages with rapidly developing techniques that are much less established than manufacturing processes used for other generation technologies, such as the fabrication of steel components. Given this uncertainty, we combine a variety of individual PV technologies, mostly thin-films, into a single 'other' category.

Water use for operations is minimal. Experimental evidence demonstrates that although frequent washing increases output, it likely leads to economic losses (Sahm *et al* 2005). DOE (2012) reports that few operators wash PV panels in actual practice. The higher water use of concentrated PV likely reflects certain shared operational characteristics with CSP, such as a need for mirror washing.

3.7. Wind

Although wind data come from few references, these estimates appear of high quality due to thorough information, including paired reporting of withdrawal and consumption,

Table 10. Summary statistics of selected, harmonized estimates of water consumption and withdrawal for major life cycle stages and production pathways for geothermal power-generated electricity.

		Consumption (gal MWh^{-1})[b]				Withdrawal (gal MWh^{-1})[b]			
	Sub-category[a]	Median	Min	Max	n[c]	Median	Min	Max	n[c]
Power plant	Upstream and downstream[d]	2	2	2	1	3	<1[g]	10	11
Operations[e]	Binary: hybrid cooling[f]	460	220	700	2	460	220	700	2
	Binary: dry cooling[f]	290	270	630	3	290	270	630	3
	Flash	11	5	360	5	18	11	25	2
	EGS: dry cooling[f]	510	290	720	2	510	290	720	2

[a] EGS = enhanced geothermal system.
[b] Statistics based on harmonized estimates, with respect to life cycle stage boundaries as well as relevant parameters shown in table 1.
[c] For categories with exactly 2 estimates, the median is defined as the arithmetic mean.
[d] Due to limited information, upstream water use includes estimates only for manufacturing power plant raw materials and construction. In addition, although the stage is expected to be negligible, no estimates for power plant downstream water use were found.
[e] We omit many collected estimates, which conflate produced water with external water; only external water use is reported in the table.
[f] Reflecting data limitations and the nature of water use, we assume withdrawal and consumption are equal for all estimates in this category.
[g] <1 designates a value between 0.1 and 0.5 (due to rounding), and ≪1 designates a value less than 0.1.

Table 11. Summary statistics of selected, harmonized estimates of water consumption and withdrawal for major life cycle stages and production pathways for PV-generated electricity.

		Consumption (gal MWh^{-1})[a]				Withdrawal (gal MWh^{-1})[a]			
	Sub-category	Median	Min	Max	n[b]	Median	Min	Max	n
Power plant[c]	C-Si (crystalline silicone)	81	10	210	3	94	1	1600	24
	Other (primarily thin-film)	6	5	7	2	18	<1[d]	1400	19
Operations	Flat panel[e]	6	1	26	9	6	1	26	9
	Concentrated PV[e]	30	24	78	4	30	24	78	4

[a] Statistics based on harmonized estimates, with respect to life cycle stage boundaries as well as relevant parameters shown in table 1.
[b] For categories with exactly 2 estimates, the median is defined as the arithmetic mean.
[c] Power plant estimates include both upstream (i.e., raw materials, manufacturing, construction, and transportation) and downstream (decommissioning) water use. Due to a lack of data, we assume for downstream processes that consumption is negligible and withdrawal is equivalent across sub-categories.
[d] <1 designates a value between 0.1 and 0.5 (due to rounding), and ≪1 designates a value less than 0.1.
[e] Reflecting data limitations and the nature of water use, we assume withdrawal and consumption are equal for all estimates in this category.

relatively close agreement on withdrawals across sources, and relatively common reporting for power plant downstream water use. We omit older estimates of manufacturing water use that are based on standard manufacturing practices and the bulk volume of materials (Inhaber 2004) in favor of detailed data from manufacturers and a national laboratory, resulting in a median withdrawal of 26 gal MWh^{-1} and consumption of 1 gal MWh^{-1}. Wind turbines require no fuel and little, if any, washing and maintenance, so operational water use is very low.

4. Results: water use across the full life cycle

Figures 4 and 5 depict estimated total life cycle water consumption and water withdrawal, respectively, for selected production pathways for each generation technology, lever-

aging the best available evidence collected and screened herein. We construct life cycle water use by summing water use factors for relevant stages presented above using the consistent performance parameters presented in table 1 and using consistent definitions for each life cycle stage. These estimates are based on median values and thus ignore the important variation within estimates for each stage. More generally, life cycle water use estimates are a limited indicator of aggregate impact on water resources, given the critical spatial and temporal characteristics of resource demands and availability.

Operations dominate the life cycle water use for most electricity production pathways, with the exceptions of dry-cooled thermoelectric technologies, PV, and wind. Accordingly, relative rankings of life cycle water use mirror those for the operations stage presented in Macknick *et al*

Table 12. Summary statistics of selected, harmonized estimates of water consumption and withdrawal for major life cycle stages and production pathways for wind-generated electricity.

	Sub-category	Consumption (gal MWh^{-1})[a]				Withdrawal (gal MWh^{-1})[a]			
		Median	Min	Max	n[b]	Median	Min	Max	n[b]
Power plant	Upstream and downstream[c]	1	≪1[d]	9	12	26	13	83	19
Operations	Onshore	<1[d]	≪1[d]	2	10	1	1	1	2
	Offshore	≪1[d]	≪1[d]	1	4	2	≪1[d]	3	9

[a] Statistics based on harmonized estimates, with respect to life cycle stage boundaries as well as relevant parameters shown in table 1.

[b] For estimates constructed from multiple disaggregated stages or processes, 'n' reports the average number of estimates over each of the stages. For categories with exactly 2 estimates, the median is defined as the arithmetic mean.

[c] Power plant includes both upstream water use estimates (pertaining to manufacturing, materials, and construction) and downstream water use estimates (for water used in dismantling and disposal of power plants). The latter contributes negligibly to the total for this life cycle stage.

[d] <1 designates a value between 0.1 and 0.5 (due to rounding), and ≪1 designates a value less than 0.1.
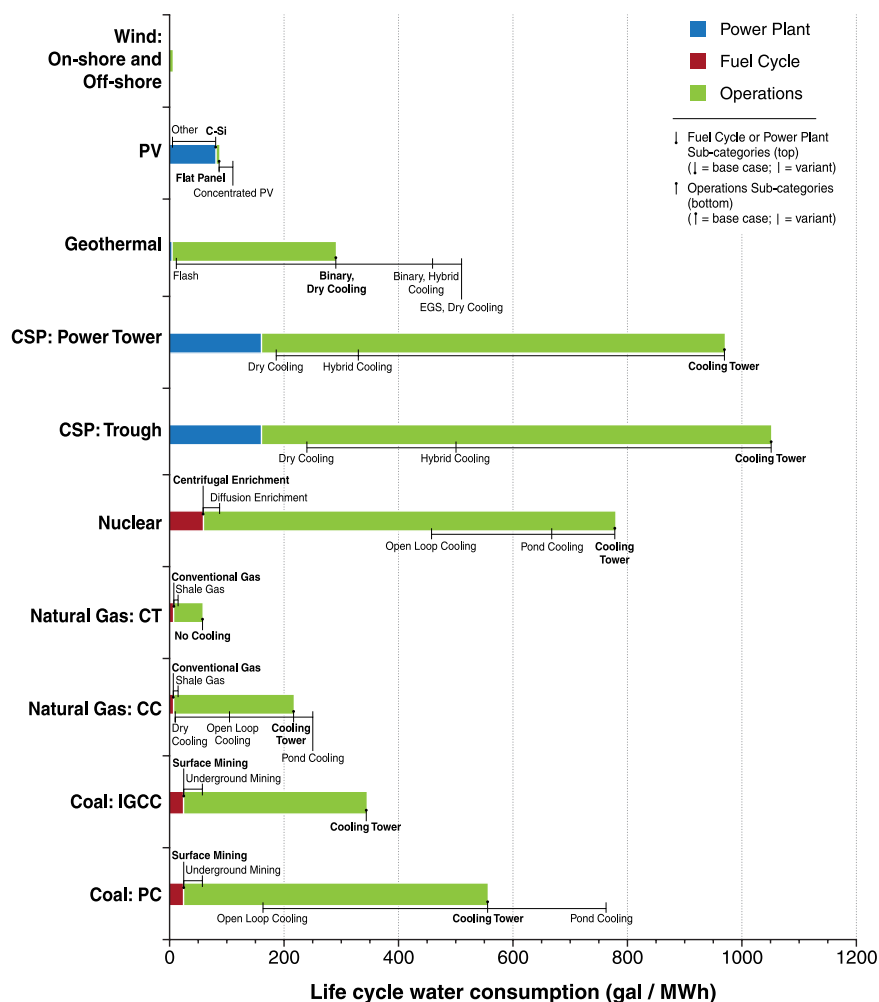

Figure 4. Estimated life cycle water consumption factors for selected electricity generation technologies, based on median harmonized estimates, demonstrate significant variability with respect to technology choices. Base case estimates for each life cycle stage, presented in bold font, are held constant for estimating life cycle water consumption factors for other life cycle stages. Estimates for production pathway variants in fuel cycle or power plant (labeled on top of the bars) or operations (bottom) are labeled at points connected to the base case estimate with horizontal lines. Note: PV = photovoltaics; C-Si = crystalline silicone; EGS = enhanced geothermal system; CSP = concentrating solar power; CT = combustion turbine; CC = combined cycle; IGCC = integrated gasification combined cycle; and PC = pulverized coal, sub-critical.
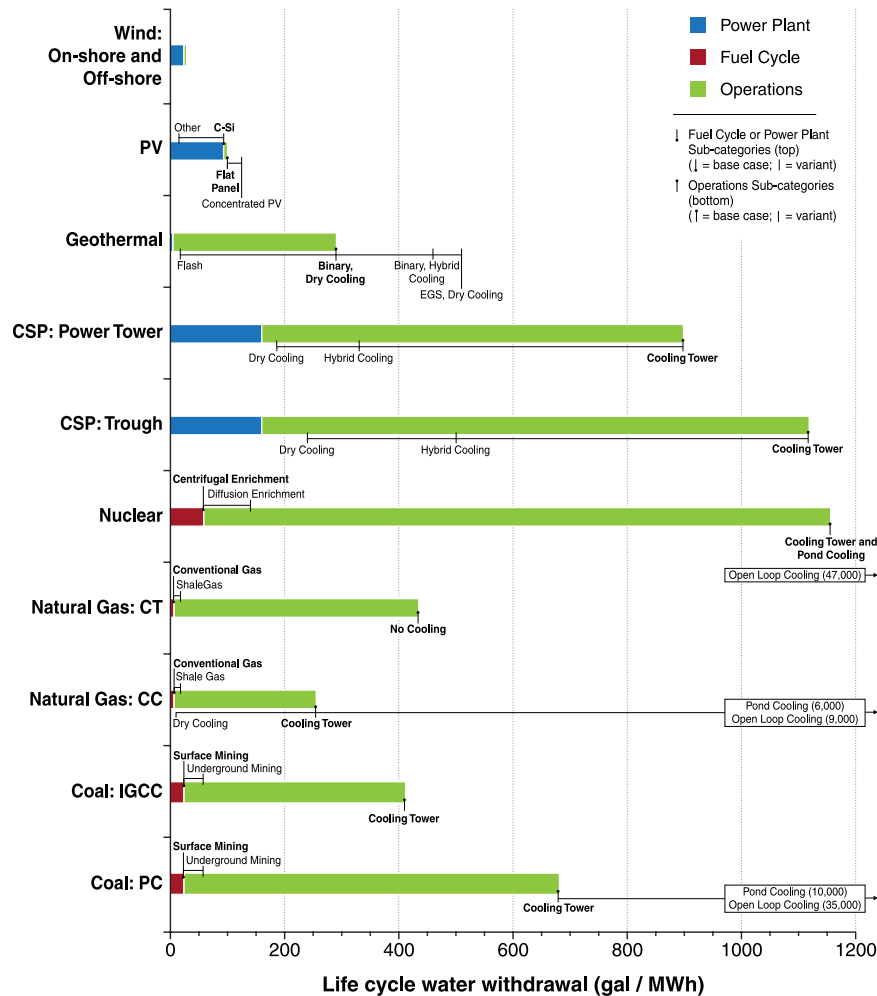
Figure 5. Estimated life cycle water withdrawal factors for selected electricity generation technologies, based on median harmonized estimates, demonstrate significant variability with respect to technology choices. Base case estimates for each life cycle stage, presented in bold font, are held constant for estimating life cycle water consumption factors for other life cycle stages. Estimates for production pathway variants in fuel cycle or power plant (labeled on top of the bars) or operations (bottom) are labeled at points connected to the base case estimate with horizontal lines. Note: PV = photovoltaics; C-Si = crystalline silicone; EGS = enhanced geothermal system; CSP = concentrating solar power; CT = combustion turbine; CC = combined cycle; IGCC = integrated gasification combined cycle; and PC = pulverized coal, sub-critical.

(2012). For coal, natural gas, and nuclear, the fuel cycle contributes a small but non-negligible amount to total life cycle water use. For these technologies, power plant equipment life cycle water demands are negligible in relation to the life cycle total. In contrast, the power plant contributes a large portion of the total water use for the thermoelectric renewable technology of CSP, and represent the majority of life cycle water use for non-thermoelectric renewables (PV and wind). With the exception of prominent distinctions between withdrawal and consumption requirements for different cooling technologies, most estimates of water consumption and withdrawal across the life cycle of a given production pathway follow similar relative patterns to each other. In both figures 4 and 5, the relative rankings of water use across major generation technology categories switch according to production pathways.

Figure 6 demonstrates the sensitivity of the life cycle water consumption estimates shown in figure 4 to the selection of performance parameters for harmonization. The range of

parameters used match the extremes found in the published literature or reported in reviews on electricity generated by coal (Whitaker *et al* 2012), natural gas (O'Donoughue *et al* 2012), nuclear power (NETL 2012a, Warner and Heath 2012), CSP (Burkhardt *et al* 2012, DOE 2012), PV (Hsu *et al* 2012), and wind (Dolan and Heath 2012). We base the range for geothermal on the ranges used for other technologies.

Parameter values can alter the relative rankings of water consumption across major generation technology categories (e.g., coal versus nuclear). The relative sensitivity of the life cycle total consumption to performance parameter values corresponds to the relative contribution of the major life cycle stages to which they pertain. In addition to demonstrating a source of variation in published estimates, this figure reflects how operations characteristics interact with relative water use in other life cycle stages to influence water use per unit of electricity output. For example, variation in thermal efficiency corresponds with substantial variation in life cycle water use because the factor affects the amount of cooling water
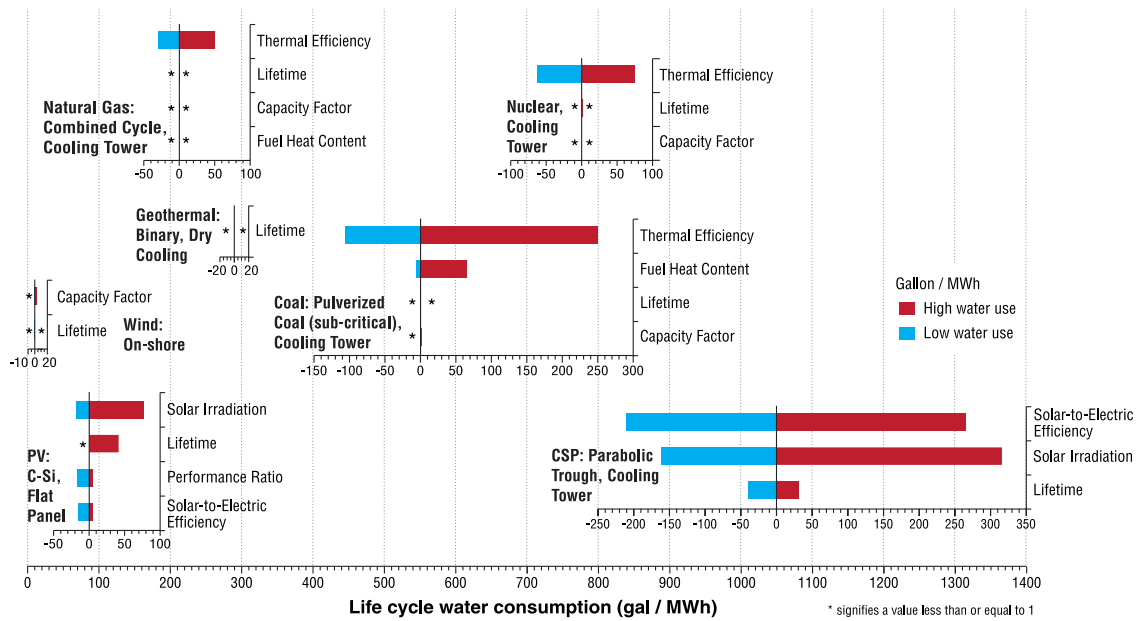
Figure 6. Sensitivity analysis reveals differing influence of certain performance parameters on the median estimate of life cycle water consumption factors for selected electricity generation technology production pathways. The figure depicts the variation of median life cycle stage estimates across a range of reasonable performance parameters. See text and section A.4 of the supplemental data (available at stacks.iop.org/ERL/8/015031/mmedia) for further details. Note: PV = photovoltaics; C-Si = crystalline silicone; and CSP = concentrating solar power.

required in operations, but also how much fuel is required and therefore how much water is required for fuel extraction (which is measured in terms of water use per unit of fuel). Furthermore, factors affecting only the amortization of power plant equipment, such as lifetime or capacity factor, have little influence on life cycle water factors when the power plant equipment contributes only negligibly to the life cycle total.

5. Conclusion

In a water-constrained world, it is critical to understand how water is used throughout the entire life cycle of electricity generation. From a wide array of sources, we gathered available evidence for water use in any stage of the electricity generation life cycle for selected technologies. We screened and harmonized estimates to common performance parameters and boundaries and consolidated them into water consumption and withdrawal factors for major life cycle stages for each electricity generation technology considered.

This concise presentation of life cycle water use factors, built from a thorough review of the available literature, offers a unique and comprehensive look at the water requirements of different electricity generation and fuel supply choices. In many cases, operations dominate life cycle water use in absolute magnitude. However, the water implications of choices about electricity generation technologies clearly do not end at those due to the cooling water demands for thermoelectric generation. The fuel cycles of coal, natural gas, and nuclear power all require significant water volumes, and renewable generation technologies require significant water for manufacturing and construction. Such considerations may be important to the development both of local fuel resources

and of local electricity generation capacity in regions with current or potential constraints on water resources. In general, based on review and harmonization of the available evidence, total life cycle water use across the generation technologies considered here appears lowest for electricity generated by photovoltaics and wind, and highest for nuclear and conventional coal technologies. Depending on cooling and prime mover technologies, natural gas and CSP technologies can be ranked either among the highest or lowest water users. For a given generation technology and cooling type, evaluated CCS technologies can increase operational water use by a factor of two and upstream water use by an amount proportional to the associated loss in efficiency.

Despite extensive collection, screening, and harmonization efforts, gathered estimates for most generation technologies and life cycle stages remain few in number, wide in range, and many are of questionable original quality. These constraints should be considered for proper interpretation and use of the results reported here in future analyses. For example, reflecting a general lack of rigorously tracked and recorded comparisons of consumption to withdrawal, median estimates of consumption in some cases exceed the corresponding median estimate for withdrawal and were thus adjusted in the results reported herein to conform to physical laws. Estimates for nearly all processes and life cycle stages vary significantly, reflecting a combination of issues including methodological inconsistency, sub-category heterogeneity, and the effect of local conditions on water use. Data limitations highlight the need for new sources of primary data for many life cycle stages of many generation technologies. Although most categories would benefit from new sources of more recent, well-documented primary data,

the limitations suggest particular value from further research into areas with relatively large variation in estimates, such as the PV power plant equipment life cycle, or with few available estimates, such as the nuclear fuel cycle or the full life cycle of geothermal electricity generation.

This analysis establishes a foundation for estimating water requirements of different electricity generation choices. Estimation of water use for actual projects should use the most specific data possible, in light of the finding that the ranking of water use across generation technologies is not fixed but varies with production pathway and by specific performance parameters. However, this paper provides insight by consolidating and screening the wide breadth of available information into robust first order estimates of water used by archetypal production pathways across the life cycle. Improved understanding of water use can inform management of risks associated with water resource variability, within each part of the production pathway.

Acknowledgments

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