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Water use of electricity technologies: A global meta-analysis

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ABSTRACT

Understanding the water use of power production is an important step to both a sustainable energy transition and an improved understanding of water conservation measures. However, there are large differences across the literature that currently present barriers to decision making. Here, the compiled inventory of the blue water use of power production from existing studies allowed to uncover the characteristics of water use and to investigate current uncertainties. The results show that photovoltaics, wind power, and run-of-the-river hydropower consume relatively little water, whereas reservoir hydropower and woody and herbaceous biomass can have an extremely large water footprint. The water consumption of power production can differ greatly across countries due to different geographic conditions. Only a few studies provided the values for the influencing factors of water use, such as the capacity factor. Values that are reported came mainly from assumptions and other literature rather than direct measurement. Omitting a life cycle stage may lead to significant underestimations. Water scarcity is attracting more attention, but the few existing results are not useable for a regional comparison due to data gaps and inconsistent measurements. In the future, a clear and detailed definition of the water footprint and system boundary of power production is essential to improving comparisons and energy systems modelling.

1. Introduction

Electric power production is a major driver of water stress worldwide [1,2]. This situation is likely to be exacerbated due to growing energy demands and climatic change [3–6]. In recent decades, technically plausible energy transition pathways have been designed to meet climate goals, but a concurrent analysis of the implications for water resources is mostly lacking. In some scenarios, emission mitigation benefits drive increased pressure on water resources [7,8]. For instance, many climate stabilization scenarios rely on bioenergy with carbon capture and storage (BECCS) as a negative-emission technology, but it is a very water-intensive option [9,10]. Rising water stress is of increasing concern to both renewable [11,12] and non-renewable power production [13,14]. Further energy system planning would greatly benefit from the incorporation of water stress perspectives and there are increasing efforts to include water resources as significant components in energy transition modeling [15–18]. The existing scientific literature provides a variety of water use estimates for various energy technologies and life cycle stages. However, many of these estimates differ widely or are even conflicting, giving an unclear picture of the energy-water nexus.

The use of water in the electricity system can be assessed using multiple metrics. The most common measure is the volumetric water footprint. It includes direct (i.e. water use for cooling at the point of generation) and indirect water use (i.e. upstream water use in the supply chain of fuels or equipment). It is defined by the volume of freshwater used by a consumer or producer over the entire supply chain [19,20]. In recent years this concept has been extended to impact-oriented water footprints that assess not just the volume of water use but the potential environmental impacts [21]. The impact-oriented approach additionally considers regionalized impact indicators as part of traditional impact assessment frameworks [22]. Although both methods have been applied to studies on the water use of power production, most existing studies consider only the volume of water use of power production, which is therefore the main focus of our study.

Previous reviews on the water use of power production have

Abbreviations: CCS, carbon capture and storage; CSP, concentrating solar power; DAC, direct air capture; DNI, direct normal irradiation; EGS, enhanced geothermal system; IOA, input-output analysis; ISL, in-situ leaching; L/MWh, Liter/Megawatt hour; LCA, life cycle assessment; OWC, Operational Water Consumption; PLCA, process-based LCA; PV, photovoltaics

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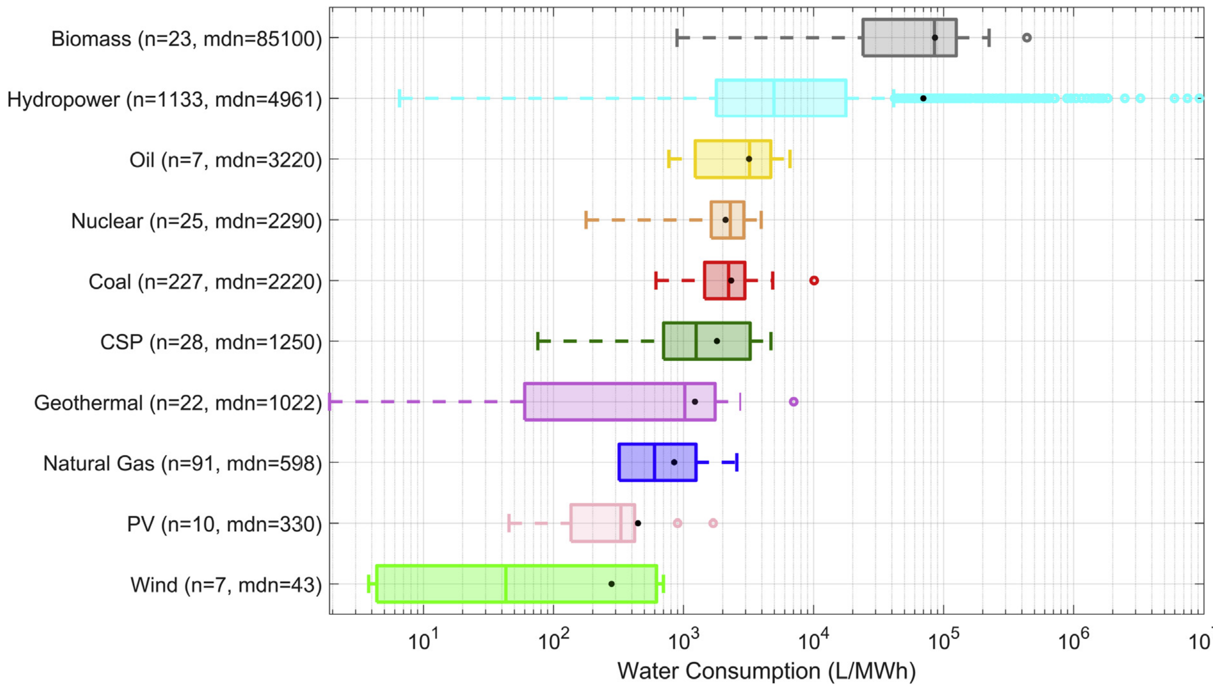

Fig. 1. Blue water consumption over the life cycle across energy generation types. Water consumption is visualized on a log scale. The annotation mdn gives the median value of water consumption for each fuel type. Circles represent the outliers, while the dots represent the average for each power type. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

focused on the United States (U.S.) [23–25]. Global assessments [26,27] often rely on data from the U.S. and assume that generation in other countries have similar water use characteristics. A global overview of the differences in water use of power production is currently lacking. Water use covering the life cycle of power production have been used for estimating water use at the global [26–28] and country level [29–32]. For power production, the life cycle of water use can be split into fuel cycle, plant operation, and plant infrastructure stages. Analyses typically focus on the operational stage, distinguishing the water use by different cooling technologies and energy types. However, there are other important factors driving water use including fuel type, power plant type, and environmental conditions.

Although there must be uncertainties in the water use of power production, these are often not estimated in studies generally. This is often due to a lack of information on how to assess these uncertainties. This systematic literature review serves to investigate the above knowledge gaps by tearing apart the differences between previous studies, and presenting a picture of the current state of knowledge.

2. Methodology and data

Estimates from the literature were gathered following the PRISMA guidelines [33]. The meta-analysis focuses on the variations in water use estimates across technologies and locations, and the completeness of data reported across papers. In terms of the type of water uses, this study focuses on blue water (i.e. the use of surface or groundwater, such as irrigation water for biomass). In the framework of volumetric water footprints, blue, green (soil moisture), and grey water (hypothetical volume needed to dilute pollutants) are often added as if they were equivalent. In contrast in the life cycle assessment (LCA) community, green water use and water pollution are assessed through separate impact categories due to their fundamental differences [21], and are beyond the scope of this study. The gathered data represent two types of blue water use: withdrawal and consumption, with more emphasis on the latter. The former reflects the volume of water diverted from a water source for use, while the latter refers to the volume of withdrawn water not returned to the source due to evaporation, transpiration or incorporation into products [23,34–36].

The database search was conducted in April 2019 using Web of Science and ScienceDirect without applying a time restriction. Search terms related to water footprints were used: *water footprint, water use, water consumption, water withdrawal, water demand, water requirement*, in combination with other terms representing both renewable and non-renewable power production: *renewable, non-renewable, fossil fuel, coal, oil, natural gas, shale gas, nuclear, hydropower, biomass, biofuel, geothermal, wind, solar, photovoltaic* and *electricity*. The full list of terms and their relevant variations, together with the numbers of results for each stage of screening, are shown in Appendix B.

This search yielded 910 publications, which were filtered depending on whether the following inclusion criteria were met: (1) the value of the water use during the entire life cycle or a specific life cycle stage was reported; (2) the type of water use (consumption or withdrawal) could be distinguished; and (3) the information on the energy type was provided. Snowball sampling was also used. The final sample included 93 publications (see Fig. A1 in Appendix A for the full selection processes).

Data were extracted from publications either directly from tables, or from figures using WebPlotDigitizer, version 4.1. Common categories of analysis included: the type of energy (e.g. natural gas), energy sub-type (e.g. shale gas), type of water use (i.e. consumption or withdrawal), and the life cycle stage (e.g. fuel cycle). Extracted information on other factors included the country of assessment (e.g. Canada), cooling type (e.g. dry cooling), generator technology (e.g. combined cycle), conversion efficiency, capacity factor, lifetime, and environmental conditions (e.g. solar irradiation). The full dataset and influencing variables are shown in Appendix C and Appendix D, respectively.

Due to data limitation and inconsistency for impact-oriented water footprints (namely water scarcity footprints), these are discussed separately (Section 4.2). Generally, studies estimated blue water use based on the values of the influencing factors, such as the conversion efficiency. However, the effects of such factors on water use lack quantitative assessment. In this study, correlation analysis and linear regression are used to investigate the relationships between key factors and water use of power production. As for linear regression, this study investigates the relations between operational water consumption and its influencing variables (cooling type and conversion efficiency) for five power types (coal, natural gas, oil, nuclear and biomass).

3. Results

3.1. Overall results

Blue water consumption and withdrawal for the total life cycle were reported in 32 studies (34% of sample, see Fig. 1 for consumption and Fig. A2 Hydrol Earth Syst Sci for withdrawal). As expected, there is a large range in water uses across energy types. For instance, the median life cycle water consumption for biomass is 8.5×10^4 L/MWh, one to three orders of magnitude larger than other types. Generally, biomass can be classified into four groups, including wood and woody biomass, herbaceous biomass, aquatic biomass, and animal and human waste biomass [37]. Previous studies on the water use of biomass power focused on the first two above-mentioned groups, as they are the main feedstock of biomass power. Hence, the latter two biomass types are not included in this study. The extreme estimate represented the large requirement for irrigation of herbaceous perennials in the arid Southwestern U.S [24]. Although the water consumption for wind power is widely thought to be negligible [14,28,38–40] and it is characterized by the lowest median water consumption, it can still reach 700 L/MWh if direct and indirect material inputs for wind power are included using hybrid LCA (see detailed discussion in section 4.1) [41]. Similarly for photovoltaics (PV), the outliers of life cycle water consumption were caused by using a hybrid method [41,42]. For geothermal energy, the only outlier resulted from the large belowground water consumption for an enhanced geothermal system (EGS), in which case 10% belowground water loss during operation was assumed [43]. However, as the belowground water consumption is for maintaining the reservoir, the water does not need to be of high quality. If the water used for belowground operation was not freshwater, then its life cycle water consumption would decrease dramatically from 7037 L/MWh to just 185 L/MWh.

Another point to note is the generally high variability in water consumption across power plants of the same type. Coal power plants has relatively low variabilities in life cycle water consumption, whereas hydropower has a marked variability, with a coefficient of variation of 634% (Table A2). Local estimates are especially important for biomass, oil power and hydropower. For water withdrawal, the ranking of energy technologies based on the median or average values remains the same, except for natural gas which ranks higher than geothermal energy in terms of water withdrawal (Fig. A2). The range of water withdrawal is generally much wider than of consumption due to large withdrawal differences between once-through cooling and other cooling types. Water consumed during once-through cooling is generally negligible (around 1%).

3.1.1. Water use of fuel supply

The water uses of fuel supply reported in this section only apply to fuels for electricity generation, that is: coal, natural gas, oil, nuclear, and biomass, as shown in Fig. A3. The water uses here refer to the blue water used for fuel supply, i.e. extraction (for biomass, it refers to crop cultivation), processing and transport. For biomass power, the key stage of life cycle water consumption is the fuel cycle due to the considerable water input in crop cultivation [44,45]. Herbaceous and woody biomasses are separately examined in terms of the fuel cycle, as they have different water demands for growth. The median water consumption for herbaceous biomass (7.6×10^4 L/MWh) is much larger than that of other fuel types by more than two orders of magnitude, but still much smaller than that of woody biomass (8.3×10^5 L/MWh). Within biomass, water consumption varies greatly, from 7200 L/MWh [46] to 2.8×10^7 L/MWh [45]. An exception excluded in this figure is Mann and Spath [47] where hybrid poplar was assumed to be rain-fed (i.e., no irrigation water is used). In terms of fuel cycle, natural gas has the lowest median water consumption (128 L/MWh), lower than that of nuclear (156 L/MWh) and coal (231 L/MWh). Within natural gas, there are three fuel sub-types: conventional gas, coal-bed methane and shale gas, with median consumptions of 60 L/MWh, 70 L/MWh, and 222 L/MWh respectively. Water use in fracturing rock for shale gas explains the large volume (65% of the median variation), with the remaining from indirect water use in the supply chain (33% of the median variation) [25,48]. Oil is a large water consumer at the fuel cycle, with median water consumption of 891 L/MWh for conventional and 1658 L/MWh for unconventional oil (oil sand and oil shale) [26,35]. Studies generally assume that water withdrawal in the fuel cycle is equal to water consumption in the fuel cycle [25,35,49–52].

3.1.2. Operational water use

The water uses here refer to the blue water used in the operational process of power plants. Studies typically focus on cooling systems, as it accounts for most of the operational water use. Hereinafter, cooling water consumption refers to the blue water evaporated during operation for cooling purposes. Water consumption is reported first. Hydropower is the largest water consumer during the operational phase (median = 5.1×10^4 L/MWh), one to three orders of magnitude larger than that of other types (Fig. A4). Large differences exist within hydropower, ranging from 0 [53,54] to 1.2×10^8 L/MWh [12]. Most studies estimated water consumption based on the gross water evaporation from reservoirs, which changes as a function of the reservoir surface area. According to Demeke et al. [53] and Liu et al. [54], the gross water consumption was regarded as zero for those hydropower stations running without reservoirs (i.e. run-of-river plants). Similarly, for plants running with reservoirs, evapotranspiration was assumed to occur from the same area prior to the establishment of the reservoir [55]. Taking this into account, some studies calculated the net water consumption by subtracting the evapotranspiration before the dam construction from the gross water evapotranspiration [12,35,56–58]. These studies show that net water consumption is on average 54% of the gross water consumption. However, because reservoirs offer multiple purposes, such as water supply, flood control, and navigation, some studies suggest that for a fair comparison with other energy types the impacts of the reservoir should be allocated among its multiple purposes [12].

A once-through cooling system is a technically simple system, which requires large amounts of water withdrawal and directly returns most of that water to its source. In closed-loop (wet tower) cooling system, water goes through a cooling tower where some of the water is consumed through evaporation. Closed-loop cooling generally withdraw less but consume more water than once-through cooling. An air cooling system (dry cooling), uses air-cooled condensers for steam cooling and can avoid evaporative water losses [59]. For coal, extremely large operational water consumption was generally caused by closed-loop plants with low conversion efficiency or with carbon capture equipment [24,25,60,61]. Once-through cooled units may also have high water consumption rates, driven by low electricity output and large incoming flows of cooling water in unique locations [60,62].

In terms of water withdrawal, nuclear is a large water withdrawer, with a median value of 2.67×10^4 L/MWh (see Fig. A5). Compared to other thermal power plants, nuclear plants generate steam at lower temperatures and pressure for operational safety, and consequently, are less thermally efficient and withdraw more cooling water per unit of electricity [63]. The median value for oil is much larger than for coal and gas because studies on oil mainly focused on wet cooling technology, especially once-through cooling [9,64]. PV plants may withdraw a considerable amount of water for mirror washing, but in practice, PV panels are seldom washed by operators [25].

Fig. 2 and Fig. A6 present detailed values for water consumption and water withdrawal for different cooling technologies, indicating that water uses of operation show greater agreement when grouped

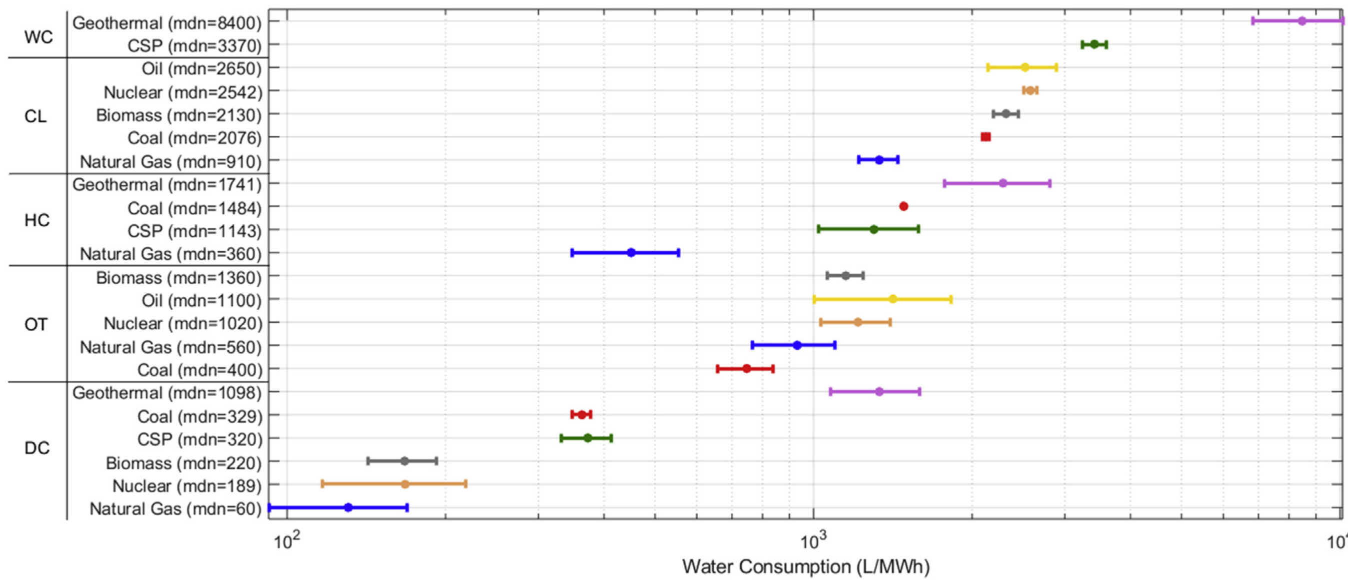

Fig. 2. Blue water consumption of operation distinguished by power type and cooling type. The dots represent the average water consumption, while the line segments represent the standard error of the average. The annotation mdn gives the median value. Hydropower, wind, and PV do not have cooling needs and are not included. The two-letter codes are as follows: WC wet cooling, CL closed-loop cooling, HC hybrid cooling (combining wet and dry cooling), OT once-through cooling, and DC dry cooling. Colours map to fuel type for the estimate. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

according to cooling types as opposed to power types. For coal, natural gas, oil, nuclear and biomass, power plants with closed-loop cooling technology are the largest water consumers, while plants with once-through cooling technology are leading water withdrawers. For concentrating solar power (CSP) and geothermal, water withdrawal was widely assumed to be equal to water consumption at the operational stage [9,24,25,34,65–67].

3.1.3. Water use of plant infrastructure

The water uses of plant infrastructure refer to the blue water used to manufacture each material input of power plants, with the indirect blue water embodied in material inputs also included. The water use of plant infrastructure was often neglected due to its small proportion in the total life cycle for most power types. However, this does not apply to all types. As shown in Fig. A7 and Fig. A8, large amounts of water consumption and withdrawal are required for the plant infrastructure of CSP. PV can consume more water than CSP, reaching up to 794 L/MWh if the PV material is crystalline silicon [25]. Wu et al. [68] indicated that coal thermal power plant requires significantly more water for infrastructure than natural gas combined cycle plant. According to our study, coal thermal plant's infrastructure is the largest water user among all fuel-powered thermal plants. Nuclear power has the lowest water consumption per unit of power production due to the high electricity output over generally longer lifetimes.

3.1.4. Water use of carbon capture and storage

Carbon capture and storage (CCS) heavily influences the water use of thermal power plants [69–73]. The water uses of CCS refer to the additional blue water used due to the addition of the CCS system. All estimates related to CCS adopted by natural gas and biomass power were available for combined cycle cooling only. Due to the additional water requirement for CCS equipment and the loss in operation efficiency [25], plants using CCS generally consume more water than the counterparts without CCS (Fig. 3). Biomass also faces the challenge of large water uses for the feedstock, while for BECCS, water use is increased further by the CCS additions. Direct air capture (DAC) is an emerging technique that capture the carbon dioxide from the ambient air, and may potentially provide negative emissions. Yet, it may have large water requirements due to the evaporative loss of the DAC unit based on amine technology [10,74]. DAC water requirements may change as the technology scales but further research is necessary.

3.2. Country-specific water use of power production

The number of studies per region and per power type are shown in Fig. 4. Hydropower and coal are widely studied across many regions, whereas geothermal lacks research in all regions except the U.S. The water consumption and withdrawal of each life cycle stage for the different countries studied previously are shown in Tables A4-A8. China and the U.S. are the predominant focus, and their specific water uses of power production are presented in Tables A9-A14 with the consideration of both cooling type and generating technology (e.g. combined cycle or steam turbine).

Studies on shale gas in China focused on the shale-rich Sichuan basin [75,76], whereas U.S. shale plays are distributed more widely [77,78]. The more complicated shale formations and water-intensive fracturing techniques in China led to higher water consumption for shale gas extraction and power production as compared to the U.S [79]. For nuclear power, the water use of the fuel cycle depends on the type of mining activities and enrichment [25,52]. There are three types of mining activities: in-situ leaching (ISL), surface mines, and underground mines. There are also two types of enrichment: diffusion and centrifugal enrichment. In France, Uranium used was mainly from underground mines, and processed through the diffusion enrichment, both activities generally consume less water than counterparts in the U.S. Poinssot et al. (2014) indicated that the use of ISL techniques in France could consume a larger amount of water than underground mines [52]. However, the water consumption of underground mines varies greatly. For countries where underground mines consume more than 87 L/MWh, the maximum of ISL techniques, the application of ISL instead becomes a way to save water [25].

For both CSP and nuclear, China consumes more water than the U.S. (Fig. 5). Direct normal irradiation (DNI) determines CSP operating efficiency [80]. As such 99% of U.S. CSP capacity is in three states: California, Arizona, and Nevada [81]. According to Refs. [24,25,65], DNI of these U.S. regions ranges from 2400 to 2940 kWh/m^2/year. In China,

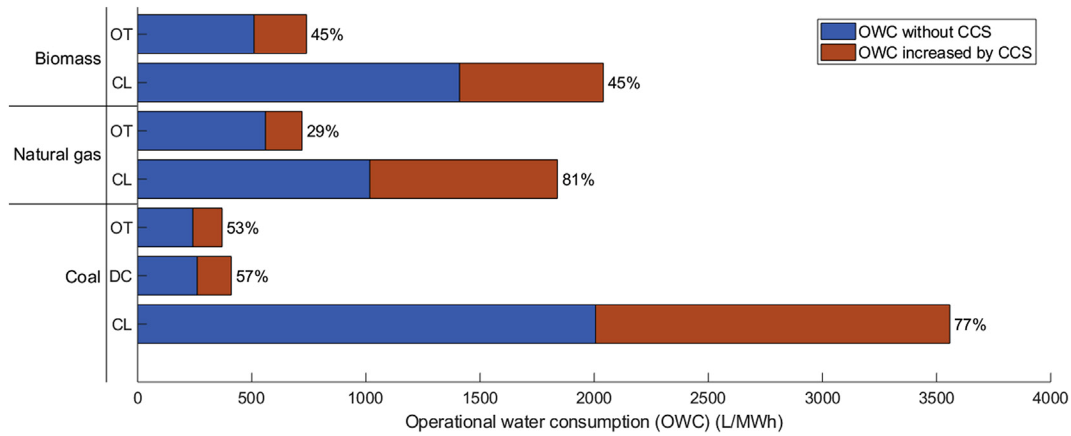

Fig. 3. Additional blue water consumption due to the addition of CCS for different fuels and cooling types. The numbers on the right of each bar indicate the percentages for CCS compared to operational water consumption (OWC) without CCS. Only the literature which reports both the OWC with and without CCS are included. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

CSP plants are mainly in northwest and Wu et al. [82] indicated high operational water consumption of a CSP plant in Gansu province. According to the World Solar Atlas [83], this area receives less DNI (a maximum: 2193 kWh/m^2/year) than in the U.S., contributing to a lower operating efficiency and a higher water use. Geographic conditions also influence the water uses of nuclear power [84]. In the U.S., operational water consumption for nuclear power plants with closed-loop cooling could be more than 3000 L/MWh [23–25,60,66,85], with a minimum of 1408 L/MWh. Even within China, differences in the nuclear power water requirement could reach 24% due to climate differences between northern and southern regions [86]. Coal power plants with closed-loop cooling consume more water in India and China than in Canada and the U.S. Conversely once-through cooling consumes less water in India and China than in Canada and the U.S.

3.3. Key factors influencing the water use of power production

Studies generally presented estimates of water uses without simultaneously presenting their influencing factors. Compiling the key factors from the literature and analyzing their effects on water uses allows for a better understanding of the drivers behind different water uses.

Beyond cooling and power type there are other important factors driving footprints. These can include the resource quality (e.g. heat content of fuel), power plant specifications (e.g. conversion efficiency, capacity factor, lifetime) [23,25] and environmental conditions (e.g. ambient temperature [88], direct normal irradiation [65], wind velocity [89], geofluid temperature [67], reservoir area [90], evaporation rate [56]). Influencing factors were collected from the literature for each life cycle stage of power production. As shown in Fig. 6, there are many data gaps across studies. Further, most values came from assumptions and other literature rather than direct measurements. There is no evidence of increased reporting of these factors over time. Water scarcity is an exception, having received more attention recently, even though the numbers of studies are still limited. Ambient temperature is typically a determinant of the operational water use due to its influence on production efficiency, cooling efficiency, evaporation rate, etc. However, it is not generally reported. The reported conversion efficiency, capacity factor, plant lifetime, and heat content of fuel are shown in Tables A15-A18.

Of the common factors, conversion efficiency is most frequently cited in the literature (31% of studies). It has been identified as a key driver of operational water consumption for most power types, especially those with cooling water demands [91]. Here a regression model is used to calculate the impact of each factor on water consumption with cooling type and conversion efficiency included. Since the operational water consumption of five power types (coal, natural gas, oil, nuclear, and biomass power) closely agree when grouped by cooling

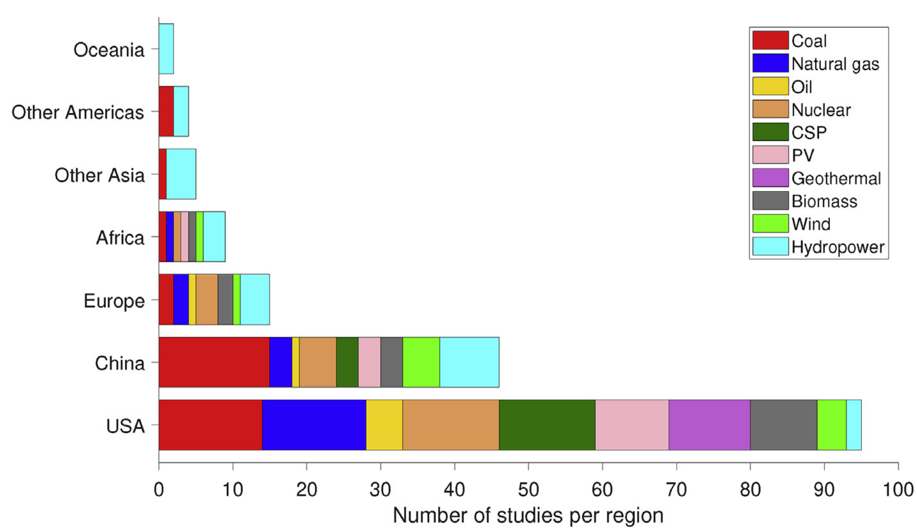

Fig. 4. Number of studies per energy source per region. Many studies investigated more than one energy source and region, and can therefore occur multiple times.

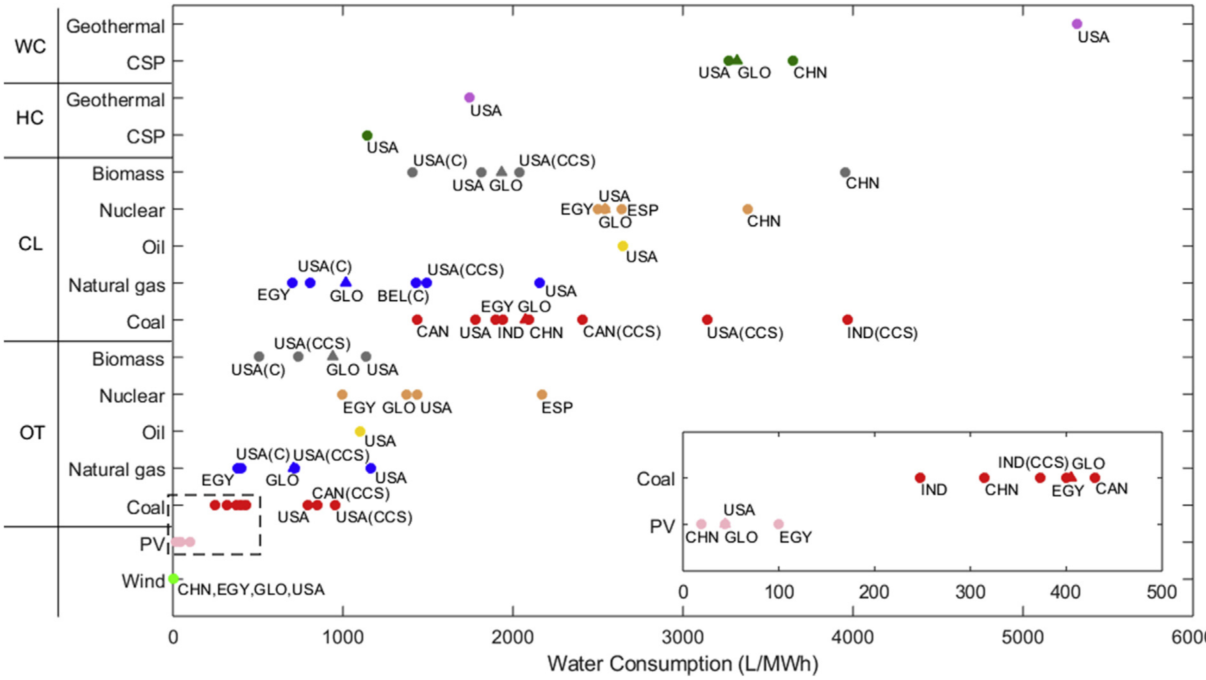

Fig. 5. Operational blue water consumption for each power type and country. Countries are indicated by ISO3 codes [87]. GLO denotes the global median value and is represented as a triangle. For clarity, the contents of PV and coal power in the dashed box are enlarged and shown in the inset on the bottom right. The two-letter codes denote WC wet cooling, HC hybrid cooling (combining wet and dry cooling), CL closed-loop cooling, and OT once-through cooling. "C" in parentheses denotes combined cycle power plants. "CCS" in parentheses denotes power plants using carbon capture and storage technology. The median operational water consumption of wind power is zero for all countries herein. The operational water consumption of hydropower is not included in this figure due to its wide range, but is available in Table A5. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

type (Fig. 2), these five power types are considered in the model without distinctions. The model established is shown in Appendix A, and the results are presented in Table A20. The impact of conversion efficiency on operational water consumption varies across cooling types. On average, −36.8, −16.2, and −10.3 L/MWh of operational water can be saved with every 1% increase in conversion efficiency for closed-loop cooling, once-through cooling, and dry cooling, respectively. Compared to improving conversion efficiency, adopting dry

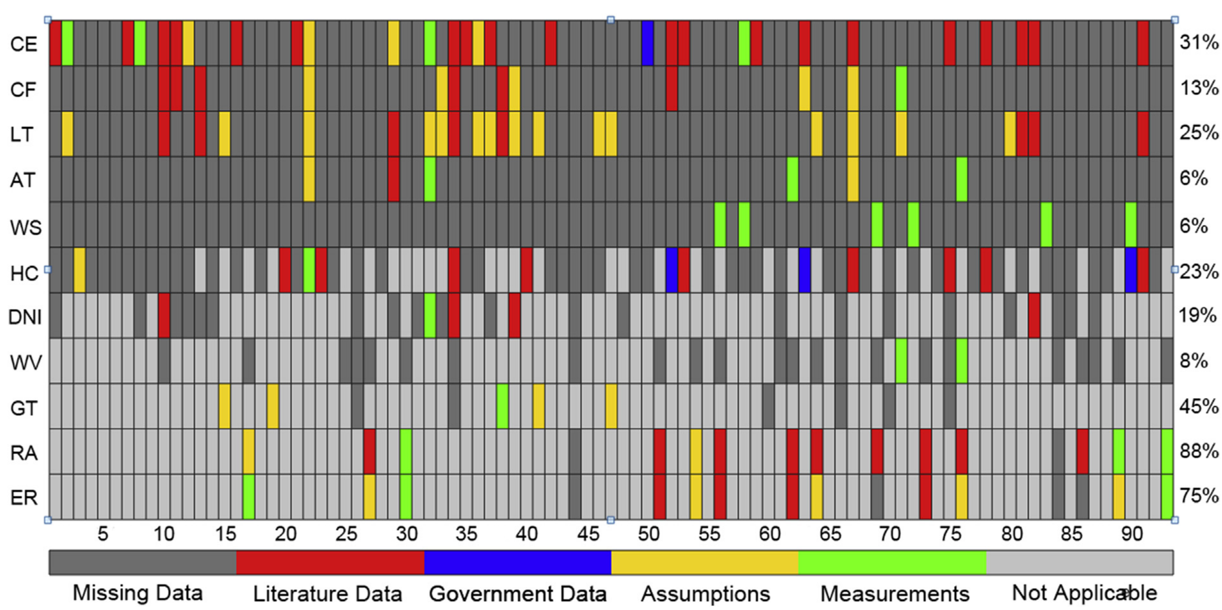

Fig. 6. Influencing factors reported across the literature. The x-axis presents each study, numbered from 1 to 93 chronologically from left to right (these studies are listed in Appendix D). The y-axis (left) presents influencing factors: CE (conversion efficiency), CF (capacity factor), LT (lifetime), AT (ambient temperature), WS (water scarcity), HC (heat content of fuel), DNI (direct normal irradiation), WV (wind velocity), GT (geofluid temperature), RA (reservoir area), ER (evaporation rate). The y-axis (right) presents the percentage of reporting in the literature (the ratio of reporting to the total applicable studies). Colours denote the data sources of factors in the literature. "Measurements" means that values were directly measured, or came from primary data. "Not Applicable" means that the factor is not relevant to the study, e.g. the reservoir area only applies to studies including hydropower. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

cooling technology is a direct approach for conserving water but generally increases investment costs [92,93] and lowers plant efficiency [94,95]. Wet cooling can bring synergistic benefits, e.g. energy conservation and emission reduction [96].

There are additional factors for each power type. The heat content of fuel is important for coal, natural gas, and biomass. Generally, biomass has a lower heat content than natural gas and coal. The operational water consumption of hydropower varies greatly depending on two factors: the evaporation rate and the surface area of reservoir [12,90,97,98]. The evaporation rate in different locations could range from 486 mm yr^{-1} to 3059 mm yr^{-1} [99]. The reservoir area also varies over time due to changes in water volume throughout the year [90,99,100]. However, these are usually only estimated annually due to data limitations in monitoring area over the year. This may change as better remote sensing methods become available; already some studies have estimates at a monthly resolution Lu et al. [101]. An analysis of variance is conducted to look at the contributions of both evaporation rate and surface area on the operational water consumption of hydropower. Results show that the evaporation rate typically plays a more important role in determining the operational water consumption (Table A21). For geothermal energy, the plant type (flash cycle, binary cycle) typically determines the water requirement. For flash power plants, a lot of freshwater can be saved, as most cooling water is provided by the geothermal fluid that flashes to steam and during the generation process condenses to form high quality water that can be used for cooling [67].

Finally, the water source (i.e. freshwater water and sea water) for plant cooling differs across regions. For example, many nuclear power plants in Spain and the U.S. use water from rivers and lakes for cooling, whereas China has all presently operable nuclear power plants in coastal areas with seawater as cooling medium to save freshwater [102,103]. The deployment of power plants and cooling water sources make big differences to the blue water use of power production.

4. Discussion

4.1. Uncertainties in water use assessment

Uncertainties derive from the methodological choice, the system boundary cut-off, and the water source.

Methodological choices: The two main methods are process-based LCA (PLCA) and hybrid LCA (a method linking PLCA and input-output analysis (IOA)). PLCA is a bottom-up approach based on production processes [42,104], whereas IOA is a top-down approach [105,106]. Hybrid LCA was developed based on PLCA and IOA to combine their strengths and reduce weaknesses from data quality, system boundary, difficulty of application, etc. [107–109]. In recent decades, hybrid LCAs have increasingly been employed in energy-related environmental footprint analyses [105,110–112] and water footprint analyses (as mentioned above). The application of both methods to carbon footprinting for wind power indicated that emissions for hybrid LCA was more than double that for PLCA [113]. Equivalent differences by method in water use estimates are shown in Table A22. Hybrid LCA leads to larger water use estimates for most power types, especially wind and PV. The additional input from economic sectors not covered by process analysis was the major contributor to the differences. Though it remains an open question of which method should be recommended for life cycle inventory compilation, since both are in line with the ISO standard [114], the differences between PLCA and hybrid need to be appreciated. Firstly, using a pure PLCA approach may lead to significant underestimation because power production relies indirectly on large amounts of inputs from various sectors, especially heavy industries (steel, metal and cement) [41,42,50,115] and agriculture (e.g. wood used for fuel extraction and construction; agricultural products used for chemical production) [13,48], which are generally water-intensive [48,116,117]. Second, using IO-based hybrid LCA presents a challenge in sector disaggregation. Power production is typically a homogenous sector in IO tables [118,119], even though each power type has a distinctive water use. Efforts are needed to isolate the targeted power type from the power production sector [118]. Third, IO tables are normally released later than process-based data [114]. This may be an issue for emerging power production technologies.

For some energy technologies, there are specific methodologies that influence water use estimates. For hydropower, the main issue is the lack of methodological consistency in allocating water consumption among multiple purposes [27,56,120]. Many allocation methods were used to separate the water consumption of electricity from the total reservoir evaporation by using an allocation factor. The allocated water consumption of electricity may be much lower than the reservoir evaporation or remain unchanged [12,98,121], depending on the allocation factors as shown in Table A23. The temporal resolution of models can also lead to different estimates due to the seasonal fluctuations in the reservoir water level.

Choices for boundary cut-off: Although some studies cover the entire life cycle of power production, operational water uses are a focus across the literature. The water uses of the fuel cycle and plant infrastructure are often omitted. Omitting the water uses of a certain stage can lead to a bias that varies across power types (Fig. 7). Over the total life cycle of water consumption, the share of water consumption from the plant infrastructure varies greatly, especially for renewable energy with the exception of bio-power. Likewise, the fuel cycle of coal, natural gas, oil, and nuclear, ranges from 2 to 79%, largely depending on the cooling

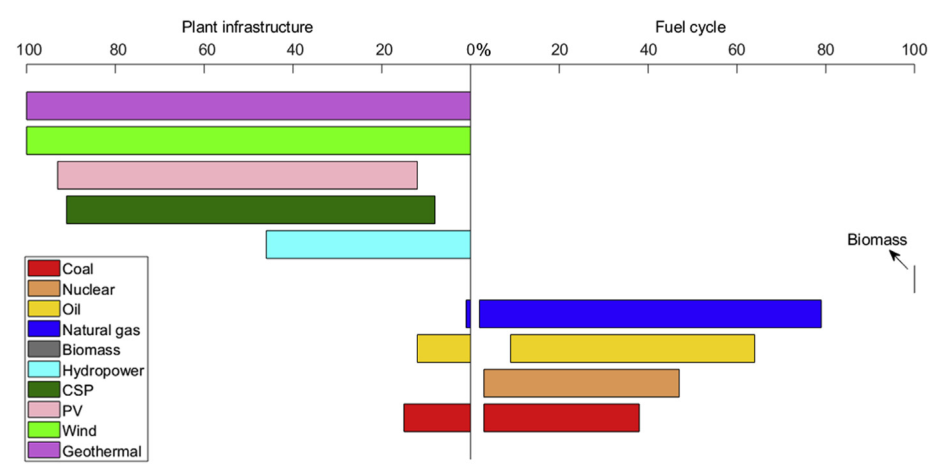

Fig. 7. Proportions of the blue water consumption of fuel cycle and plant infrastructure in the total life cycle. Values are shown in Table A24. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

water consumption of power plants. Within the fuel cycle, the water consumption of each sub-stage is presented for coal and natural gas (Fig. A10). For coal, the transport by pipeline, especially the slurry pipeline, is a highly water-consuming choice. For natural gas, processing and pipeline transport are large water consumers. The sum of their median water consumption is approximately half of the median water consumption of fracturing, thus narrows the gap between conventional gas and shale gas for total fuel-cycle water consumption.

Water source: For biomass and geothermal, water sources considered in the assessment make a difference. Irrigation (blue water) and soil moisture from precipitation (green water) are main sources of water required for biomass growth. The former accounted for 0–60% of the total water consumption [11,46,122]. It is essential to identify the feedstock type, as water demand varies across types [123]. Geothermal fluid and freshwater are two sources of operational water use of geothermal power production but geothermal fluid is not typically considered as freshwater consumption because it is not sourced from a body of freshwater [23,67]. Either or both types of water resources are used in operation, depending on the practical situation [43,67], which leads to variations in estimates. Nuclear power plants in coastal areas typically use seawater for cooling [61], which is irrelevant to blue water use.

4.2. Water scarcity related to power production

The large amount of water abstracted for power production might exacerbate local water scarcity [89,124–126]. This depends on two factors: the life cycle water use of power production, and the water scarcity in the region [20]. A certain amount of water use in water-poor regions typically has larger impacts on other local water users than in water-rich regions. To alleviate the risk of water use in water-scarce regions, the regional water scarcity needs to be considered in addition to volumetric water use [21]. However, there is no consistent measurement to reflect the impact of power production on water scarcity. Two main approaches have been used, which are both related to water scarcity indices. One measures the energy-related water scarcity index by dividing the water use of power production either by total water availability [54,125,127], or by the remaining water availability after subtracting non-power production uses in a water basin [6]. Another approach uses the water scarcity footprint, which is calculated by multiplying the water use of power production with a regional water scarcity index [12,13,126,128,129]. Thus, the water scarcity footprint includes the information of both the volumetric water footprint (i.e. the water use inventory) and regional water scarcity.

Apart from the different approaches to assess water scarcity, the differences in the scaling of the water scarcity index used across studies also imply that their water scarcity measurements are not comparable [129]. Hence, it is suggested to still report water use besides the water scarcity footprint. According to Hoekstra et al. [130], the value of the water scarcity indicator exceeds 100% when the blue water use is higher than 20% of the natural runoff within a region (i.e. the water availability), whereas in Pfister et al. [131] and Boulay et al. [132,133], the scaling of 0.01–1 and 0.1 to 100 were used for the values of the water scarcity indicator, respectively. In addition, it is worth noting that the terminology “water scarcity footprint” is used by the LCA community. A similar concept was proposed by the Water Footprint Network and named water footprint impact index [19]. The impacts of power production on local water scarcity have raised increasing concerns. However, the existing studies on water scarcity footprinting seldom provided cross-regional strategies for mitigating water scarcity. More efforts are needed to figure out synergies between water and energy management (i.e. water allocation and energy deployment).

4.3. Water in energy system modelling

Energy systems typically consider three aspects: reliability, affordability, and sustainability [134]. Integrating water use into energy system modelling is important from both reliability and sustainability perspectives. The two key factors influencing reliability are capacity factor and installed capacity, both of which dictate the reliability of plants when water availability changes. However, relevant information is seldom provided in studies on water use, making it difficult to link water and energy system modelling.

For example, natural gas plants are used in many different modes on different electricity grids. While some studies assume a capacity factor of natural gas of 80% [51] or 85% [25,50], natural gas plants can often act as ‘peakers’, that is they only operate during high demand. According to EIA [135], the capacity factor of natural gas thermal power plants in the U.S. in 2017 was 6.7% and 10.4% for combustion turbines and steam turbines, respectively; and even for the combined cycle plants it was only 51.2%. Clearly, this also has a temporal aspect since plants may be peaking under high cooling loads, which may be at the same time as low water availability or thermal constraints.

Additionally, installed capacity is often underreported in studies (except those on hydropower), as is cooling type. Both variables are needed for a realistic and complete energy system model. For instance, if the water use of energy systems is optimized without data on the capacity of each cooling technology, results may suggest that plants convert to dry cooling (a water-saving technology), despite the fact that this may not be suitable in regions where air temperature is high and results in low production efficiencies [136]. Providing the capacity of each operating technology is essential to give a baseline when looking for trade-offs between water saving and energy production.

The studies on the water sustainability of energy systems rely on the information of water availability. Hydrological models are often used to show water availability at regional or basin level. Although there are many global hydrological models [137], they are highly uncertain and need to move to a finer spatial resolution to address more targeted water scarcity at plant levels. In addition, the upper limit of water use in regulations is another index that has been used as a reference to water availability [127]. In practice, the water availability of energy systems is sometimes more restricted by water use regulations [72,127] other than the water scarcity limitation shown in hydrological models, to ensure long-term water security [138–140]. To figure out whether water will be a barrier for energy systems, a better understanding of both the natural water scarcity and water use regulations is needed.

Besides water, there is also a need to consider other critical resources that are required as an input into energy systems and influence its sustainability. To do so, the exergy concept has recently been applied to evaluate the environmental impacts [141,142] or economic performance [143,144] of energy systems. Exergy accounting enables studies to reveal the resource depletion and measure all impacts in homogeneous units [145].

5. Conclusions and future prospects

This study gathered available data of water uses of power production at different life cycle stages. Differences and uncertainties in water use estimates were analyzed for each power type. The following conclusions are reached:

Renewable energy may be water saving or water intensive: PV, wind power, and run-of-river hydropower consume relatively little water; CSP and geothermal power consume intermediate volumes of water; whereas woody and herbaceous biomass and reservoir hydropower may possess an extremely high volumetric water footprint. Non-renewable energy falls within the two higher water use classes, except for natural gas between the two lower water use classes of renewable energy. The deployment location of power production largely affects countries' water use of energy systems due to different climate conditons and water resources, as well as the impacts caused by it due to water scarcity; however, the latter are rarely considered. For thermal power plants, the operational water consumption increases up to 81% due to the addition of CCS.

Inconsistent system boundaries may cause uncertainties in water use estimates across studies. For example, the fuel cycle of biomass, nuclear power and natural gas is worth more consideration in the future. Besides clarifying the water use type (consumption vs. withdrawal), clarifying the water sources also helps reduce uncertainties in water use estimates for biomass (precipitation vs. irrigation), geothermal (geofluid vs. freshwater) and nuclear power (seawater vs. freshwater). Emphasis for future studies should be to increase transparency and report key influencing factors, such as conversion efficiency, capacity factor, lifetime, ambient temperature, and depending on applicability also the heat content of the fuel, direct normal irradiation, wind velocity, geofluid temperature, evaporation rate, and reservoir area. Finally, the inclusion of water scarcity in energy system optimisation models is essential for mapping the energy transition.

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Appendix A. Supplementary data

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