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Evaluation of sector-specific AWARE characterization factors for water scarcity footprint of electricity generation

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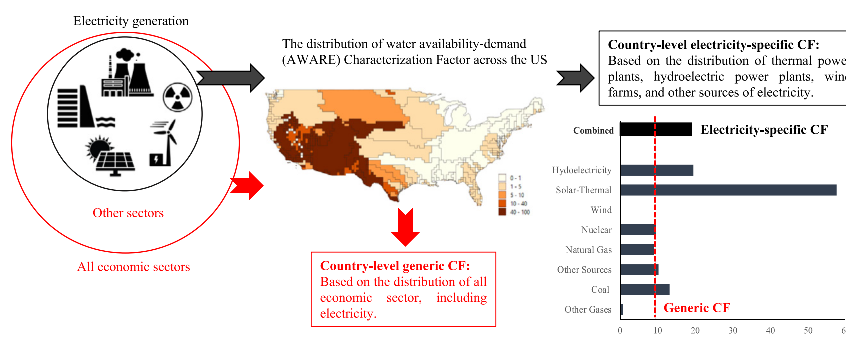
HIGHLIGHTS

- Water consumption varies greatly among various sources of electricity.
- The regional Characterization Factors (CFs) for water-use in Life Cycle Impact Assessment (LCIA) varies greatly in the US.
- The tempo-spatial distribution of electricity and its sub-sectors has a notable impact on the total impact score.
- Across the US, the use of generic water-use CF for electricity leads to under-estimation of impact score in LCIA.
- Hydroelectricity and coal-based electricity have the highest CFs among other electricity sub-sectors.

GRAPHICAL ABSTRACT



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ABSTRACT

Life Cycle Impact Assessment (LCIA) links the emissions and resource abstractions of a product system or process to potential impacts on the environment through characterization factors (CF). For regionalized impact categories like water-use, the regional CFs can vary over several orders of magnitude within the same country. The aggregated country-level CF, often used in LCIA, represents an average of local CF weighted by the local water consumption of all (or most) human water use including water use by all (or most) economic sectors. There is, however, great variability in spatio-temporal distribution of human water consumption across different industries. This study provides industry-specific water-use CFs for the electricity sector across the US. Our analysis shows that for electricity generation, the use of all-sector aggregated water-use CF would lead to an underestimation of impact scores compared to industry-specific CFs, by two folds. Even within the electricity sector, for two of the major subsectors, electricity based on natural gas and hydroelectricity, the country-level CFs can be significantly different due to the geographic distribution of powerplants. Our findings signify that the use of industry-specific CF can have a high influence in LCIA, especially for impact categories, such as water-use, with great spatio-temporal heterogeneity.

1. Introduction

Environmental impacts of energy generation are complex and are not limited to greenhouse gas emission. Natural freshwater is a resource

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that is indispensable for ecosystems, human health, human activities, and economic growth, and the demand for this resource has been increasing over the last decades due to economic development and population growth. Energy generation has both quantitative and qualitative impacts on freshwater resources. Primary and secondary energy generations account for a major portion of water demand in terms of withdrawals. Across the US, total daily water withdrawal in 2015 were estimated to be 1.22 billion cubic meters per day, with thermoelectric power plants alone withdrawing 41% and agriculture at about 37% (Dudley, 2018). Freshwater resources availability is subjected to space and time heterogeneity. Water scarcity can be exacerbated in regions where there is significant human demand for water consumption in domestic, industrial, irrigation, and energy production sectors.

In Life Cycle Assessment (LCA), the water-use impact category has been first proposed by Koehler (2008) and since further developed (Bayart et al., 2010; Kounina et al., 2013, Boulay et al., 2011; Boulay et al., 2018). The water-use impact category addresses the potential impacts inflicted on the environment (ecosystems and human health) due to quantitative shortage of water, i.e. water unavailability or water scarcity. Water-use impact Characterization Factors (CF) in Life Cycle Impact Assessment (LCIA) stage, have been developed based on the concept of withdrawal to availability (e.g. Frischknecht et al. (2006); Pfister et al., 2009), consumption to availability (e.g. Hoekstra et al., 2012; Berger et al., 2014; and Boulay et al., 2011), or more recently availability minus demand (Boulay et al., 2018). Most current water-use impact assessment methods focus on the impact of water consumption at the source, overlooking the hydrological processes and flow hydrodynamics (Núñez et al., 2018). These methods, however, differentiate CFs at regional-level (watershed-scale) as well as country-level. In the LCIA, the regional-scale CFs are often used when regional water-use data is available in the inventory phase and the aggregated country-level CFs are used in the absence of sufficient spatial information. Regionalization is critical in water-use, both in inventory and impact assessment phases, due to heterogenous tempo-spatial distribution of water availability and water consumption (Ercin and Hoekstra, 2012; Frischknecht et al., 2019).

Estimation of country-specific CFs is carried out on the basis of either aggregation of smaller-scale CFs with weighted averages or country-level directly based on average availability and consumption, including all human-use and environmental flow. In the human-use water consumption, there is variability in tempo-spatial distribution across different industries and economic sectors. Socio-economic conditions, resource availability and local and governmental policies are among the determinants of geo-distribution of different economic sectors and industries. This geo-variability is not homogenous for different industrial sectors and calculating one generic aggregated country-level CF overlooks this geo-variability. In recent years the water-consumption geo-variability is acknowledged and broadly taken into consideration in calculating the aggregated CFs by separating agricultural and non-agricultural economic activities in larger than regional-scales (Boulay et al., 2018). Electricity generation accounts for a major part of water demand and the selection of the most suitable and efficient locations for electric powerplants is decided based on multiple criteria. Powerplant locations are selected to maximize the overall value of the power plant, reduce power generation and its transmission cost, minimize adverse socio-environmental impacts, and maximize the power plant's productivity (Choudhary and Shankar, 2012). Whereas in another economic sector, e.g. agriculture, farmland's location is dictated by suitability of soil type and favourable environmental conditions for growing crops. These diverse ranges of factors that collectively shape the geospatial distribution aren't similar across different industrial sectors or even sub-sectors. In the energy sector specifically, the water consumption and plant locations can also differ greatly among different energy sources (Jin et al., 2019) and hence even aggregating all energy sub-sectors may lead to under- or over-estimation of the total impact score in LCIA.

This study aims to develop water-use Characterization Factor's for the sector- and sub-sector of electricity generation. In most electricity sub-sectors across the US robust and official datasets are available. The impact assessment in this study is based on quantitative analysis of official datasets on energy information, while complementing these data with measurements and estimates for proxy in areas where date isn't available due to the complexity of water-use. The objective of this semi-quantitative study is to provide an industry-specific water-use CFs for electricity sector across the US, and to evaluate the significant of using industry-specific water-use CFs compared to all (or most)-sector aggregated country-level CF. The methodology can also applicable to other LCA impact categories, such as land-use, in which regionalization and the location of impact has high influence on environmental impact scores.

2. Methodology

The life-cycle water-use (withdrawal and/or consumption) of electricity generation can consist of various stages: fuel acquisition and preparation, plant construction, generation phase, and fuel disposal. This study focuses on the water consumption in the operational phase. A comprehensive inventory and life-cycle impact analysis through all phases of electricity generation is only possible if detailed data on all the stages of electricity production from fuel acquisition, preparation location, technology, and disposal strategies are available at power plant scale. Furthermore, the location of fuel acquisition and cleaning is not permanent in the lifetime of a powerplant and thereby defining a consistent and permanent system boundary for the entire life-cycle of electricity generation for a powerplant is challenging (Jin et al., 2019). A breakdown of water withdrawals by Fthenakis and Kim (2010) have demonstrated that for most cooling technologies and fossil fuel sources as well as biomass, the on-site water withdrawal for powerplants during the generation phase comprises over 80% of the total water withdrawal. An exception is the on-site water withdrawal for oil/gas recirculating cycle, where about 60% water withdrawal is from upstream activities such as water usage associated with energy and material inputs. Additionally, published literature on full life-cycle water consumption varies significantly, due to variations in definition of system boundaries, production pathways, and infrastructure (Jin et al., 2019; Meldrum et al., 2013). Using proxy values from literature without referencing the background process in this semi-quantitative study adds great levels of uncertainty to results and analysis. Therefore, in this study we focus on the impact assessment of on-site water consumption during the electricity generation phase (operational) alone, without negating the role of water-use impact from other stages in the entire life-cycle of electricity generation.

In order to assess the water scarcity factor, the operational water consumption of different energy sources has to be linked to the appropriate CF on the regional scale. In this section, the Water Consumption (WC) inventories and data extraction and extrapolation from database used in the article are addressed. Furthermore, various water scarcity indices as well as suitability of AWARE model are discussed, followed by aggregation method and formulations that are the basis for analysis in this study.

2.1. Data collection

Here, we address the “water consumption” as it represents freshwater-use in the LCA inventory. Water consumption along with a characterization model are used in the Life Cycle Impact Assessment to estimate the Water Scarcity Footprint (WSF). Water consumption is defined as the water displaced (evaporated, transpired, incorporated into product, or otherwise removed) from the immediate freshwater body (Macknick et al., 2011). Water withdrawal on the other hand, defines as the water diverted from the freshwater body. Water-use in general refers to consumption or withdrawal, when no specific reference is made.

The US Energy Information Administration (EIA) survey data collects detailed electric power data - monthly and annually - on electricity generation, fuel consumption, prime mover, among many other information. The operational freshwater consumption of hydroelectric powerplants are, however, not reported to EIA, as it is due to net evapotranspiration and is not directly measurable. The data from EIA combined with estimated hydroelectricity's WC are the basis to form the fresh water-withdrawal and consumption inventory by various energy sources and technologies across the US.

2.1.1. Water consumption inventory for hydroelectric power plants

Hydropower is currently the largest source of renewable energy in the US and worldwide. Reaching 1000 GW of installed capacity in 2013, it generated 16.4% of the world's electricity from all sources. In 2018, hydropower accounted for about 292 T-watthours of electricity in the US, which was nearly 7% of the total utility-scale electricity generation in the country.

Through the construction of a dam and a hydropower plant (HPP), the course of the river, its dynamics, and land cover change significantly in the vicinity of the dam. The operational and indirect WC by hydropower by far exceeds that of most other electricity generating technologies and is one of most serious damages of hydropower generation (Sathaye et al., 2011; Pfister et al., 2011; Mekonnen et al., 2015). The WC by storage-based hydropower is due to the large area of reservoirs, which are subjected to evapotranspiration from the surface. Despite the evidence that points towards a high level of WC in reservoir-based HPPs, EIA does not collect and process WC data in this subsector, as it is not a deliberate water-use intended for cooling. Therefore, accounting for the WC for this subsector in this study is based on estimates and indirect measurements assimilated from past studies.

Several studies have attempted to estimate global ranges and averages of hydropower water consumption. Gerbens-Leenes et al. (2009) reported a rough estimate water consumption of 79 m^3/MWh, whereas Sathaye et al. (2011) provided a range of 0 to 209 m^3/MWh based on US HPPs. Mekonnen and Hoekstra (2012) provided a wider range between 1.1 and 3060 m^3/MWh, based on 35 HPPs distributed across the globe. Bakken et al. (2013), in a review article, have consolidated various regional and global studies and have reported values between 0.04 and 6250 m^3/MWh. A more recent comprehensive study by Scherer and Pfister (2016), including 1473 HPPs worldwide, has provided an even large range for WC, varying from 0.4 to over 172,800 m^3/MWh. This study covers the net and gross water consumption of hydropower plants in over 108 countries between 2004 and 2009.

Scherer and Pfister's Data (SPD) entails information on 351 HPPs across the US and is used here for the basis of WC in the hydropower subsector. As described in Section 2.3, the Total Water Consumption (TWC) for each of these HPPs in 2015 is established by linking the net evaporation rates for individual plants to the annual Electricity Generation (EG) reported by EIA for 2015. Changes in factors such as weather trends and reservoir area are assumed negligible for these HPPs between the periods of investigation in two data sources. The geographic location and the name of 351 HPPs in SPD are validated against energy generation data reported in EIA-923. Among 351 plants, 10 could not be matched, based on their geographical location or their names. These 10 power plants are discounted in this study. The remaining 341 plants comprise about 46% of the total 244.0 hydropower generation in 2015, reported in EIA-923.

2.1.2. Water and energy for other forms of electric power generation

Annual and monthly WC and EG based on other sources of energy directly come from the EIA forms 860 (Annual Electric Generator Report) and 923 (Power Plant Operations Report). These forms collect plant information from all grid-connected plants larger than 1 MW. Plants with a total steam-electric nameplate capacity of 10 MW or greater are required to report the configuration of their environmental equipment through EIA-923, whereas, the cooling system data in the EIA-923-Schedule 8- Part D, Cooling System Information, is limited to plants where the steam-generating units have a combined nameplate capacity of 100 MW. In this form discharge rate and the total volume of water diversion, water consumption, water discharge (returned to the watershed), and water withdrawal are provided. The majority of water used in steam-electric power plants are used in condensing and cooling the steam, used as a prime mover, in conventional as well as parts of combined cycle generators. Water withdrawal and water consumption values for the powerplants reported in EIA-923 are either measured or estimated based on different techniques available at the powerplant site and the cooling system. This includes the plant's cooling type from once-through, recirculating, cooling tower to dry cooling and even hybrid cooling systems with draft cooling towers combined with air cooling. The water flow rates and water-use values are computed and evaluated through different techniques. 33.4% of the total water withdrawal and consumption in this form is directly estimated from “pump capacity and pump running time” and 27.1% are based on “cumulative or continuous” readings from flow meters, where water consumption is directly or indirectly measured. In another 13.1% of water consumption, no measuring technique is identified, however, in these plants, measurements of water withdrawal and discharge rates back to the freshwater bodies are reported. Overall, among all methodical measurements and estimates of water consumption, over 73% are directly or indirectly calculated from readings obtained by flow meters and pumps. Water withdrawal and consumption in thermoelectric operations in the EIA-923 form are due to cooling and this form does not reflect the additional water withdrawal for example for carbon capture or plant operation.

2.2. Water scarcity index

Water impacts cover a wide range of qualitative and quantitative risks and problems. In LCA the qualitative aspect of water consumption is addressed in categories such as eutrophication and aquatic ecotoxicity. Development of water-use impact category in LCA was first reported by Bayart et al. (2010). This study uses the Available Water Remaining, AWARE, method which was developed as the international consensus for water scarcity assessment by the WULCA group (Boulay et al., 2018). In this method, the Availability Minus Demand (AMD) is first estimated per month and unit surface area of a watershed, considering that human and aquatic ecosystem demands are met. The factor is then calculated by dividing the world average AMD with the local AMD, with upper and lower limits of 100 and 0.1 respectively. The CF is therefore equal to unity where the local AMD equates the world average AMD and its unit is expressed as $m^3{}_{\text{world eq.}}/m^3$. This method possesses advantages over its predecessors: it considers the total demand, including ecosystems, in the watershed and presents itself in the form of a subtraction of demand from availability instead of a ratio. Furthermore, this method differentiates and addresses broadly the impact of temporal and spatial variability of different sectors in the aggregation of CFs by defining two sets of country-level CFs: one for agricultural and another for non-agricultural use.

Water availability data, demand data, and watershed delineation and definitions from WaterGAP2.2 (Müller Schmied et al., 2014) are the source for AWARE method and are used in this study. To limit our analysis to the US, the watershed boundaries defined by WaterGAP2.2 are restrained to country's jurisdiction. Water availability and demand data in WaterGAP, as well as EIA and SPD data on water consumption and electricity generation are available in monthly and watershed scales. However, detailed inventory information is often missing on where and when the water consumption has occurred. Therefore, in this study the tempo-spatial distribution of WC across powerplants are aggregated from smaller (monthly and watershed-level) to larger scales (annual and country-level).

2.3. Analysis of HPP water consumption data

The SPD provides a partial coverage of large hydropower plants across the US and hence does not represent the total water consumption across the entire subsector. The following approach was adopted to estimate the total WC of hydroelectricity across the US using available data. As the sample data in SPD are distributed across different watersheds, an aggregated weighted average of WC (m^3/MWh) is first estimated and assigned to each watershed. These aggregated WC values are then used as proxies for HPPs listed by EIA but absent from SPD in which site-specific WC is unavailable. SPD does not contain HPP representation across all of the delineated watersheds. Across these watersheds without SPD representation, a similar approach is taken to estimate a country-level weighted average of WC, based on all HPPs in SPD distributed across the US. Therefore, the practice is to use finer geographic scale weighted average WC values as proxies in watershed levels, wherever WC data representation is available in the geographic zone in SPD, and use a larger scale proxy, i.e. country-level, for watersheds without SPD representation. The TWC (m^3/year), in each HPP is estimated using site-specific WC and EG data with units of m^3/MWh and MWh/year, respectively:

$$\mathrm{S}_{\mathrm{EG-SPD}} = \sum_{i=1}^{n_{SPD}} EG_{\mathrm{SPD}-i} \tag{1}$$

$$\mathrm{S}_{\mathrm{WC-SPD}} = \sum_{i=1}^{n_{SPD}} TWC_{\mathrm{SPD}-i} = \sum_{i=1}^{n_{SPD}} WC_{\mathrm{SPD}-i} \times EG_{\mathrm{SPD}-i} \tag{2}$$

where n_{SPD} is the number of HPP representation in a geographic zone in SPD. While TWC (m^3/year) is the total annual water consumption across each plant, $\mathrm{S}_{\mathrm{WC-SPD}}$ (m^3/year) is the total annual WC, and $\mathrm{S}_{\mathrm{EG-SPD}}$ (MWh/year) the total annual EG across a geographic zone.

$$\overline{\mathrm{WC}}_{WS} = \frac{\mathrm{S}_{\mathrm{WC-SPD(WS)}}}{\mathrm{S}_{\mathrm{EG-SPD(WS)}}}; \overline{\mathrm{WC}}_{US} = \frac{\mathrm{S}_{\mathrm{WC-SPD(US)}}}{\mathrm{S}_{\mathrm{EG-SPD(US)}}} \tag{3}$$

$$\mathrm{S}_{\mathrm{EG-HYD}} = \sum_{i=1}^{n_{HPP}} EG_{HYD-i} \tag{4}$$

$$\mathrm{S}_{\mathrm{WC-HYD}} = \sum_{i=1}^{n_{HPP}} TWC_{\mathrm{HYD}-i} = \sum_{i=1}^{n_{HPP}} WC_{\mathrm{HYD}-i} \times EG_{\mathrm{HYD}-i} \tag{5}$$

$\overline{\mathrm{WC}}_{WS}$ and $\overline{\mathrm{WC}}_{US}$ in Eq. (3) are watershed level and US-level aggregated WC proxies that are used in estimating the TWC in Eq. (5) and are expressed in the unit of WC.

2.4. HPP allocation

Among the 341 reservoirs reported in SPD and studied here, hydroelectricity is identified as the sole ecosystem service in only 68 reservoirs. The rest of the enlisted reservoirs serve multiple purposes and ecosystem services such as flood control, irrigation, recreation, etc. Therefore, in reservoirs with multiple ecosystem services, the net water consumption must be proportionally distributed among various ecosystem services. Zhao and Liu (2015) have suggested an allocation factor to hydroelectricity based on the economic ratio of benefits derived from hydroelectricity generation, to the total economic benefits by the total economic value of all ecosystem services of a reservoir. In the present US-wide study, detailed local scale data on market value of products and services or the value of damages prevented aren't readily available for all HPP sites. In the SPD the allocation factor of the net evapotranspiration to hydroelectric power generation in such reservoirs is based on the ranking of the hydroelectricity among all purposes. A similar strategy is assumed here and the hydroelectricity allocation factor, f_{HE}, is defined by:

$$f_{\mathrm{HE}} = \frac{n+1-Rank}{\sum_{i=1}^{n} i} \tag{6}$$

where n and $Rank$ are the number of ecosystem services and the ranking of hydroelectricity, respectively, and both are based on the list of purposes in the US National Inventory of Dams database (NID, n.d.).

2.5. Water consumption in thermoelectric power plants

In thermoelectric power plants, steam is often generated by burning fossil or nuclear reactions and the high-pressure steam derives the turbine generator. The steam subsequently is cooled, condensed in a heat exchanger or condenser through which cooling water flows, and returned to a steam generator (Fthenakis and Kim, 2010). A thermal power-plant might comprise of one or few generators, where the steam in each generator is provided by a group of boilers. Similar interconnections exist between boilers and cooling systems, where a boiler-generator unit is not necessarily connected to one isolated cooling system, but rather a few, among which some cooling might be shared with other boiler-generator group(s). In this architecture, allocating total on-site water consumption in a cooling system directly to electricity generation need details of the architecture, amount of fuel burnt, the steam output of the boilers, and other relevant data, which can be challenging. In this study, both total operational water consumption, and total net electricity generation are linked to energy source and the aggregation of the two interconnections are performed separately: combining boiler-cooling system data provides the total operational water consumption associated with fuel types and combining boiler-generator system data yields the total net electricity generation. In the boiler-cooling linkage, the total water consumption is associated with the fuel/source types at the boilers. With more than one fuel source, the allocation is done based on the reported consumption amount of each fuel at the boiler.

2.6. Sub-sector specific CFs

The total water consumption across the hydropower subsector is estimated using Eq. (5) based on the aggregated watershed- and country-level WC, $\overline{\mathrm{WC}}_{WS}$ and $\overline{\mathrm{WC}}_{US}$. Hence the total WSF, across the country, WSFHYD (m^3 $_{\text{world eq.}}$/year), can be established for HPPs using regional AWARE CF:

$$\mathrm{WSF}_{\mathrm{HYD}} = \sum_{i=1}^{n_{HPP}} WC_{\mathrm{HYD}-i} \times EG_{\mathrm{HYD}-i} \times CF_{\mathrm{AWARE}} \tag{7}$$

where n_{HPP} is the total number of HPPs across the US reported in EIA. Based of which US-specific subsector's CFs, $\overline{\mathrm{CF}}_{\mathrm{HYD}}$($m^3$ $_{\text{world eq.}}$/m^3), is defined:

$$\overline{\mathrm{CF}}_{\mathrm{HYD}} = \frac{\mathrm{WSF}_{\mathrm{HYD}}}{\mathrm{S}_{\mathrm{WC-HYD}}} \tag{8}$$

For other sources of electricity, the total water consumption across the US in each sector, S_{WC}, is directly calculated from plant-level water consumption data. Total energy generation, S_{EG} (MWh/year) and water scarcity footprint, $\mathrm{S}_{\mathrm{WSF}}$ (m^3 $_{\text{world eq.}}$/year), across the US are similarly defined for other subsectors, noted as “ss” in the subscript:

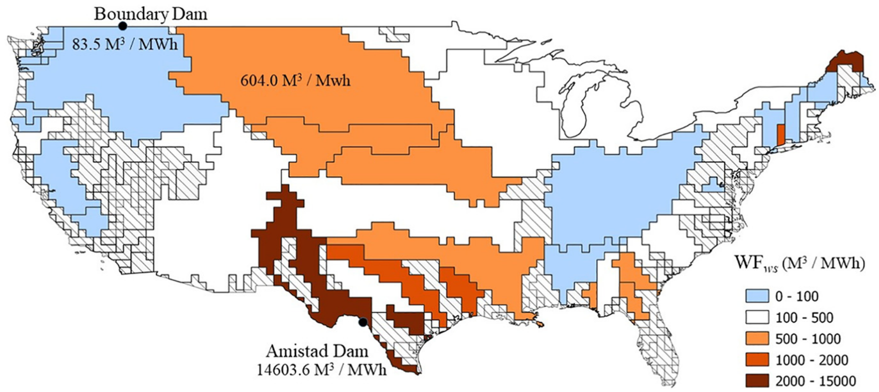

Fig. 1. Distribution of $\overline{\text{WC}}_{WS}$ across the US obtained from SPD. The watersheds where data on reservoir net water consumption is missing are hatched and are represented by $\overline{\text{WC}}_{US}$.

$$S_{EG-ss} = \sum_{i=1}^{n_{ss}} EG_{ss-i} \tag{9}$$

$$S_{WC-ss} = \sum_{i=1}^{n_{ss}} TWC_{ss-i} \tag{10}$$

$$WSF_{ss} = \sum_{i=1}^{n_{ss}} TWC_{ss-i} \times CF_{\text{AWARE}} \tag{11}$$

where n_{ss} is the number of powerplants across the US for "ss" subsector. Accordingly, CFs for various subsectors, $\overline{\text{CF}}_{ss}$ (m^3 $_{\text{world eq.}}$/m^3), is defined:

$$\overline{\text{CF}}_{ss} = \frac{WSF_{ss}}{S_{WC-ss}} \tag{12}$$

3. Results and discussion

3.1. Hydropower plants water consumption and allocation

The range of estimated mean watershed-level net evapotranspiration for reservoirs in various watersheds based on Eq. (3) is from $\overline{\text{WC}}_{WS} = 1.9$ M^3/MWh to about $\overline{\text{WC}}_{WS} = 14{,}603.9$ M^3/MWh (see Fig. 1). The Boundary reservoir with the net evaporation of 0.13 M^3/MWh and Amidstad dam with net evaporation of 24,179.0 M^3/MWh mark powerplants with minimum and maximum net water consumption across the US. The Boundary and Amidstad reservoirs serve 2 and 4 purposes and their allocation coefficients for hydroelectricity are $f_{\text{HE}} = 0.67$ and 0.2, respectively. With 0.9 Km^2 estimated spread of the reservoir and the structural height of about 110 m, in the Boundary reservoir, hydroelectricity generation was ranked as the first ecosystem service. The Amistad dam with 87.5 m in height and the reservoir area of about 131.5 Km^2 is constructed mainly for irrigation. Such variability in water consumption highlights the importance of employing a site-specific WC in this growing industry within the energy sector.

Based on the net energy generation from HPPs across each watershed and corresponding net evaporation, the regional values for $\overline{\text{WC}}_{WS}$ are calculated using Eq. (3) and plotted in Fig. 1. In this figure, watersheds with relatively lower average hydroelectric WC, with $\overline{\text{WC}}_{WS} <$ 100 M^3/MWh, are marked with blue, watersheds with $\overline{\text{WC}}_{WS} > 500$ M^3/MWh are marked with light orange to dark red, and watersheds with average net evaporation close to the country-wide average of net evaporation ($100 < \overline{\text{WC}}_{WS} < 500$ M^3/MWh), are marked in white. Hatched fills are areas with missing HPP representation where proxy value of $\overline{\text{WC}}_{US} = 234.3$ M^3/MWh is applied. The Amistad dam is positioned in the watershed with the highest $\overline{\text{WC}}_{WS}$ whereas the Boundary reservoir is in a watershed with a $\overline{\text{WC}}_{WS}$ below the aggregated country level.

In the Supplementary section, Fig. A.1 demonstrates the variability of WC among the HPPs. While the weighted average is $\overline{\text{WC}}_{US} = 234.3$ M^3/MWh, 50% of total electricity generation have WC of 65.36 M^3/MWh and lower, while about 84% have a WC of 600 M^3/MWh and lower.

3.2. Total water scarcity footprint

Annual net EG reported by EIA for 2015, is available based on fuel/source type. In this report, the total utility-scale electricity generation by coal, representing anthracite, bituminous, lignite coal and coal-based *syn*-fuel, was at 1.35TWh in 2015, followed by natural gas which accounted for 1.34TWh of electricity generation. Nuclear energy ranks third, followed by hydroelectricity, and wind power. With water withdrawal of about 0–4 L/MWh mostly for cleaning (Leitner, 2002), the water-use of wind power is negligible compared to the water-use reported for thermoelectric powerplants and is not reported to EIA. For photovoltaic-plants the on-site WC is employed primarily for cleaning and is reported at about 15 L/MWh (Leitner, 2002). Solar-thermal plants however, require water for cooling and for generating steam, which can range between 300 and 3700 L/MWh (Kelly, 2006). These operational water consumption for several solar-thermal plants are reported to EIA. Fig. 2 shows a summary of 2015's EG sorted by source type and ranked based upon net EG, reported by EIA. Hereinafter, the Annual Energy Review (AER) alphanumeric codes are used to distinguish fuel type.

Among the 17 AER source categories reported by EIA, here we only focus on presenting a few based on the following two criteria: firstly the annual reported energy generation in the category, and secondly the sector's strategic growth. As demonstrated in Fig. 2, coal, natural gas, and nuclear are the 3 top primary sources of electricity across the US. Hydroelectricity, wind, and solar energy are the most dominant renewable sources of energy across the US and worldwide and therefore explicitly discussing WC in these growing renewable sectors is critical. Gases other than natural gas are categorized and represented separately; and other fuels and sources are grouped and presented under "Other Sources". Table 1 is the summary of aggregated data on total annual energy generation, along with their water consumption and corresponding water scarcity footprint. The rankings per column are provided in brackets beside each number using Latin numerals. Hydroelectricity is separated from the rest of the table. As described in Section 2.1.1, hydroelectricity has the highest averaged direct WC compared to other electricity subsectors, with great plant-level

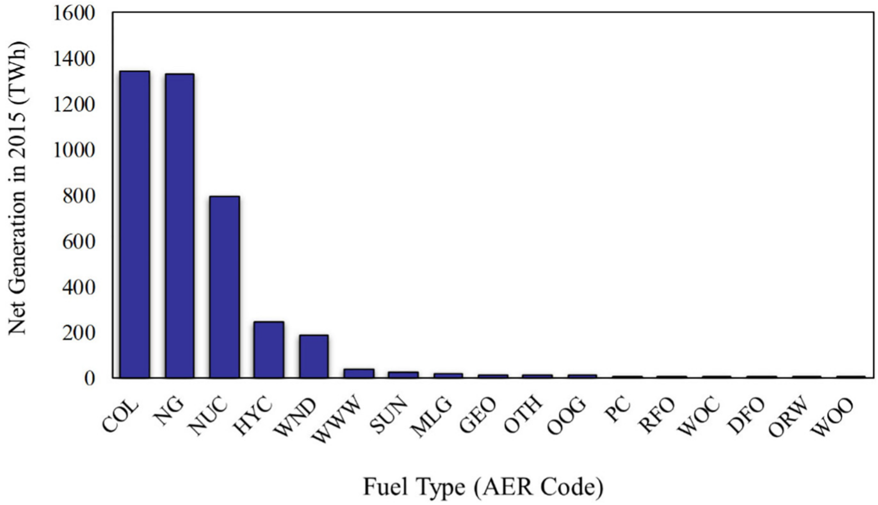

Fig. 2. Annual Electricity Generation for various Fuel Types in 2015: Coal (COL), Natural Gas (NG), Nuclear Fusion (NUC), Conventional Hydroelectric Turbines (HYD), Wind (WND), Wood and Wood Waste (WWW), Thermal and Solar PV (SUN). Full description of all the fuel type abbreviations based on the Annual Energy Review (AER) can be found in Table B.2.

and geospatial variability linked to it. This leads to an aggregated WC that is significantly greater that the WC by all other electricity sub-sectors, combined. The hydropower plants reported and cross-correlated between SPD and NID, excluding the pumping storage reservoirs, account for about 6.1% of annual electricity generated in the US in 2015, included in this study. The estimated on-site WC due to evapotranspiration in this sub-sector is about 41 Gm^3/year and represents more than 90% of on-site WC of all electricity sub-sectors combined across the US. Hence, hydroelectricity is ranked first among all sources for both $S_{WC\text{-}ss}$ and WSF_{ss}. Furthermore, the water consumption data for HPPs are extracted and extrapolated using quantitative data in the literature, whereas data for other sub-sectors are directly measured and reported on-site.

Fig. 3 illustrates the fractional share of net EG in different fuel/source categories, corresponding overall fractional WC, and WSF across the US, denoted by $F_{EG\text{-}ss}$, $F_{WC\text{-}ss,}$ and $F_{WSF\text{-}ss}$ respectively:

$$F_{EG-ss} = \frac{S_{EG-ss(US)}}{\sum_{ss} S_{EG-ss(US)}};\, F_{WC-ss} = \frac{S_{WC-ss(US)}}{\sum_{ss} S_{WC-ss(US)}};\, F_{WSF-ss} = \frac{WSF_{ss(US)}}{\sum_{ss} WSF_{ss(US)}} \tag{13}$$

Due to considerable WC and for a better representation of other sub-sectors, hydroelectricity is excluded from this figure in estimating the national level energy generation, WC, and WSF.

Table 1
Aggregated electricity generation, operational water consumption, and related water scarcity footprint impact score in some of electricity sub-sectors across the US in 2015.

Sources/fuels	Annual net EG, $S_{EG\text{-}ss}$ (TWh/yr)	Total annual operational electricity WC, $S_{WC\text{-}ss}$ (Million m^3/year)	Total annual electricity WSF, WSF_{ss} (Million m^3 $_{world\ eq.}$/year)
Coal	1344 (i)	1874 (ii)	24,665 (ii)
Natural gas	1333 (ii)	953 (iv)	8760 (iv)
Nuclear	797 (iii)	1051 (iii)	10,019 (iii)
Other gases	13 (viii)	71 (v)	58 (vii)
Wind	191 (v)	NA	NA
Solar	25 (vii)	3 (vii)	184 (vi)
Other sources	125 (vi)	39 (vi)	401 (v)
Hydroelectricity	249 (iv)	40,782 (i)	798,230 (i)

As demonstrated in Fig. 3, for natural gas these three normalized values, $F_{EG\text{-}ss}$, $F_{WC\text{-}ss}$, and $F_{WSF\text{-}ss}$ are, respectively, 34.8%, 23.9%, and 19.9%. On the contrary, nuclear-based electricity generation and coal-based electricity, have a dissimilar trend. The fractional EG for coal and nuclear stands at 35.1% and 21.8% respectively, whereas the corresponding fractional WCs are at 46.9% and 26.3%. The geospatial distribution of power plants exacerbates the WSF, leading to overall fractional WSF, F_{WSF}, of 55.9% and 22.7%.

3.3. Regional fractional water consumption and electricity generation

In freshwater use impact assessment, freshwater's regional scarcity as well as uneven geographic demand for freshwater, make this environmental impact category vulnerable to the distribution of electric power plants. The inflicted environmental impacts due to WC of an electric power plant might change severely across various watersheds, despite similar water consumption and energy generation. Thus, this section investigates the watershed-based geographic distribution of EG, WC, and WSF. Across each fuel/source category, the fractional cumulative values of these three parameters across each watersheds, $S_{EG-ss(WS)}$, $S_{WC-ss(WS)}$, and $S_{WSF-ss(WS)}$, with respect to their country-level variables, $S_{EG-ss(US)}$, $S_{WC-ss(US)}$, and $S_{WSF-ss(US)}$, are defined as:

$$f_{EG-ss(WS)} = \frac{S_{EG-ss(WS)}}{S_{EG-ss(US)}};\, f_{WC-ss(WS)} = \frac{S_{WC-ss(WS)}}{S_{WC-ss(US)}};\, f_{WSF-ss(WS)} = \frac{WSF_{ss(WS)}}{WSF_{ss(US)}} \tag{14}$$

3.3.1. Hydroelectricity

In Fig. 4, Basin# 28464, has the highest fractional hydroelectricity generation, $f_{EG-HP(\#28464)}$, at 47.4%. In this watershed, the aggregated watershed-level WC, $\overline{WC}_{WS} = 83.54$ M^3/MWh, is below the national aggregated WC, $\overline{WC}_{US}$. This indicates that the net evapotranspiration from the surface of reservoirs in this basin, are moderately lower than the mean aggregated national level. With lower than average net evapotranspiration rates, the combined effects of all the hydroelectric reservoirs in this watershed, $f_{WC-HP(\#28464)}$, only accounts for 22.9% of the hydropower's total WC, $S_{WC-HP(US)}$. Furthermore, regional CF of $CF_{AWARE} = 0.82$ (m^3 $_{world\ eq.}$/m^3) implies a greater AMD across this zone than the world-wide average, which leads to the fractional WSF, $f_{WSF-HP(\#28464)}$, of only 1.4%.

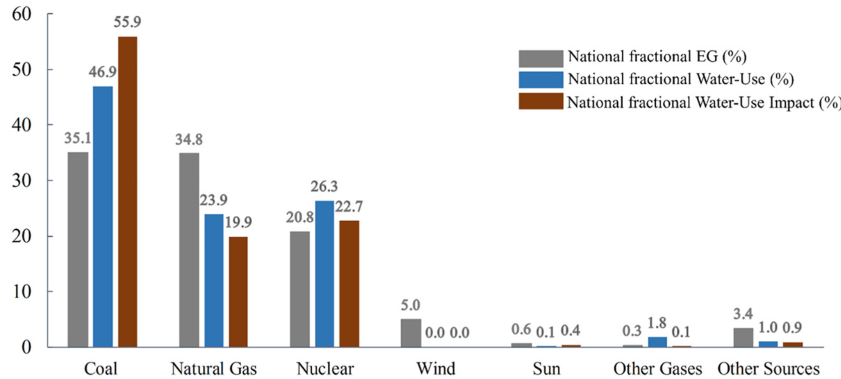

Fig. 3. State of national fractional EG, its water-use, and water-use impact score in the US. The variables are normalized by cumulative national level variables in 2015.

On the contrary Basins #38801 and #42615 have respectively 4.8 and 0.0% of the total EG, while accounting for 53.8 and 18.6% of the fractional WSF. Both watersheds have a CFs of 100 with $\overline{\mathrm{WC}}_{WS}$ levels above the national aggregated WC level, $\overline{\mathrm{WC}}_{US} = 234.3\ \mathrm{M}^3/\mathrm{MWh}$. These watersheds are among the watersheds with the highest solar irradiance. The effects of solar irradiance on freshwater availability are multifaceted. The high solar irradiance has a twofold impact on the overall freshwater-use impact of hydroelectricity: it impacts the freshwater availability and increases evapotranspiration rates. These trends are associated with higher hydropower WC and regional CF. With cumulative fractional EG of about 4.8%, these two watersheds inflict more than 70% of hydroelectricity's water-consumption potential impacts across the US.

As discussed in the Methodology, in the network of watersheds delineated by WaterGap2.2, the spread and the size of watershed vary and hence the total WC and EG. What emerges from this analysis and is important to note is the ratio $S_{\mathrm{WC-HYD(WS)}}$ to $S_{\mathrm{EG-HYD(WS)}}$ and $S_{\mathrm{WSF-HYD(WS)}}$ to $S_{\mathrm{WC-HYD(WS)}}$, and not the value of fractional WC and WSF. In Table 2, $f_{\mathrm{WSF-HYD(WS)}}$, $f_{\mathrm{WC-HYD(WS)}}$, and $f_{\mathrm{EG-HYD(WS)}}$ values in selected watersheds with high or low CFs are listed. These watersheds are critical as they either exhibited large fractional WSFs during operation, despite small energy generation, or have insignificant fractional WSFs compared to their fractional EG.

These findings indicate that the impact of water scarcity is two folded in the LCIA for hydroelectricity. In the inventory phase, areas with high water scarcity (see $f_{\mathrm{WC-HYD(WS)}}$ for basins #38801 and #42615 in Table 2) show higher WC of hydroelectricity production. In the LCIA phase, the total impact score in these watersheds is affected by the combination of high WC rates and high CFs, leading to significantly higher environmental impacts.

3.3.2. Other sources of energy

Similar to hydroelectricity, the geospatial distribution of other electricity subsectors influences their WSF. The regional CF proposed by Boulay et al. (2018) is distributed unevenly across the globe, owing to inhomogeneous remaining water availability as well as consumption and ecosystem demands. Hence, fractional WSF patterns do not necessarily overlap with WC patterns. As demonstrated in Fig. 5, the fractional WC of coal-based electricity generation in the Basin#3524, for instance, is at 31.8%. With low regional CF of 0.77, the fractional WSF in this watershed is only 1.8%. The opposite trend emerges in watersheds with highest CFs. Basin#38801 with fractional WC of 3.6% and 8.7% for natural gas and nuclear, respectively, imposes fractional WSF of 39.2% and 90.8%.

3.4. Sub-sector water scarcity factors (AWARE)

Fig. 6 shows the country-level subsector-specific CFs, defined by Eqs. (8) and (12), compared with the annual country-level non-agricultural. For electricity generation based on nuclear and natural gas, the freshwater-use CF is close to the aggregated non-agricultural CF, $\mathrm{CF}_{\text{AWARE-nonagri}} = 9.51$ (Boulay et al., 2018) for the US. For solar-thermal plants, only 7 data points are reported to EIA. The high average $\overline{\mathrm{CF}}_{\mathrm{SUN}} = 57.63$ is correlated to high regional AWARE CFs (i.e. relatively low remaining water available compared to the world average) in the reported 7 plants. Solar energy potential is greater in areas with greater solar irradiance, which can be associated with areas of higher water scarcity and regional CFs.

The aggregated CF for hydropower and coal-based electricity, as other primary sources of electricity, with $\overline{\mathrm{CF}}_{\mathrm{HYD}} = 19.57$ and $\overline{\mathrm{CF}}_{\mathrm{COL}} = 13.18\ \mathrm{m}^3{}_{\text{world eq.}}/\mathrm{m}^3$, are higher than $\mathrm{CF}_{\text{AWARE-nonagri}}$, meaning that those electricity-producing activities are located in regions with higher scarcity in comparison with other non-irrigation activities. The aggregated US-level CF for the electricity generation, is the combination of all operational WCs and is based on monthly and watershed level consumptions across all fuel/source types. This value at $\overline{\mathrm{CF}}_{combined} = 18.81$, is almost twofold the non-agricultural annual characterization factor, $\mathrm{CF}_{\text{AWARE-nonagri}}$. The annual non-agricultural $\mathrm{CF}_{\text{AWARE-nonagri}}$ does not reflect the regional or seasonal variation of WC in industries and technologies. For instance, $\mathrm{CF}_{\text{AWARE-nonagri}}$ includes both pulp and paper and energy industries. The spatial location of pulp and paper industries are directly correlated to biomass availability, whereas this is not a driver in the location of electric thermal powerplants. This significant difference between these two CFs, $\mathrm{CF}_{\text{AWARE-nonagri}}$ and $\overline{\mathrm{CF}}_{combined}$, points to the importance of sector-based regional WSF calculation in freshwater-use category. In this study, in both combined and separate fuel/source types, the aggregated annual US-level operational CFs in the electricity generation phase, are above $\mathrm{CF}_{\text{AWARE-nonagri}}$ (with the exception of NG which is marginally below and other gases).

These CFs are aggregated based on the freshwater consumption of electric subsectors as reported by EIA combined with data from the literature. We anticipate that with gradual changes made to this industry, owing to factors such as plant expansion and operation, construction of new or closure of powerplants, changes of these CFs would be insignificant in the short term. In medium- and long-term, on the other hand, these CFs will be subjected to significant changes. This is due to the fact that energy production and use is currently the largest source of greenhouse gas (GHG) emissions. There are proposed and ongoing actions to limit the GHG emission from energy sector. Governments are implementing

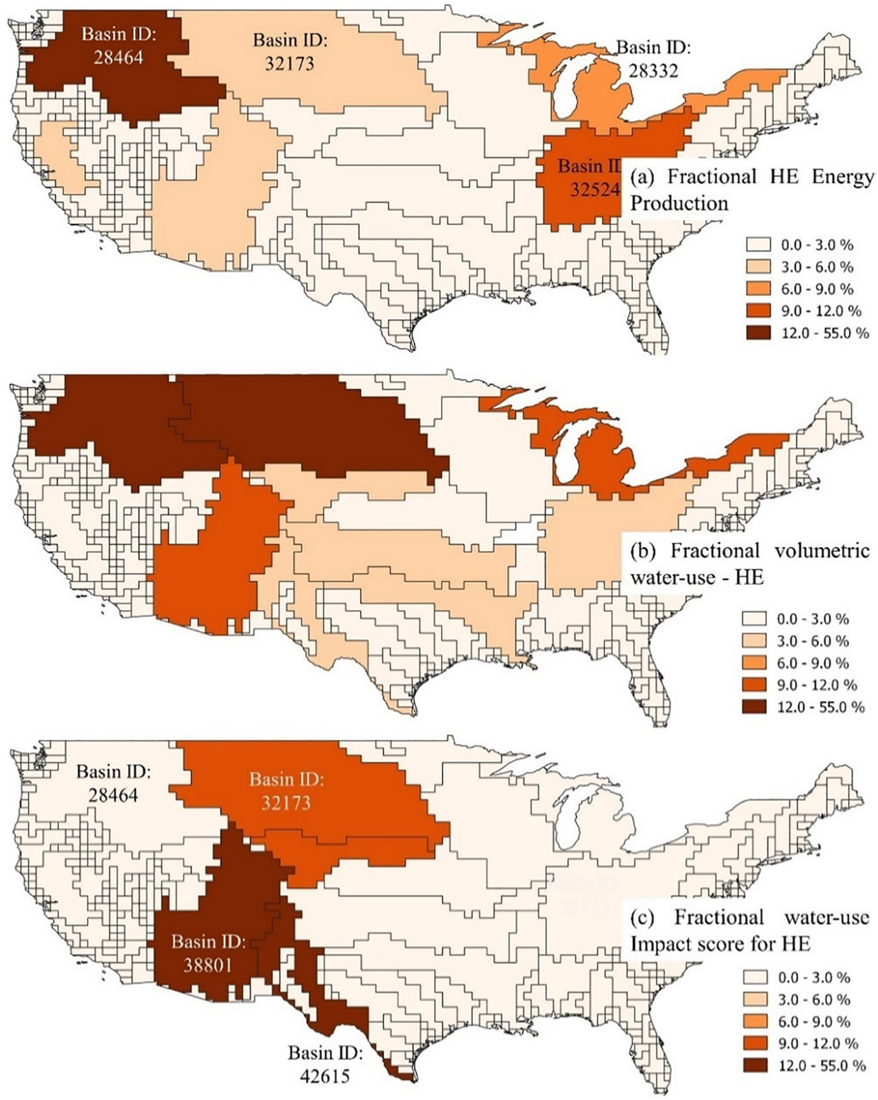

Fig. 4. (a) Fractional EG: $f_{EG-HYD(WS)}$ (top), (b) Fractional WC: $f_{WC-HYD(WS)}$ (center), and (c) Fractional WSF: $f_{WSF-HYD(WS)}$ (bottom) for the utility-scale hydroelectric power plants listed in EIA.

domestic energy sector policies (e.g. legislative and policy measures including a carbon tax and development and implementation a cap and trade framework in Canada), and making pledges and commitments to global efforts such as U.N.'s Framework Convention on Climate Change, based on their capabilities and national priorities. Furthermore, response to population growth and increasing energy demand (e.g. strategies such as expanding plants, replacing fossil-based energy with renewables, or adopting new technologies with lower overall footprints) would also change the energy landscape in regional and global level, which in turn will impact aggregated and sector- and industry-specific CFs in medium- to long-term.

Table 2
Fractional electricity generation, operational water-consumption, and operational water scarcity footprint for hydroelectricity across selected watersheds.

Basin ID	$f_{WSF-HYD(WS)}$	$f_{WC-HYD(WS)}$	$f_{EG-HYD(WS)}$	CF_{WS}
#38801	53.8	9.9	4.8	100
#42615	18.6	3.4	0.0	100
#28646	1.4	22.9	47.4	1.73
#32173	9.9	17.6	5.0	8.61
#28332	0.5	7.9	11.2	0.82
#35324	0.2	4.5	9.4	0.77

4. Conclusion

As demonstrated in this paper, spatial distribution of energy sector can significantly impact the outcome of Life Cycle Impact Assessment. Operational water consumption data for the different electricity sub-sectors was compiled for the production stage, associated with plant location. Operational water consumption in the electricity generation phase has on average a CF approximately twofold the value previously reported as non-agricultural value. Coal and hydroelectricity are, respectively, ranked 1st and 4th among all sources of electricity in the US in terms of energy generation, and the aggregated US-wide CF for both sectors are higher than the generic non-agricultural CF. Hence, the use of a generic CF for the electricity sector and some of its subsectors would grossly underestimate the potential inflicted impacts in water-use impact category. Furthermore, our analysis shows that importance of hydropower plant locations, as the impact of water scarcity is

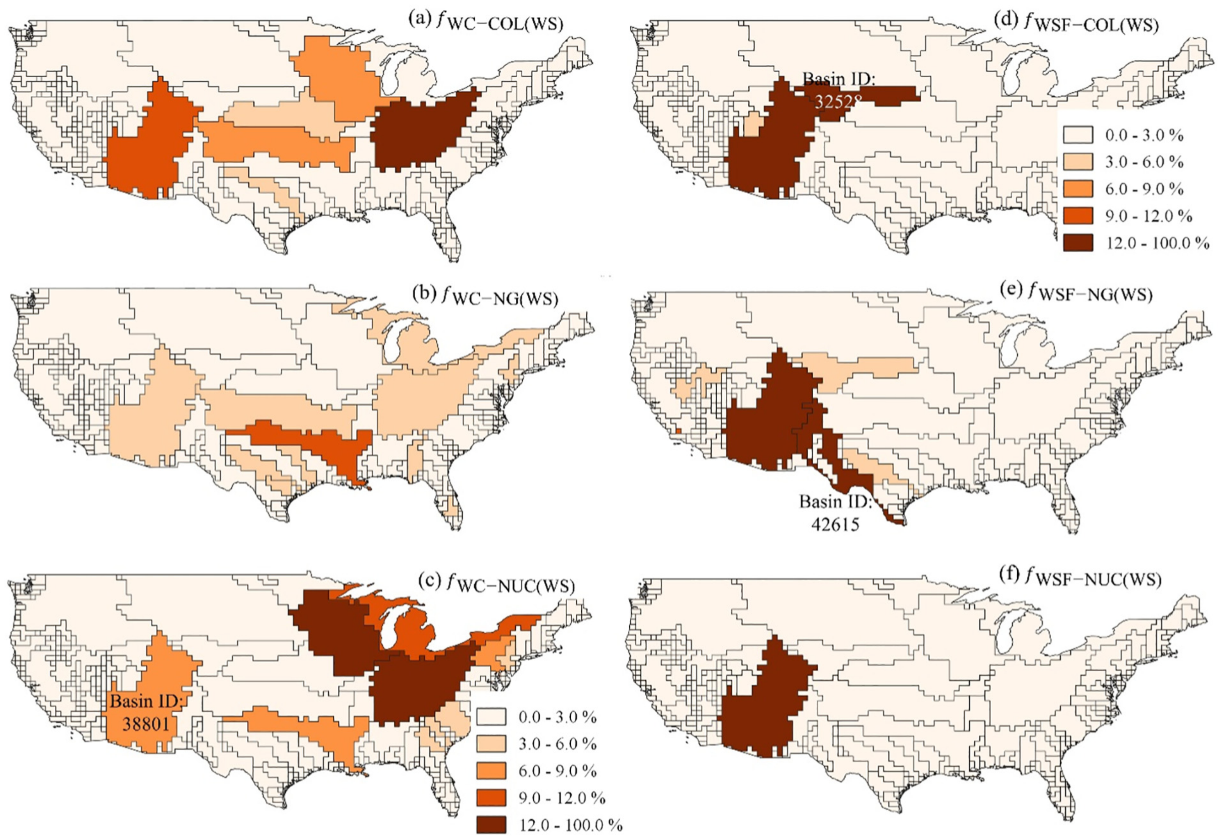

Fig. 5. (a), (b), (c) Fractional-operational WC by coal, natural gas, and nuclear: $f_{WC-COL(WS)}$, $f_{WC-NG(WS)}$, $f_{WC-NUC(WS)}$ (d), (e), (f) and their respective fractional WSF: $f_{WSF-COL(WS)}$, $f_{WSF-NG(WS)}$, $f_{WSF-NUC(WS)}$.

often reflected in both high WC (due to high rate of evapotranspiration) and CF values in this subsector.

Extension of this works to WC across the entire life-cycle of electricity generation and other economic sectors is subjected to data availability. Even with data availability, generating an industry-specific CF across all LCIA impact categories is a data-intensive endeavour. Therefore, to extend this study, it is important to identify the industries, countries, and impact categories with large environmental impacts and tempo-spatial variability.

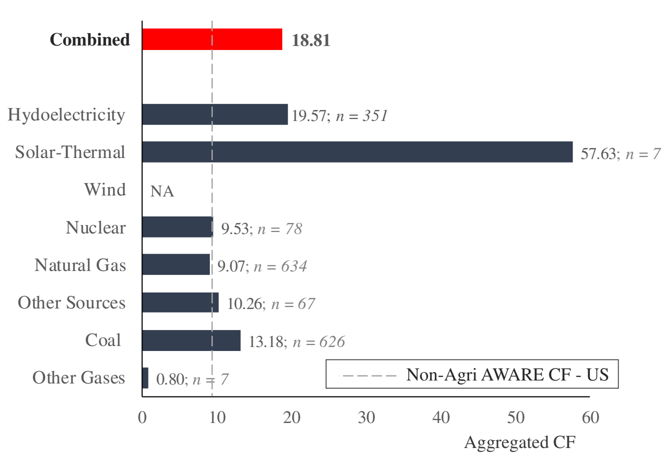

Fig. 6. Electricity sub-sector AWARE CF for United States, based on monthly and spatial water-consumption for electricity production and watershed-scale CF (m^3 $_{world\ eq.}$/m^3), compared to the country-scale AWARE CF for non-agri usages ($CF_{AWARE\text{-}nonagri}$ = 9.51 m^3 $_{world\ eq.}$/m^3). n is the number of sub-sector's powerplants across the US used in the analysis.

As illustrated in this study, compiling sector-specific data, in economic sectors and industries with sizable environmental impacts, and in impact categories with great variability across geographic boundaries, can lead to significantly different CFs than the generic country-level ones. In water-use impact category, this study shows that aggregating all, or some, of the economic sectors in LCIA, has a relatively high influence and leads to under- or over-estimation of impact score. Energy-sectors is one of the major economic sectors and is subjected to continuous change due to the growing energy demand and its major environmental impact. Therefore, across this diverse and impactful economic sector, defining sub-sector specific CFs is important to correctly assess potential environmental impacts associated with water-use.

CRediT authorship contribution statement

Shooka Karimpour: Conceptualization, Methodology, Investigation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Anne-Marie Boulay:** Conceptualization, Methodology, Writing - review & editing. **Cecile Bulle:** Conceptualization, Methodology, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Hydropower WC variability

Aggregated Water Consumption (WC) values, as well as site-specific WC of hydropower plants in *Scherer and Pfister's Data* (SPD) show large geographic variability across the US. This section addresses this spatial variability, while providing a weighted statistics of WC data based on each site's WC and EG. While the water consumption is presented as M^3/MWh, EG indicates the weight of the site-specific WC in calculating the total water consumption across the geographic zone. This weight can be normalized by the total Electricity Generation across the zone, P_i, which reflects the fractional EG across each powerplant:

$$P_i = \frac{EG_{\mathrm{SPD}-i}}{S_{\mathrm{EG-SPD}}} \tag{A.1}$$

$$\overline{\mathrm{WC}}_{\mathrm{WS}} = \sum_{i=1}^{n_{SPD}} WC_{\mathrm{SPD}-i} \times P_i \tag{A.2}$$

The definition of normal frequency, P_i, also transforms the definition of aggregated WC for various geographic zones, from Eq. (3) to Eq. (A.2). The number of HPPs from SPD that are spread across one watershed, *i*, varies from 1 to 41 from one watershed to another. With greater numbers of powerplant data aggregated to obtain the $\overline{\mathrm{WC}}_{WS}$ over one geographical zone, variability can disclose the range of WCs that are collectively represented by $\overline{\mathrm{WC}}_{WS}$. For instance, 41 sample HPPs are spread across the watershed # 35324 with $\overline{\mathrm{WC}}_{WS} = 101.04$ M^3/MWh, where the plant-level WC ranges from 1.36 to 2008.80 M^3/MWh.

Fig. A.1 illustrates this variability, where normal weight, P_i, is defined based on $S_{\mathrm{EG\text{-}SPD}}$ evaluated across the US. The left and right vertical axes are the normal frequency and the cumulative normal frequency, respectively. For better visual demonstration, this histogram showcases the WC only up to 500 M^3/MWh. Cumulative normal weight of a reference WC value, $\sum P_i$, is the running total normal frequencies of WCs which are lower than the reference value. With this definition, Fig. A.2 indicates that HPPs with net evapotranspiration of 500 M^3/MWh and smaller account for about 83% of the total hydropower generation across the US. With the median of 65.37 M^3/MWh, power plants with 65.37 M^3/MWh and smaller, account for 50% of the total US-wide hydropower generation. Therefore, despite the demonstrated variability in the net consumption, only 17% of all the hydroelectric generation in the US is associated with WC of 500 M^3/MWh and higher. This histogram doesn't emerge as a single-mode histogram and isn't symmetric, and instead, it is multi-modal. This indicates that the sample date, i.e. plant-level SPD's WC values, respond substantially to plant's local climate, reservoir's spread, among other factors; and a unified mean value cannot justly represent the WC in this subsector, even at the country-level.

The $\overline{\mathrm{WC}}_{WS}$ across any given watershed is an aggregate of spatial information with variability in both total annual energy generation and site-specific water consumption. The standard deviation of the watershed, σ_{WC}, is a measure that describes the spread of the water footprint across the watershed:

$$\sigma_{WS} = \sqrt{\sum\nolimits_i p_i \left(\mathrm{WC}_i - \overline{\mathrm{WC}}_{\mathrm{WS}}\right)^2} \tag{A.3}$$

In estimating the country-level standard deviation, *i* is the total number of SPD HPPs across the US. Fig. A.2 demonstrates the variability of hydroelectricity water consumption across different geographical zones. In each geographic zone, normal frequency, P_i, is estimated based on the relative net electricity generation in the geographic zone, which then is translated into cumulative frequency. In this graph the extreme percentiles are the 2.5% and 97.5% which embody the limits of the spectrum in each zone. These characteristics are compiled and presented in Table A.1 for the 7 watersheds that encompass HPPs with total evaporations greater than the total net evaporations from HPPs based on SPD. The sampling technique used in the scope of this study disregards the geodemography in any zone, including its population and area and is only related to its pre-defined geographic boundaries.

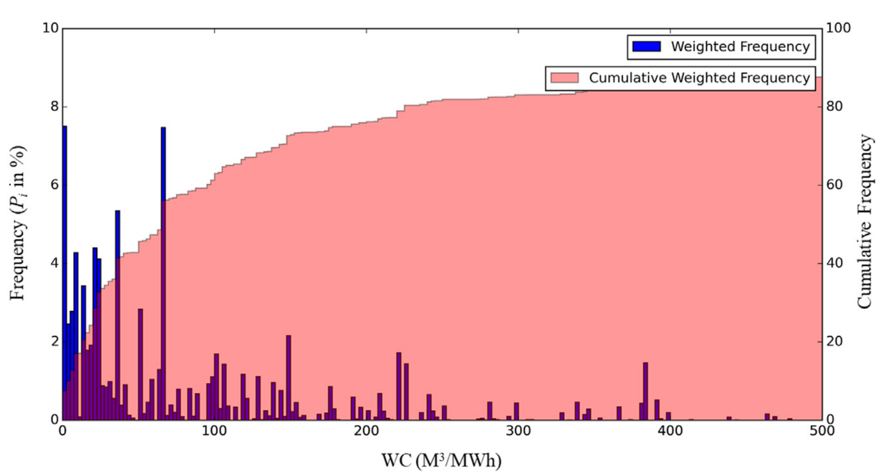

Fig. A.1. Country-level histogram for WC (M^3/MWh) using normal frequencies on the left vertical axis (*Pi* in %) for 341 HPPs in SPD. This histogram is multimodal with multiple frequency peaks distributed across the histogram. The cumulative frequency ($\sum Pi$ in %) is on the right vertical axis.

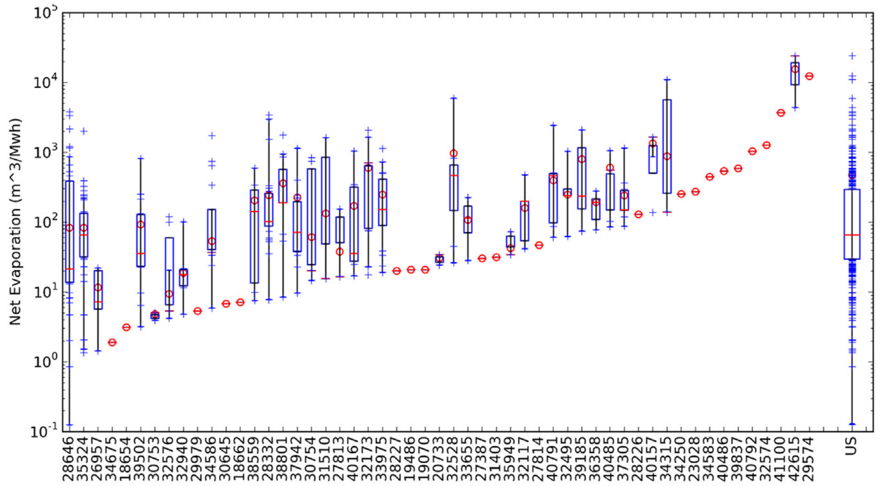

Fig. A.2. Variability of hydroelectricity water consumption in each geographic region hydroelectricity is presented in plot box: the interquartile range between first and third quartile (WF25% and WF50%) mark the boundaries of the box, with median lying in between, the top and bottom whiskers mark the 97.5 and 2.5 percentiles (WC97.5% and WC2.5%), respectively. The maximum (cross symbols) and the aggregated water consumption, $\overline{WC}_{WS}$(red circles) values are also shown in this figure.

Table A.1
Watershed-level statistical parameters of hydroelectricity water consumption variability in selected 7 watersheds and across the US and. K is the number of HPPs located in the watershed found in SPD.

Geographical Zone	K	WF_{WS} (WF_{US})	σ_{WS} (σ_{US})	WF_{Min}	WF_{Max}	$WF_{25\%}$	$WF_{50\%}$	$WF_{75\%}$
Basin ID: 41100	1	3688.56	0	3688.56	3688.56	3688.56	3688.56	3688.56
Basin ID: 38801	13	360.88	381.44	8.50	1775.71	67.30	190.54	946.89
Basin ID: 32173	10	603.95	541.02	17.63	2069.40	129.64	707.50	707.50
Basin ID: 42615	2	15523.35	9824.51	4372.10	24178.96	4372.10	24178.96	24178.96
Basin ID: 28646	40	83.53	214.93	0.13	3822.82	7.10	21.29	36.17
Basin ID: 35324	41	82.97	92.13	1.36	2008.80	40.67	65.34	101.61
Basin ID: 37305	13	241.27	261.75	87.66	1152.90	148.85	149.90	179.49
US	341	234.29	810.72	0.13	24,178.96	20.1	65.36	179.49

Appendix B. AER fuel types

Annual Energy Review (AER) fuel codes represent a partial aggregation of the fuel types into larger categories. These two or three letters alphanumeric fuel type are selected for this study. In 2015, in the US, the major energy sources in the electricity sector have been Coal, Natural Gas, and Nuclear. The AER codes and fuel source description are available in Table B.1.

Table B.1
AER fuel types and energy source description.

AER fuel code	Energy source description
COL	Coal: Anthracite Coal and Bituminous Coal; Lignite Coal Sub-bituminous Coal and Coal-based fuels
NG	Natural Gas
NUC	Nuclear Fission (Uranium, Plutonium, Thorium)
HYD	Water at a Conventional Hydroelectric Turbine
WND	Wind
WWW	Wood/Wood Waste: Wood/Wood Waste Solids and liquids; Black Liquor
SUN	Solar PV and thermal
MLG	Municipal Solid Waste - biogenic components; Landfill gas
GEO	Geothermal
OTH	Others: Purchased Steam; Municipal Solid Waste – Non-biogenic components Other
OOG	Blast Furnace Gas; Gaseous Propane; Other Gases
PC	Petroleum Coke
RFO	Residual Fuel Oil
WOC	Waste/Other Coal
DFO	Distillate Fuel
ORW	Other Renewables and Waste: Agricultural Crop Byproducts/Straw/Energy Crops; Other Biomass Solids Other Biomass Liquids; Sludge Waste; Other Biomass Gas (includes digester gas, methane, and other biomass gases); Tire-derived Fuels
WOO	Waste/Other Oil: Jet Fuel; Kerosene

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