DTU Library

Water use in electricity generation for water-energy nexus analyses: The European case

Larsen, Morten Andreas Dahl; Drews, Martin

Published in:
Science of the Total Environment

Link to article, DOI:
10.1016/j.scitotenv.2018.10.045

Publication date:
2019

Document Version
Publisher's PDF, also known as Version of record

Science of the Total Environment 651 (2019) 2044–2058

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Water use in electricity generation for water-energy nexus analyses: The European case

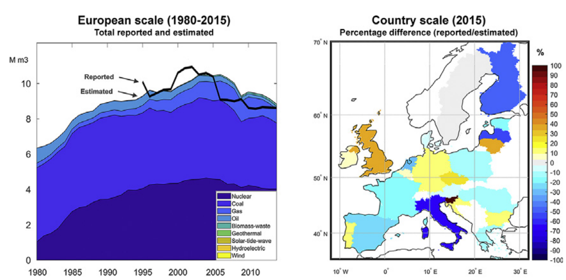
Morten Andreas Dahl Larsen *, Martin Drews

Technical University of Denmark, Produktionstorvet, Building 426, 2800 Kgs Lyngby, Denmark

HIGHLIGHTS

- Electricity plant water withdrawals are estimated using a comprehensive analysis.
- Estimates resemble reported levels on spatio-temporal scales of country/year.
- The results support perspectives in larger scale water-energy nexus management.
- More open source, freely available and detailed data are however urged.

GRAPHICAL ABSTRACT



The water withdrawal used for cooling of electricity generation plants has been estimated. The results show a resemblance of both historically reported data on a European scale (1980-2015) as well as on a country scale (2015).

ARTICLE INFO

Article history:
Received 22 June 2018
Received in revised form 2 October 2018
Accepted 3 October 2018
Available online 8 October 2018

Editor: Damia Barcelo

Keywords:
Water management
Water withdrawal
Water intensity factor
Energy systems
Europe
Large-scale water analysis

ABSTRACT

With almost 40% of the global population suffering from water scarcity, the need to manage water resources is evidently urgent. While water and energy systems are intrinsically linked, the availability of comprehensive, integrated data sets across the domains of water and energy is generally lacking. As a result, estimated indicators representing volumes of water usage per unit of electricity or fuel produced are often required to analyse the water-energy nexus. In this paper, an "ensemble" of indicators is assembled representing water usage spanning different electricity-generation technologies based on previously published works in an attempt to depict the level or lack of detail in current large-scale energy-sector water-usage data. Based on these, the degree in which using such estimates is suitable for reproducing electricity-production water-usage at coarser spatio-temporal scales is assessed. The performance of the ensemble median/min/max as a predictor of water use is evaluated for the period from 1980 to 2015 using additional information about the constituents of the European energy system. Comparing with the reported values for 1980–2015, the median provides a skillful reproduction of historical yearly water use for the EU (EU28) as a whole. A further analysis for 2015 indicates that reasonable agreement is also seen at the country level. Thus, the results suggest that an "ensemble-based approach" has the potential to provide sturdy estimates of yearly water use by energy systems for analyses at both the country and regional levels.

1. Introduction

Water and energy systems are inextricably interdependent. The water sector is a major consumer of energy for purposes such as water treatment, pumping and desalination. Similarly, water is essential for

* Corresponding author.
E-mail address: madla@dtu.dk (M.A.D. Larsen).

https://doi.org/10.1016/j.scitotenv.2018.10.045

cooling power plants, electricity generation and bio-fuel production, as well as in the extraction, mining, processing, refining and disposal of fossil-fuel residues. 44% of total global water withdrawals are used for energy production, a dominant share of which is cooling water in thermoelectric electricity generation (Collins et al., 2009). Energy and water are both limited resources that are essential for the fundamental services, including food production, required by a rapidly growing global population that is projected to reach 9.7 billion in 2050 (United Nations, 2017). As a result, it is increasingly critical to manage the nexus between energy and water properly (Kurian, 2017) in the broader context of dependent socio-economic sectors, including the wider water–energy–food nexus (Griggs et al., 2013; Howells and Rogner, 2014; United Nations General Assembly, 2015). Moreover, proper water-energy management is especially crucial in light of the fact that electricity and fuel production relies on an estimated 90% of non-sustainable water sources (WWAP, 2014), as well as the increasing demands for water, energy and food driven by, among others, the growth in population and economies (Hoekstra et al., 2012).

Over the last decade or so, analyzing issues within or related to the water–energy nexus has become increasingly important for both the scientific and policy-making communities (Dai et al., 2018; Miralles-Wilhelm, 2016). Likewise, the capacity to assess water and energy interlinkages at an increasingly higher resolution has also improved accordingly. Analyses of the water–energy nexus span a broad range of spatial levels, from the local (e.g. plant or city) (Chen and Chen, 2016) to the regional or national (Kibaroglu and Gürsoy, 2015; Mayor et al., 2015). Meanwhile temporalities range from multi-decadal (including climate change) (Mekonnen et al., 2016; Voisin et al., 2013) down to days or hours (or even lower) for operational applications (Castronuovo and Lopes, 2004).

A comprehensive review of methods and tools for macro-assessments of the water–energy nexus has recently been carried out by (Dai et al., 2018). From this analysis it is evident that, while a wide range of new methods and frameworks for comprehensively assessing interactions between water, energy and other elements have been developed, in general the availability of tools for nexus analyses that are at the same time integrative and multi-level is still poor (Daher and Mohtar, 2015; Howells et al., 2013). Instead, methodologies used for analyzing the water–energy nexus tend to be characterized by specific levels and data requirements (Liu et al., 2017), ranging from purely qualitative assessments to highly data-intensive model-based approaches (Granit et al., 2013). The review also found that none of the studies and methods considered provide a ‘singular framework’ for performing nexus studies.

The challenges of data availability at relevant spatio-temporal levels for analyzing the water–energy nexus, for example, on water use by energy systems and vice versa, is well documented (Chini and Stillwell, 2017; IRENA, 2015; Larsen et al., 2016). While in general water and energy systems can be considered to be well-monitored and managed (developing countries excluded), the availability of integrated data sets covering both domains is often severely limited at the relevant levels of aggregation in relation to nexus calculations, that is, beyond the site-specific level. Further, such data may be incomplete and inconsistent due, for example, to differences in the inherent conditions for the collection of data on water use by the energy sector between countries and regions, which can constrain the applicability and comparability of estimated water uses. For example, records from the US, while otherwise of good quality, have significant gaps concerning water-intensive energy technologies like nuclear (Macknick et al., 2012). Conversely, dependencies between water and energy systems, that is, water consumption or withdrawals related to specific energy technologies, may be expressed in terms of representative volumes of water use per unit (e.g. L/MWh) of electricity or fuel produced (Basheer and Elagib, 2018; Gleick, 1994; Inhaber, 2004; Macknick et al., 2012). This approach introduces a significant source of uncertainty arising from the (lack of) accuracy, but it also enables quantitative nexus calculations to be made at different levels and is frequently used by integrated assessment models.

In light of the poor data on water usage within the energy sector, as highlighted above, this paper addresses the extent to which reported estimates of water usage in electricity production provide an accurate ‘bridge’ when modelling the interdependencies between water and energy systems. Thus, many initiatives, like the Platform for Regional Integrated Modelling and Analysis (PRIMA) (Kraucunas et al., 2015), as well as the ETSAP-TIAM community (Føyn et al., 2011), aim at developing flexible multi-scale tools for analyzing the water–energy nexus in order to satisfy users' increasing demands by linking existing model components with new ones that use such an approach. In this context, the present study may be seen as an attempt to identify and validate a suitable set of parameters. To estimate water usage, multiple literature estimates of water withdrawal and consumption rates for electricity production technologies are collected in conjunction with the distribution of individual power plants and their corresponding technologies in order to calculate the country-level EU28 yearly water usages for 1980–2015, followed by a validation against reported numbers (Eurostat, 2018). The analysis is relevant because it highlights the best possible estimates of water usage within electricity production at coarser scales using freely available sources, albeit at coarse spatio-temporal resolutions (country/yearly). Thus, despite a certain resemblance between estimates and reported values, the paper also aims to show that the currently available data on energy-sector water usage is very inadequate, not least, in their detail and availability. Despite the current focus on providing open-access environmental data of increasing quality, data on the water–energy nexus are still limited in their availability. One aim of this paper is therefore to convey this information to users mainly in the academic community but also to politicians in light of the current tendency towards more open and available data.

2. Data and methodology

In this study, withdrawals of water are defined as the total amount of water that is extracted or diverted from its groundwater or surface water source and used during electricity-generation operations (as opposed to, e.g., including the construction phase), including the return flow. Thus, the cooling water addressed in this paper is freshwater only. Water consumption is similarly defined as the net balance, including only evaporated and transpired water, as well as water stored in crops and/or other products. Both terms (withdrawals and consumption) are jointly referred to as ‘water usage’. Using this definition water consumption becomes a subset of water withdrawals.

The term ‘median’, as used in this study, is the most commonly used term in the recent literature (Davies et al., 2013; Macknick et al., 2012). It can therefore to some extent be regarded as the standard metric. However, some literature uses the term ‘average’ (Mielke et al., 2010; NETL, 2010), whereas other, typically older literature sources simply give a representative value (Gleick, 1994; Inhaber, 2004). Furthermore, many studies build upon each other by re-issuing the findings of older studies. However, for any literature sources where the median estimate is based the middle value in between the reported minimum and maximum spans, this may introduce a certain bias towards underestimation, as argued by (Macknick et al., 2012). The span of the entire range is addressed by employing the minimum and maximum estimates. Correspondingly, the estimated mean and min/max ranges cannot be asserted to be ‘robust’ from a strictly statistical perspective (e.g., as quantified by t-procedures).

2.1. Data

The data used in this study can be grouped into three main categories depending on their nature and how they are used. I) The first category covers data on the water withdrawal and consumption rates of electricity production as a function of the energy source and cooling

Table 1
Literature sources for the estimates of water usage per unit of energy produced, an indication of the available information per relevant energy source, and the number of total occurrences in the literature of the median/minimum/maximum levels for withdrawals and consumption. The literature is sorted chronologically within the categories of peer-reviewed and grey literature respectively. 'CSP' denotes concentrated solar power, and PV denotes photovoltaic solar technology.

Energy source/Reference	(Gleick, 1994)	(Inhaber, 2004)	(Mielke et al., 2010)	(Macknick et al., 2012)	(Davies et al., 2013)	(Sanders et al., 2014)	(Spang et al., 2014)	(Byers et al., 2015)	(Zhang et al., 2016)	(U.S. Dept. of Energy, 2006)	(EPRI, 2008)	(Clark et al., 2010)
Coal	x	x	x	x	x	x	x	x	x	x	x	x
Gas	x	x	x	x	x	x	x	x	x	x	x	x
Oil	x	x	x		x		x			x	x	
Nuclear	x	x	x	x	x	x	x		x	x	x	x
Biopower				x			x	x	x	x	x	x
CSP	x	x	x	x	x		x			x	x	x
Solar PV	x	x	x	x	x		x				x	x
Wind	x	x	x	x	x		x				x	x
Geothermal		x	x	x	x					x		x
Hydro	x	x		x								x
Ocean	x	x										

Table 1 (*continued*)

								Withdrawals		Consumption	
Energy source/Reference	(NETL, 2010)	(Averyt et al., 2011)	(Kohli and Frenken, 2011)	(IEA, 2012)	(WWAP, 2014)	(Clark et al., 2015)	(NREL, 2015)	Median	Min−/max.	Median	Min−/max.
Coal	x	x	x	x	x			12	10	12	11
Gas	x	x	x	x	x			12	10	12	11
Oil	x		x		x			7	6	7	6
Nuclear	x	x	x	x	x			11	10	11	11
Biopower		x	x					7	6	7	7
CSP		x		x	x		x	8	9	8	10
Solar PV		x		x	x			6	7	6	8
Wind		x		x	x			6	7	7	7
Geothermal				x		x		6	6	7	7
Hydro								2	1	3	1
Ocean								1	0	1	0

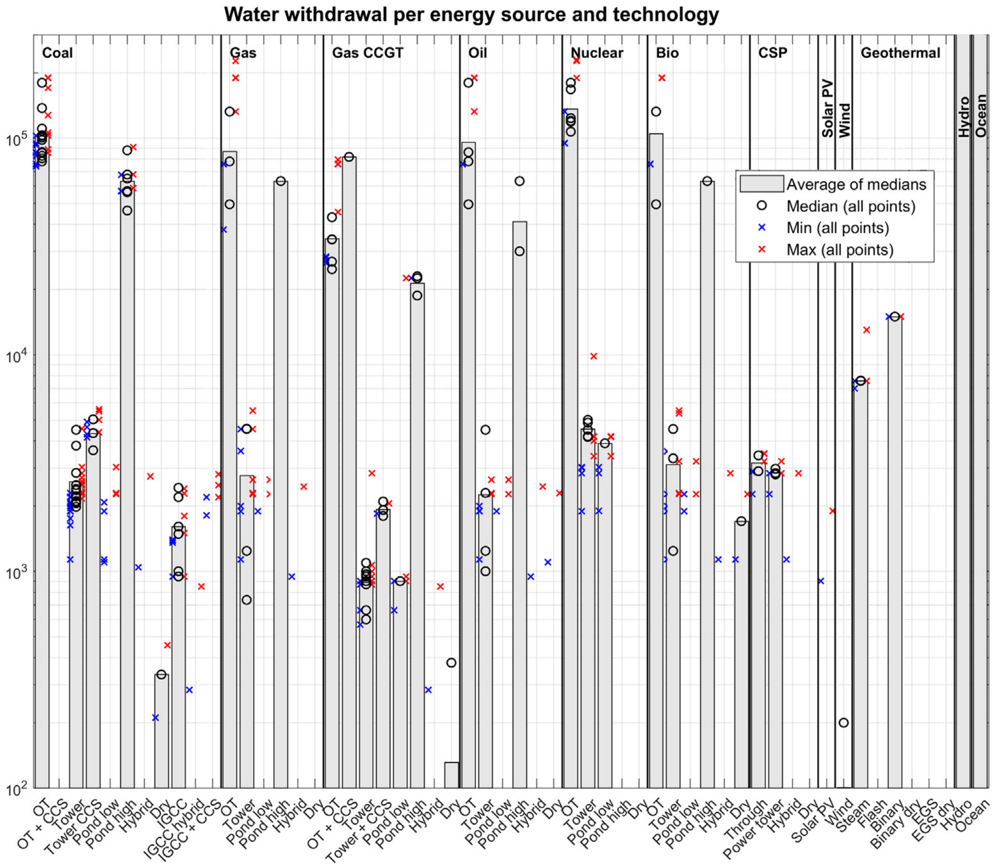


Fig. 1. All median, min, max (markers) and average of medians (bars) water withdrawal rates (L/MWh) for each energy source and cooling technologies combination (as visible within the Y-axis limits). 'CCGT' denotes combined cycle gas plants, 'OT' denotes once-through, 'CSP' denotes concentrated solar power and "EGS" denotes Enhanced geothermal system.

technology in question. The sources for these data are listed in Table 1. II) The second category covers data on individual electricity-generation plants which are used to estimate country-specific electricity generation per energy source, cooling technology and water source (fresh/saline). These data derive from (Enipedia, 2018; Global Energy Observatory, 2018; Shift Project Data Portal, 2018). These databases aim to include up-to-date information on individual power plants, although the present study necessitated substantial further online research to confirm whether or not, for example, plants were active or the type of cooling technology. III) The third category covers actual reported surface and groundwater withdrawals (both freshwater) used for cooling electricity generation plants, data being derived from (Eurostat, 2018). Annual data for the EU are available from 1970 to 2015. However, for earlier years there are an increasing number of data gaps on reported freshwater withdrawals. 1980 is therefore used as a starting point. For data gaps which are still present after 1980,linear interpolation has been used to fill the gaps, since this is the most conservative method and since a method aiming to reproduce patterns from neighbouring countries was considered too arbitrary for the short periods which needed gaps to be filled (a few years).

2.2. Estimated water use by energy source and technology

The estimated water usage related to specific energy technologies found, for example, in the scientific literature exhibit great local variations across natural, geographical, technological, hydro-climatic conditions and differences in definitions. Table 1 gives a list of previous studies within the categories of both peer-reviewed and 'grey' (report-style) literature as identified by the authors, who have estimated water usage by different energy technologies. While the list is comprehensive, it is by no means complete. Figs. 1 and 2 give all individual withdrawal and consumption factor estimates (median, min and max levels) respectively from the listed studies (markers) as well as their average value (bars) and Appendices A and B give the corresponding median values in table form. In general, the levels were found to be reasonably similar across literature sources, particularly for the median values, which also form the basis of the present study. The definitions in depicting water usage vary across literature, which is often not elaborated but instead visible from the numbers themselves or from the categories used. As an example, some sources group water usages across technologies, making the ranges appear exceptionally broad. All such cases are omitted in order to reflect only actual combinations of energy source and cooling technology. Another example includes pond cooling where the levels vary substantially which is believed to be related to definitions (using either the total withdrawn amount or only make-up water). In the present study, this is accounted for by dividing these definitions into two separate shares. It is further highlighted that data points in Figs. 1 and 2 may appear directly on top of each other having the same or corresponding values.

2.3. Reconstruction of water use by energy plants in Europe

To evaluate the performance of water-usage levels derived from the literature review, the water used by European energy systems is estimated. To do this, information on the share of different (a) energy sources and (b) cooling technologies (national), (c) the source of the water body used in nexus calculations (i.e. sea- or freshwater), principal cooling technologies related to energy source and country, and the

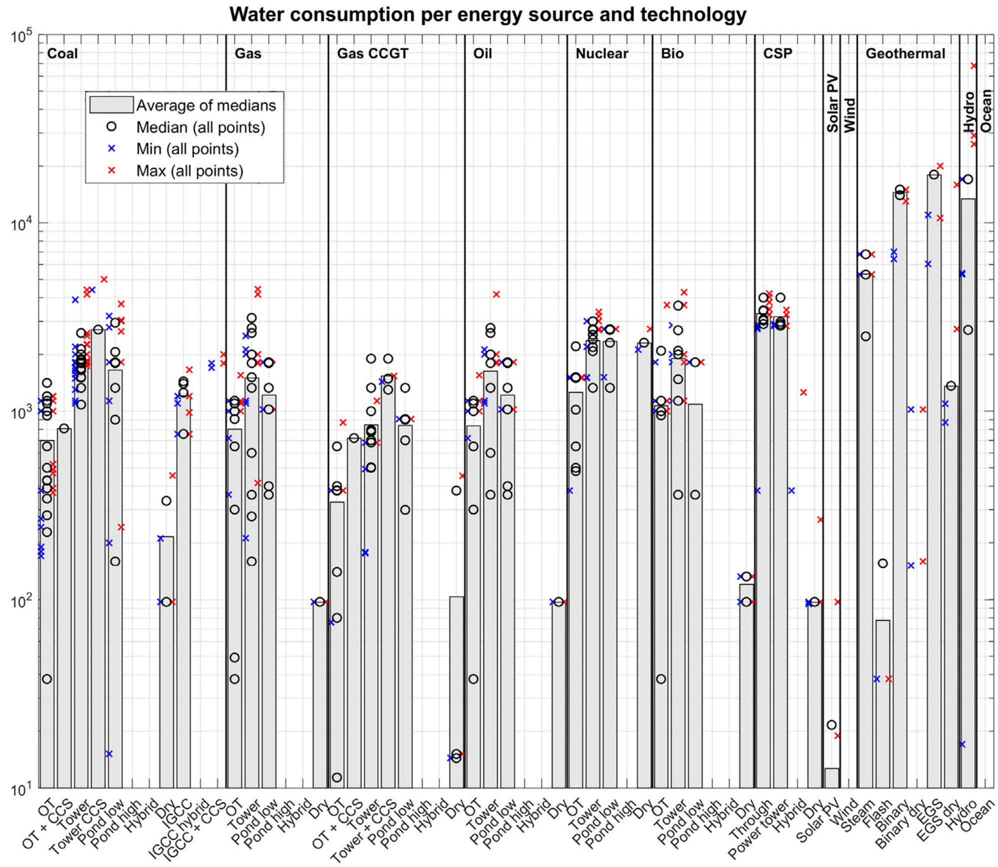


Fig. 2. Similar to Fig. 1, except for depicting water consumption rates.

electricity generated for each of the EU28 countries is collected. Only open-source data were used (see below). Based on this information, the amount of electricity plant cooling water is estimated. Hereafter this estimate of electricity plant cooling water will be referred to as EW ('estimated withdrawals'). Finally, the results are compared with the actual reported freshwater withdrawals available through Eurostat.

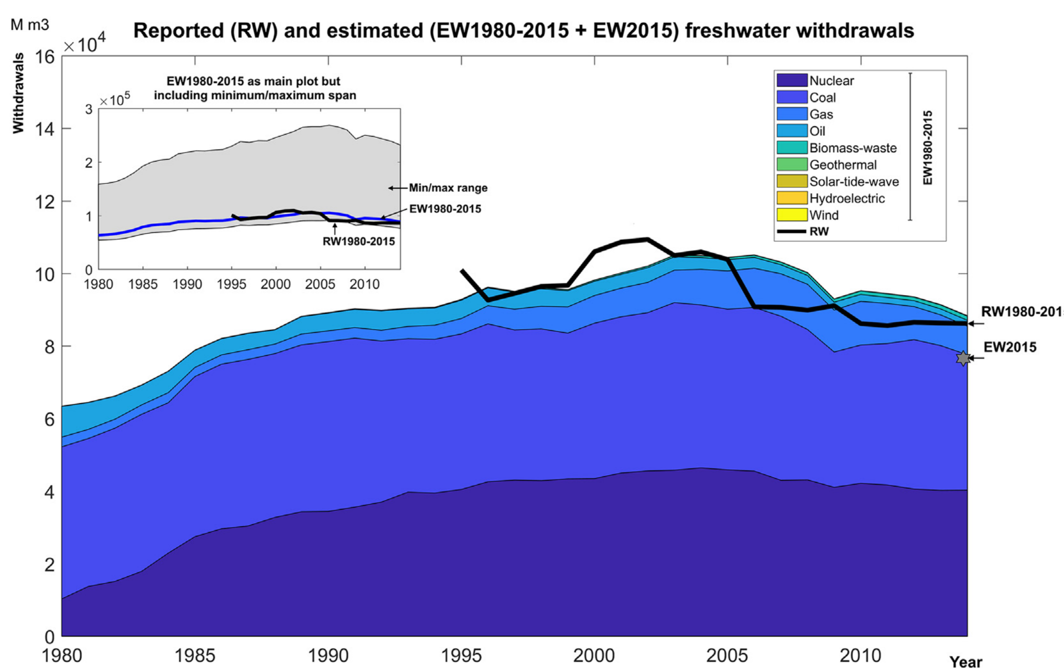


Fig. 3. *Main figure*: reported (RW) and estimated freshwater withdrawals per energy source (EW1980–2015) (as well as the sum of estimated freshwater withdrawals per country (*EW2015*) (arrow)). *Insert*: EW1980–2015 calculated based on minimum and maximum water-usage levels for each energy source, cooling technology and RW.

Hereafter, this dataset will be referred to as RW ('reported withdrawals'). As a part of the same literature review, the electricity plant cooling water consumption share (i.e. the net share excluding the return flow as defined above) is also estimated. Hereafter, this estimate is referred to as EC ('estimated consumption'). However, EC could not be validated against the reported levels, as data on reported consumption quantities could not be found (hence, the abbreviation 'RC' is not used here).

Estimates of electricity plant cooling water are divided into two separate analyses.

EW1980–2015: This analysis focuses on the temporal evolution of water use in electricity plants. It employs country-specific estimates of energy sources and cooling technologies, whereas data on the freshwater/sea-water shares are largely dependent on the plant-specific information, which is not generally available historically. The corresponding reported withdrawals are denoted 'RW1980–2015'.

EW2015: This analysis is based on the latest year for all data sources (2015). Unlike EW1980–2015, this assessment includes a comprehensive analysis of the level of a single electricity plant after (Enipedia, 2018; Global Energy Observatory, 2018), which allows country-specific water and energy sources to be taken into account, as well as cooling technologies (also feeding back into EW1980–2015). The corresponding reported withdrawals are denoted 'RW2015'.

As for EW, EC1980–2015 and EC2015 (estimated consumption) were calculated based on the same literature, methodology and years.

Steps in the analysis:

(a) *Water usage*. As described in Section 2.2, this step in the analysis assessed the water withdrawal and consumption levels (volumes of water per energy unit – e.g. L/MWh) for each energy source and sub-technology within each of these. See Table 1 for a list of the literature used and Figs. 1 and 2 and Appendices A and B for the resulting estimates of withdrawal and consumption levels.

(b) *Energy source*. The electricity generation per energy source (nine categories, see Figs. 3 and 4) was extracted for all EU28 countries in the available resolution (country-level/annual) from the Shift Project Data Portal (Shift Project Data Portal, 2018) (see Fig. 3 for EU28 aggregated values and corresponding use per technology). The energy source categories differ from those extracted from literature (Figs. 1 and 2) in that solar PV, solar CSP and ocean categories were grouped into one.

(c) *Cooling technology*. Each of the nine energy sources is further subdivided into subcategories depicting their respective cooling technologies, thus forming a total of 56 energy source/cooling technology combinations (see categories in Figs. 1 and 2).

(d) *Sea−/freshwater use*. At this point, the analysis provides an estimate of the total water usage for electricity generation within EU28. To address freshwater usage only, as described above, the databases of (Enipedia, 2018; Global Energy Observatory, 2018) were assessed for a single plant within EU28. This was done to determine the cooling water source and cooling technology. In a few select cases this information was readily available, whereas for most plants it proved necessary to inspect the plant location visually using satellite imagery. This extra inspection revealed further shortcomings in the databases that substantially affects the results (in relative terms), and these were therefore corrected accordingly. For some countries and technologies, a significant number of electricity plants exist, necessitating a substantial work load if all were to be represented. In these few cases, a threshold was used such that only the largest electricity plants constituting a minimum of 75% of the country's electricity generation were assessed. The remaining plants were then assumed to have the same distribution of technology and water sources, although this assumption might not hold fully (see Discussion). If the two databases differed, an online search was used to assess the (current) power-plant configuration. Plants with an estuary, fjord or river outlet location (most often UK and Benelux country plants) were assumed to use seawater, its usability for other sectors (e.g. irrigation) being poor or non-existent. The resulting freshwater percentages are shown in Table 2.

Below, the key energy source and country-specific methodology issues are addressed.

Geothermal. The distribution of geothermal technologies within Europe is based on (Bertani, 2015), as only a single Italian plant is listed within EU28 in (Global Energy Observatory, 2018), whereas Hungary, Ireland, Poland and UK also have geothermal electricity plants (Shift Project Data Portal, 2018).

Solar-tidal-wave. To calculate the water usages of the 95.15 TWh produced by means of solar, tidal and wave generation, it is necessary to know the share produced by concentrated solar power (CSP), since this is the only one of these technologies to use water for cooling. Installed capacities in 2014 include 90,000 MW solar PV (SolarPower Europe, 2017), 2313 MW CSP (EurObserv'ER, 2017) and 5 MW of ocean energy (tidal and wave) (Magagna and Uihlein, 2015), corresponding to a solar CSP share of 2.5%. Here, the share of CSP technologies (parabolic trough, Fresnel or solar tower) is based on the list of CSP plants in (EurObserv'ER, 2017), and the specific water usages of these technologies are from (JISEA, 2015). whether or not wet/dry cooling is used is based on a manual assessment of CSP plants, concluding that all larger plants have a capacity in the order of 50 MW, and all use wet cooling (for plants where cooling type is listed – 30 out of 45). These 45 50-MW CSP

Table 2
Freshwater share (%) in electricity plant cooling per EU28 country and energy source in cases of the plant inspection differs from EU28 levels (as shown in left-hand column; see analysis step 'd' above).

Energy source/country	EU28	AT	BE	BG	CZ	DK	EE	FI	FR	DE	EL	HU	IT	LI	MT	NL	PL	PT	RO	SI	ES	SE	UK
Nuclear	59.2			100	100				71.4	89.5		100		100	0	100			100	100		0	0
Biomass and Waste	16.9							100				100			0								0
Coal	73.5	100	100	100	100	0				93	100		0		0	76.1	100			100	60		40
Gas	52.2	100	90		100	0				100	0.43	100	41.7	90	0	88		100			45	0	19.5
Geothermal	100														0								
Hydroelectric	0														0								
Oil	43.3					0	100				0				0								0
Solar Tide Wave	100														0								
Wind	0														0								

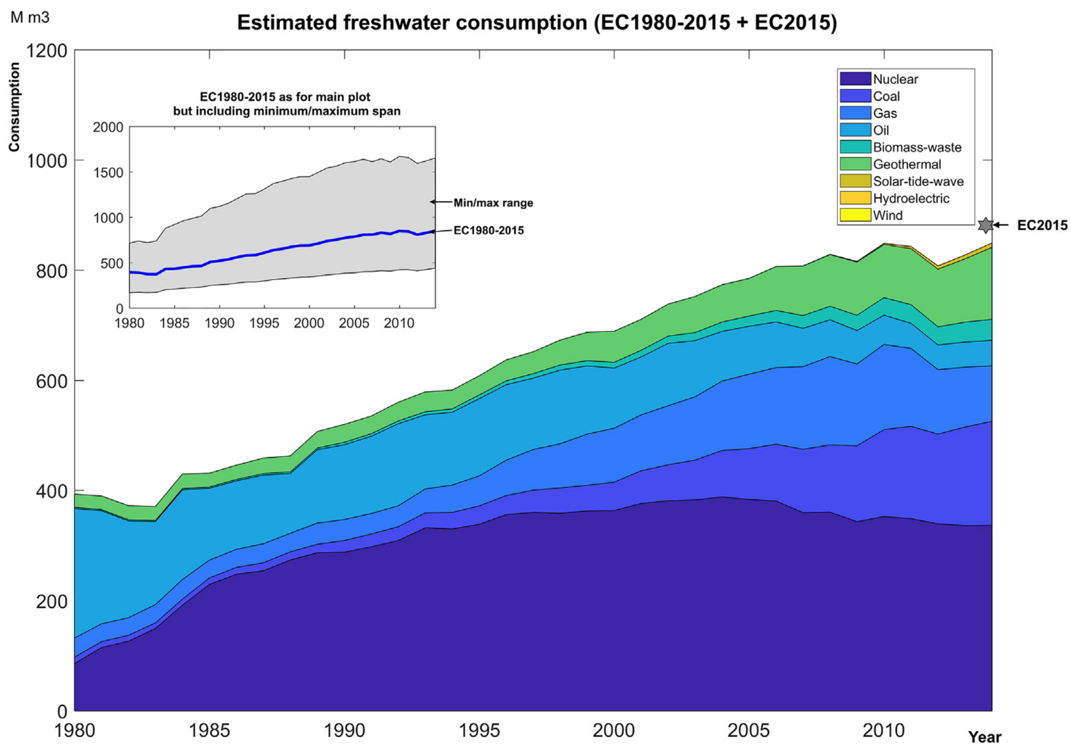


Fig. 4. *Main figure*: estimated freshwater consumption (EC1980–2015) per energy source and the sum of estimated freshwater consumption per country (EC2015) (arrow). Energy sources correspond to legend in Fig. 3. *Insert*: EC1980–2015 calculated based on minimum and maximum water usage levels for each energy source and cooling technology.

plants are all located in Spain, constitute 97% of the total EU28 capacity, and all employ parabolic trough technology.

In the Baltic States a high level of mismatch between the databases was found, necessitating correction. One example is the absence of the gas—/oil-based Elektrenai power plant in Lithuania from the Enipedia database, even though it accounts for a dominant share of electricity generation in the country. Another example is the 84% use of coal

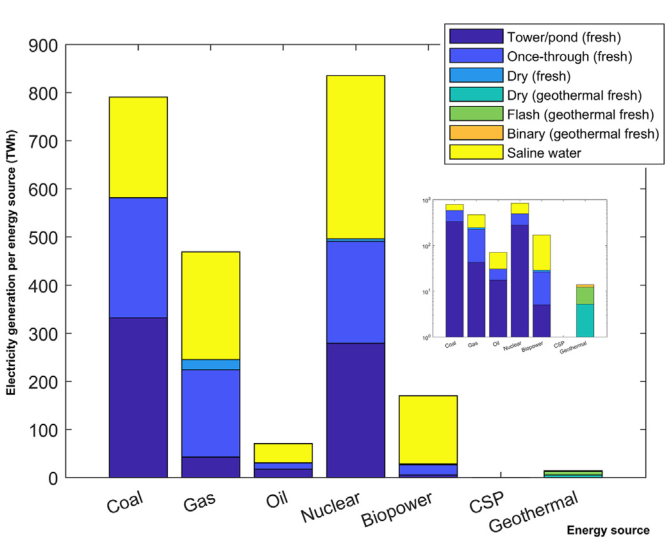


Fig. 5. Electricity generation per energy source (Eurostat, 2018), freshwater shares per energy source and corresponding cooling technologies for these freshwater shares. The 'insert' plot corresponds to the main plot but uses a log-scale y-axis for improved reproduction of low-generation energy sources such CSP.

declared for Estonian electricity generation at the Shift Project data portal, although no plants are listed either in Enipedia or by the Global Energy Observatory. Detailed data on the Czech Republic's electricity systems, including information on plants and cooling technology, were obtained from (Ansorge et al., 2016). For Greece, a lowered median water withdrawal rate of 2220 L/MWh was used compared to the 3238 L/MWh used for other countries (see references in Table 1 and values in Fig. 1 and Appendix A), as described in (Fernández-Blanco et al., 2017). For the Netherlands, the differences between RW and EW could be caused by differing definitions, since only 11 out of 32 gas plants (34% of generated electricity) are clearly located inland at river locations or by the sea, whereas for coal plants the corresponding level is 5 out of 8 (40% of generated electricity) (Global Energy Observatory, 2018). As the remaining parts are located close to the outlets of rivers or within estuaries, inconsistencies between the use of either the 'freshwater' or the 'sea' category could arise between databases. Similarly, the Borssele nuclear plant is located close to the Schelde River outlet but is listed as having freshwater cooling. Therefore, for the Netherlands, the estuary/downstream locations were defined as freshwater plants, since this was seen as the only plausible explanation for the high RW, although it is still not matched by EW using this definition. For Sweden, no coal power is listed by the Global Energy Observatory (Global Energy Observatory, 2018), whereas it is listed in Enipedia (Enipedia, 2018) and the Shift Project Data Portal (Shift Project Data Portal, 2018). This might be due to the interchangeable energy source for the Västerås power plant, the only coal-fired electricity plant in Sweden.

3. Results

In the following the results of reconstructing levels of the withdrawal and consumption of freshwater from the energy sector in EU28 are compared with reported withdrawal data from Eurostat

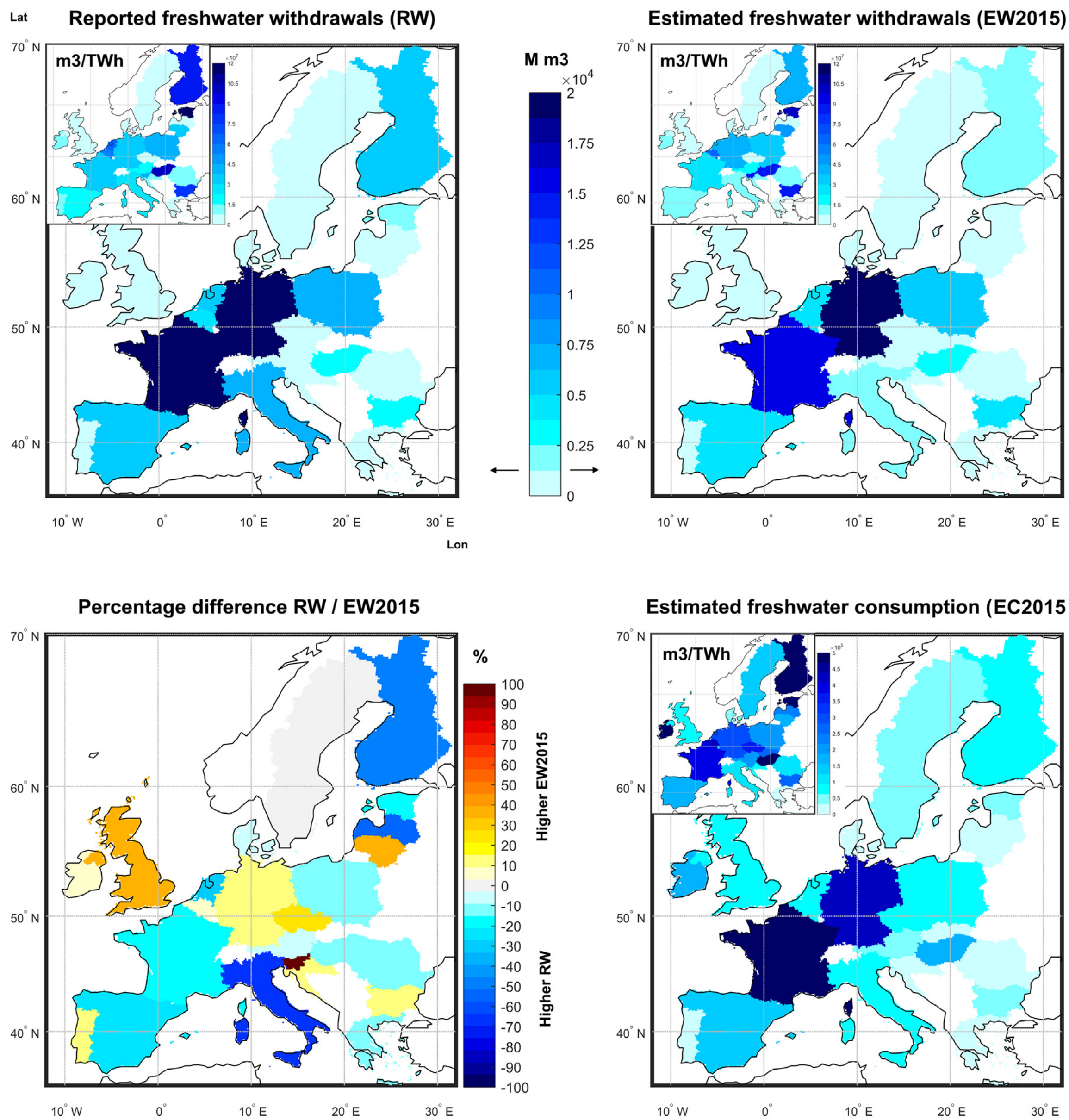


Fig. 6. Freshwater withdrawals (EW and RW) and consumption (EC) for EU28 countries. *Top left*: reported freshwater withdrawals (RW2015). *Top right*: estimated freshwater withdrawals (*EW2015*). *Bottom left*: difference between RW2015 and *EW2015* (%). *Bottom right*: estimated freshwater consumption (EC2015). Inserts show levels from the main plots but per generated electricity amounts. Cyprus, Luxembourg, Malta and Slovakia have no reported water withdrawals (white colour).

(Eurostat, 2018). As discussed above power plants and their associated energy production (in TWh) in Europe, based on the available EU28 level information for the period from 1980 to 2015, are initially characterized, followed by estimates of corresponding water usages using the median, minimum and maximum factors from Figs. 1 and 2 (EW1980–2015 and EC1980–2015). For 2015, for which more detailed information is available, an improved country-level analysis is carried out (EW2015 and EC2015).

Figs. 1 and 2 depict all the 896 median, min and max data points on electricity production water withdrawal and consumption which have been extracted in literature as a basis for this study (although a few are not visible within the selected Y-axis limits). See also Appendices A and B. A total of 56 technologies are listed based on eleven energy sources (gas is seperated between non-CCGT and CCGT for better visual overview). The span in levels from literature varies depending on energy source and technology but there is a tendency for the dominant combinations such as coal, gas and nuclear using tower and once-through cooling (see also Figs. 3 and 4) to have more consistent estimates. A tendency for the withdrawal estimates to be more similar than the corresponding consumption estimates is also seen. A reasonable level of agreement between RW and EW is seen (Fig. 3) using the median factors at the aggregated spatio-temporal levels used here. It is evident that conventional energy sources such as nuclear, coal and gas, which require excessive amounts of cooling water, clearly dominate the picture, whereas renewable (and less water-intensive) energy sources are essentially negligible. Results based on the more detailed country-level plant data from 2015 (indicated by a star), on the other hand, seems to slightly underestimate actual water use by the total European energy system. Furthermore, it is evident that the span between the minimum and maximum estimates is substantial (Fig. 3; insert).

In the case of EC (Fig. 4), select renewables such as geothermal and biomass are found to play a significant role here compared to RW/EW, and EC2015 is estimated at a higher level than EC1980–2015. As seen

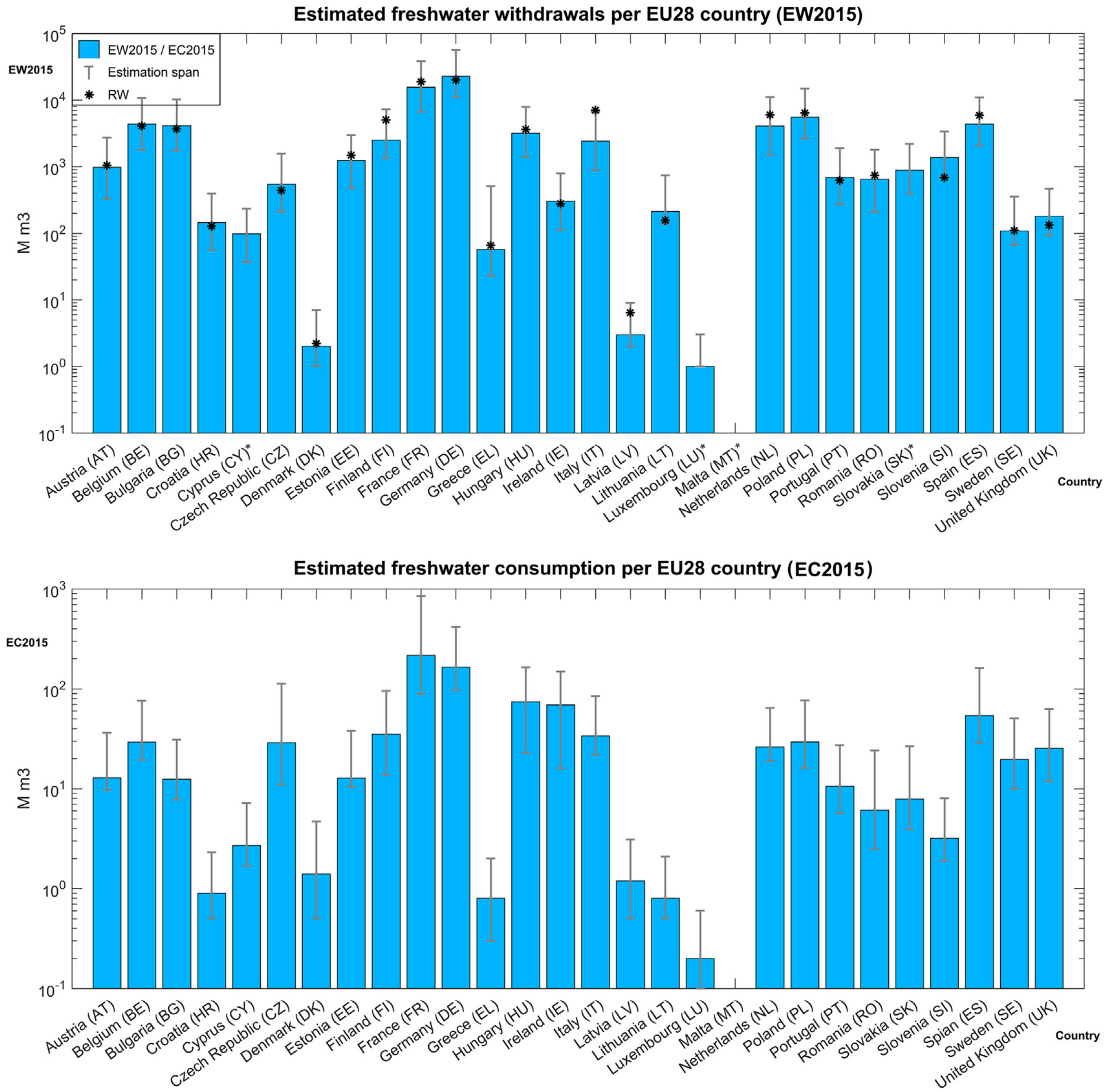


Fig. 7. Estimated and reported freshwater withdrawals, as well as estimated freshwater consumption with ranges based on minimum and maximum water-usage levels for each energy source and cooling technology. Cyprus, Luxembourg, Malta and Slovakia have no reported water withdrawals (marked with asterisk).

in the insert (Fig. 4), a large span is seen between the maximum and minimum values As compared to Fig. 3, in this case it is difficult to assert the validity of the median estimates since no figures are reported for validation in the literature.

Fig. 5 summarizes analysis step 'd' above by providing an overview of the estimated divison of cooling technologies within each energy source (sources with negligible water use are omitted) and the corresponding water source, that is, freshwater or saline water, for EU28. Despite a higher total level, the generation of electricity from nuclear sources (830 TWh) shows lower water-consumption figures than electricity generation from coal sources (791 TWh). This is related to the division of energy sources in between countries and their access to cooling water. For example, Germany produces a large share of its electricity based on coal as an energy source in inland locations. From the figure it is also clear that renewable technologies employ negligable amounts of water, though this omits biofuel production or evapotranspiration from hydropower reservoirs.

Fig. 6 compares country-level estimated withdrawals (EW2015, top right) and estimated consumption levels (EC2015, bottom right) respectively with the reported values (RW2015, top left) based on the more detailed country-level analysis for 2015. From RW2015 it is clear that energy systems in Central Europe, in particular in France and Germany, are particularly water-intensive with regard to total volumes of water compared to the rest of EU28. This pattern is less significant when correcting for the electricity produced (insert, top left), where instead Belgium, Bulgaria, Estonia, Finland, Hungary and the Netherlands stand out. Furthermore, it is seen that the estimated water withdrawals for Europe generate country-level 'patterns' that resemble those of RW (see also Fig. 7). In general, RW is found to exceed RW2015 for most countries (bottom left) with some notable exceptions like Germany, Lithuania and the United Kingdom, although the latter's deviation is likely to be related to low absolute withdrawal levels due a high degree of seawater cooling. Slovenia also stands out (approx 100% overestimate). This is likely to be related to the single nuclear plant in Slovenia, which uses approximately 74% of all national cooling water according to the calculations (EW). Therefore the RW/EW difference may be related to differences between the median values, given the conditions of this single plant. In Finland, most of the larger electricity plants are located along the coastline while still having a freshwater use (RW) of approximately 5000 M m^3. While most biomass plants in Finland are located inland, adding to the country's freshwater use, a high relative difference of approximately 50% is still seen. For Italy, little attention has been given to investigating the reasons for the large spread between RW and EW, since the latest RW reporting dates from 1980, rendering any attempts at validation futile (the 1980 level is used throughout the period).

Fig. 7 shows the water usage results for EW2015 (top panel) and EC2015 (bottom panel) for each country using the median, minimum and maximum levels. For EW2015, the results are shown in conjunction with RW2015 to enable their validation by country. Assuming this to be a first-order estimate of the 'true' associated uncertainty, the estimates (EC2015) approximate well to the corresponding reported values (RW2015), and all estimates are within the illustrated range associated with the country-level estimates except in the case of Malta, where information on local energy sources is lacking.

4. Discussion

As shown above, the estimates of water withdrawal rates compare reasonably well with the independent validation data from Eurostat and with the spatiotemporal scales assessed here, both in reproducing key aspects of the time series data from 1980 to 2015 and in representing the variability in water use for energy by country. Below the implications of the analysis presented here are discussed alongside recommendations for the direction of future data provision within the water–energy nexus.

To achieve the above-mentioned results an 'ensemble' of water-usage factors from a range of studies (cf. Table 1) was initially considered. While the authors by no means consider this factor set to be exhaustive, in each of the studies reviewed the estimated water uses (withdrawal and/or consumption) by different energy (cooling) technologies were inferred from local investigations. There was a tendency for them to originate in the USA in particular, possibly due to commercial interests resulting in data not being directly obtainable (Rothausen and Conway, 2011). One example of openly available data originating from the US is (Maupin et al., 2014), which contains very detailed information over time on, for example, water withdrawals per source (surface/groundwater) and per sector (industry, agriculture, housing), with numerous subcategories. As a result of the excessive data from the US, it might be expected that slight differences in local management practices and technology implementation between the US and Europe (and the rest of the world) might introduce a bias. A study by (Macknick et al., 2012), which also examines the water-usage data sources used in the present study, states that some median values are created based on the midpoint between the range endpoints, which may introduce an underestimation bias. Moreover, for some energy production and/or cooling technologies only a very few studies exist (cf. Table 1). In summary, these potential sources of uncertainty and biases imply a lack of complete statistical robustness with regard to the term 'median'. However, the median estimates in the studies considered here inherently agree well (results not shown), suggesting that the median factor seems to represent a fairly robust metric with which to represent yearly water usage on the larger European scale. Conversely, and not surprisingly, there is greater variability in the case of the minimum and maximum factor values (e.g. as illustrated by the inserts in Figs. 3 and 4), which are used here to represent the uncertainty associated with the factor estimates.

Another source of uncertainty is the assumption that the low-generation plants have the same technology/water source characteristics as the top 75% of electricity plants (calculated on the basis of electricity generation; see above). Smaller plants tend to have the oldest technologies (i.e. once-through cooling) using more water per unit of electricity generated (as seen in the databases listed above and in (U.S. Dept. of Energy, 2006)), which would imply a negative bias in respect of the estimates of water withdrawals. Here this bias is regarded as largely negligible for EU28 based on the low extent of countries and energy sources where not all plants were assessed.

Mapping European energy production convincingly represents another considerable source of uncertainty. In this study information from several sources is combined to represent energy production and dominant technologies across EU28, as well as to detect and account for obvious gaps or flaws in the underlying data sets. The availability of accurate information in this regard is clearly critical for the results, as this might otherwise lead to erroneous results and/or introduce significant biases in estimated water usages. That said, even for the relatively data-sparse case of modelling water use by energy sources for EU28 between 1980 and 2015, a decent level of agreement with the validation data was found (e.g. Figs. 3 and 7).

A key motivation for conducting the present study estimating water usage in electricity production is the lack of data available to analyse the water–energy nexus properly in quantitative terms, as also highlighted by (Chini and Stillwell, 2017; Larsen et al., 2016). Optimally, such data should be freely available, have wide (global) coverage, have a high temporal resolution, have detailed information on a single plant level, as well as with regard to water (source/sink), have shared and user-friendly formats, be collected using the same conventions, be forced by the same conditions (e.g. for future scenarios) and be congregated in a single database for easy acquisition. Taken together these suggestions are fundamentally out of reach for the near future for reasons of policy (Scott et al., 2011), coordination, financing and commercial interests (Goldstein et al., 2008). However, every step in this direction would improve the possibilities and range of the analytical steps and assumptions needed for most nexus analyses and, in essence, facilitate the emergence of firmer conditions for studying the implications of anthropogenic energy-related activities and water-management perspectives, as (Hussey and Pittock, 2012) also conclude.

By embedding the assembled median water-usage estimates within energy-system models such as TIMES (Simoes et al., 2013) or OSeMOSYS (Howells et al., 2011), the water-requirement impacts could be dynamically simulated and used to investigate a range of water management- and policy-related issues more reliably. In the context of the water–energy nexus, another potential issue to investigate is the impact of introducing more renewable energy technologies into the energy grid and/or add water shortages and related market demands.

5. Conclusions

This paper has investigated the extent to which estimates of an ensemble of factor sets representing volumes of water use per unit of electricity produced by different energy sources, in conjunction with a comprehensive review of the individual cooling technologies and water sources for individual electricity plants, provide an adequate predictor of water withdrawal and consumption levels generation by energy production. Based on validation data, the factor set estimates are found to generate a skilful reproduction of reported withdrawals on the coarse scales assessed here, which, on a yearly basis, include historical levels for EU28 (1980–2015) and individual country levels (2015). In the present demonstration, country-level information was extracted from a number of databases, some of which were found to be ambiguous, inadequate and/or contradictory. To support quantitative studies of the water-energy nexus at different levels and thus facilitate the improved management of water resources, the authors therefore recommend sustained and coordinated efforts towards improving the availability of data linking observations and projections of, for example, energy and water systems at relevant spatio-temporal levels using common scenarios (including climate change) and assumptions.

Acknowledgements

Parts of this work have been supported by the REEEM project (Role of technologies in an energy efficient economy – model-based analysis of policy measures and transformation pathways to a sustainable energy system) funded by the European Union Horizon 2020 research and innovation programme under grant agreement No 691739.

Appendix A Median water withdrawals. Table form of median values in Fig. 1. Literature sources with several values are numbered accordingly.

	Water withdrawal per literature source/energy source/technology (L/MWh)	Inhaber, 2004	Macknick et al., 2012 (1)	Macknick et al., 2012 (2)	Macknick et al., 2012 (3)	Davies et al. (2013) (1)	Davies et al. (2013) (2)	Davies et al. (2013) (3)	Davies et al. (2013) (4)	Davies et al. (2013) (5)	Davies et al. (2013) (6)	Davies et al. (2013) (7)
Coal												
	OT	78,000	137,600	102,539	85,512			180,000				
	OT + CCS											
	Tower		3804	2222	2400			4500				
	Tower + CCS		5031	4342								
	Pond low											
	Pond high		46,277	67,812	56,955							
	Hybrid											
	Dry											
	IGCC		1488	2430					1000		2200	
	IGCC Hybrid											
	IGCC with CCS											
Gas												
	OT	78,000	132,489									
	Tower		4554									
	Pond low											
	Pond high											
	Hybrid											
	Dry											
Gas CCGT												
	OT		43,078									
	OT + CCS											
	Tower		965				900			1000		
	Tower + CCS		1915							2100		
	Pond low						900					
	Pond high		22,523									
	Hybrid											
	DRY		0									
Oil												
	OT	78,000						180,000				
	Tower							4500				
	Pond low											
	Pond high											
	Hybrid											
	Dry											
Nuclear												
	OT	107,000	167,883					180,000				
	Tower		4168					4500				
	Pond low											
	Pond high											
	Dry											
Biopower												
	OT		132,489									
	Tower		3324									
	Pond low											
	Pond high											
	Hybrid											
	Dry		1703									
CSP												
	Through		3430									2900
	Power tower		2975						2800			2800
	Hybrid											
	Dry											
Solar PV												
	Solar PV	10										
Wind												
	Wind	1										
Geothermal												
	Steam								7600			
	Flash											
	Binary					15,000						
	Binary dry											
	EGS											
	EGS dry											
Hydro												
	Hydro	1.E + 07										
Ocean												
	Ocean	4.E + 07										

(*continued on next page*)

Appendix A (*continued*)

Davies et al. (2013) (8)	Davies et al. (2013) (9)	Sanders et al. (2014)	Byers et al. (2015)	Zhang et al. (2016) (1)	Zhang et al. (2016) (2)	Zhang et al. (2016) (3)	U.S. Dept. of Energy (2006)	NETL (2010) (1)	NETL (2010) (2)	NETL (2010) (3)
	98,000	110,526	102,530	103,100	100,600	82,800		80,633	86,182	
	2500	2847	2220	2370	2061	2110		1984	2090	
			3620							
	65,000							56,191	87,769	
				334						
							946	1609		
								49,449		
		738		4540				1242		
								63,292		
34,000		24,787	43,070	34,070				26,876		
			81,840							
600		1094	970	946			871	662		
			1920							1800
23,000								18,730		
		379						15		
86,000	86,000							49,449		
1000	2300							1242		
30,000	30,000							63,292		
119,000	120,000							123,616		
4200	5000							4860		
	3900									
			132,480					49,449		
			3320	4540				1242		
								63,292		
							2839			
	200									
							7571			
	80									

Appendix B Median water consumption. Table form of median values in Fig. 2. Literature sources with several values are numbered accordingly.

	Water consumption per literature source/energy source/technology (L/MWh)	Gleick (1994)	Mielke et al. (2010)	Macknick et al., 2012 (1)	Macknick et al., 2012 (2)	Macknick et al., 2012 (3)	Davies et al. (2013) (1)	Davies et al. (2013) (2)	Davies et al. (2013) (3)	Davies et al. (2013) (4)	Davies et al. (2013) (5)	Davies et al. (2013) (6)	Davies et al. (2013) (7)	Davies et al. (2013) (8)
Coal														
	OT	1200	1136	946	428	390		1100		650	1100			
	OT + CCS													
	Tower	2600	1514	2601	1813	1866		1800		1330				
	Tower + CCS													
	Pond low			2063	2949	159		1800		1330	1800			
	Pond high													
	Hybrid													
	Dry													
	IGCC			1438								1400		
	IGCC Hybrid													
	IGCC with CCS													
Gas														
	OT	1100	1136	908				1100		650	1100			
	Tower	2600	1514	3127				1800		1330				
	Pond low							1800		1330	1800			
	Pond high													
	Hybrid													
	Dry													
Gas CCGT														
	OT		379	379				400		650	400			
	OT + CCS													
	Tower		681	776				700	1900	1330	700	1000	700	
	Tower + CCS			1488								1900	1300	
	Pond low			908				700		1330				
	Pond high													
	Hybrid													
	DRY			8										
Oil														
	OT	1100						1100		650	1100			
	Tower	2600						1800		1330				
	Pond low							1800		1330	1800			
	Pond high													
	Hybrid													
	Dry													
Nuclear														
	OT		1514	1018				1500		650	1500			
	Tower		2082	2544				2700		1330				
	Pond low							2700		1330	2700			
	Pond high													
	Dry			2309										
Biopower														
	OT		1136	1136										
	Tower		1476	2093										
	Pond low													
	Pond high													
	Hybrid													
	Dry		132	132										
CSP														
	Through	4000	3028	3430										2900
	Power tower			2975			4000							2900
	Hybrid													
	Dry													
Solar PV														
	Solar PV			4										
Wind														
	Wind													
Geothermal														
	Steam	6800	2498	6800										
	Flash			0										
	Binary			14,000			15,000							
	Binary dry													
	EGS			18,000										
	EGS dry													
Hydro														
	Hydro	17,000	17,034	17,000			2700							
Ocean														
	Ocean													

(*continued on next page*)

Appendix B (*continued*)

Davies et al. (2013) (9)	Sanders et al. (2014)	Spang et al. (2014)	Byers et al. (2015)	Zhang et al. (2016) (1)	Zhang et al. (2016) (2)	Zhang et al. (2016) (3)	U.S. Dept. of Energy (2006)	NETL (2010) (1)	NETL (2010) (2)	Kohli and Frenken (2011)	Clark et al. (2010)	Clark et al. (2015)	NREL (2015)
500	1412	947	430	343	280	228	1136	38	8	1000			
			810										
	2135	2599	1810	1890	1650	1688		1507	1083	2000			
			2710										
		2063					1817	901					
		97		334									
							757	1253					
300	49	1098					1136	38		1000			
600	159	2765		276				360		2000			
400		1022					1817	360					
		97											
80	140	378	380	379			379	11					
			720										
500		796	780	795			681	503					
			1490										
900		907						299					
	379	14						15					
300		1098					1136	38		1000			
600		2765						360		2000			
400		1022					1817	360					
		97											
500	2211	1516					1514	481		1500			
2400		2725						2188		3000			
		2308					2725						
		2092	950				1136	38		1000			
		1134	2690	3630				360		2000			
							1817	360					
		97											
		3067											3407
							2839						
		97											
		22											
							5300						
												155	
											1363		

References

Ansorge, L., Water, T.G.M., Republic, C., 2016. Model of Water Needs for Energy Production. Statistika.

Averyt, K., Fisher, J., Huber-Lee, A., Lewis, A., Macknick, J., Madden, N., Rogers, J., Tellinghuisen, S., 2011. Freshwater Use by U.S. Power Plants: Electricity's Thirst for a Precious Resource, Energy and Water in a Warming World Initiative - Union of Concerned Scientists.

Basheer, M., Elagib, N.A., 2018. Sensitivity of water-energy Nexus to dam operation: a water-energy productivity concept. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2017.10.228.

Bertani, R., 2015. Geothermal Power Generation in the World 2010 – 2014 Update Report. Proc. World Geotherm. Congr. https://doi.org/10.1016/j.geothermics.2011.10.001.

Byers, E.a., Qadrdan, M., Kilsby, C.G., Tran, M., Alderson, D., Leathard, A., Chaudry, M., Amezaga, J.M., Hall, J.W., 2015. Cooling water for Britain's future electricity supply. Proc. ICE - Energy 168, 188–204. https://doi.org/10.1680/ener.14.00028.

Castronuovo, E.D., Lopes, J.A.P., 2004. Optimal operation and hydro storage sizing of a wind-hydro power plant. Int. J. Electr. Power Energy Syst. https://doi.org/10.1016/j.ijepes.2004.08.002.

Chen, S., Chen, B., 2016. Urban energy–water nexus: a network perspective. Appl. Energy https://doi.org/10.1016/j.apenergy.2016.03.042.

Chini, C.M., Stillwell, A.S., 2017. Where are all the data? The case for a comprehensive water and wastewater utility database. J. Water Resour. Plan. Manag. 143. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000739.

Clark, C.E., Harto, C.B., Sullivan, J.L., Wang, M.Q., 2010. Water Use in the Development and Operation of Geothermal Power Plants. https://doi.org/10.2172/1013997.

Clark, C.E., Harto, C.B., Schroeder, J.N., Anderson, A., 2015. The Geothermal Energy-Water Nexus. Proc. World Geotherm. Congr. 2015 Melb.

Collins, R., Kristensen, P., Thyssen, N., 2009. Water resources across Europe — confronting water scarcity and drought. EEA Report 2/2009., Eea https://doi.org/10.2800/16803.

Daher, B.T., Mohtar, R.H., 2015. Water–energy–food (WEF) Nexus Tool 2.0: guiding integrative resource planning and decision-making. Water Int. https://doi.org/10.1080/02508060.2015.1074148.

Dai, J., Wu, S., Han, G., Weinberg, J., Xie, X., Wu, X., Song, X., Jia, B., Xue, W., Yang, Q., 2018. Water-energy nexus: a review of methods and tools for macro-assessment. Appl. Energy 210, 393–408. https://doi.org/10.1016/J.APENERGY.2017.08.243.

Davies, E.G.R., Kyle, P., Edmonds, J.A., 2013. An integrated assessment of global and regional water demands for electricity generation to 2095. Adv. Water Resour. https://doi.org/10.1016/j.advwatres.2012.11.020.

Enipedia, 2018. Portal:Power Plants - Enipedia. [WWW Document]. URL. http://enipedia.tudelft.nl/wiki/Portal:Power_Plants, Accessed date: 17 May 2018.

EPRI, 2008. Water Use for Electric Power Generation (No. 1014026). Palo Alto.

EurObserv'ER, 2017. Solar Thermal and Concentrated Solar Power Barometer 2017.

Eurostat, 2018. Eurostat Database. [WWW Document]. URL. http://ec.europa.eu/eurostat/web/energy/data, Accessed date: 1 May 2018.

Fernández-Blanco, R., Kavvadias, K., Hidalgo González, I., 2017. Quantifying the water-power linkage on hydrothermal power systems: a Greek case study. Appl. Energy 203, 240–253. https://doi.org/10.1016/J.APENERGY.2017.06.013.

Føyn, T.H.Y., Karlsson, K., Balyk, O., Grohnheit, P.E., 2011. A global renewable energy system: a modelling exercise in ETSAP/TIAM. Appl. Energy 88, 526–534. https://doi.org/10.1016/J.APENERGY.2010.05.003.

Gleick, P.H., 1994. Water and energy. Annu. Rev. Energy Environ. 19, 267–299.

Global Energy Observatory, 2018. Global Energy Observatory. [WWW Document]. URL. http://globalenergyobservatory.org/, Accessed date: 31 August 2018.

Goldstein, N.C., Newmark, R.L., Dunham Whitehead, C., Burton, E., Mcmahon, J.E., Ghatikar, G., May, D.W., Goldstein, N.C., 2008. The energy-water Nexus and information exchange: challenges and opportunities. Int. J. Water 4, 5–24.

Granit, J., Fogde, M., Hoff, H., Joyce, J., Karlberg, L., Kuylenstierna, J., Rosemarin, A. (Eds.), 2013. Unpacking the Water-Energy-Food Nexus: Tools for Assessment and Cooperation Along a Continuum (No. REPORT 32). Stockholm.

Griggs, D., Stafford-Smith, M., Gaffney, O., Rockström, J., Öhman, M.C., Shyamsundar, P., Steffen, W., Glaser, G., Kanie, N., Noble, I., 2013. Policy: sustainable development goals for people and planet. Nature 495, 305–307. https://doi.org/10.1038/495305a.

Hoekstra, A.Y., Mekonnen, M.M., Chapagain, A.K., Mathews, R.E., Richter, B.D., 2012. Global monthly water scarcity: blue water footprints versus blue water availability. PLoS One 7. https://doi.org/10.1371/journal.pone.0032688.

Howells, M., Rogner, H.H., 2014. Water-energy nexus: assessing integrated systems. Nat. Clim. Chang. https://doi.org/10.1038/nclimate2180.

Howells, M., Rogner, H., Strachan, N., Heaps, C., Huntington, H., Kypreos, S., Hughes, A., Silveira, S., Decarolis, J., Bazillian, M., Roehrl, A., 2011. OSeMOSYS: The Open Source Energy Modeling System. An introduction to its ethos, structure and development. Energy Policy https://doi.org/10.1016/j.enpol.2011.06.033.

Howells, M., Hermann, S., Welsch, M., Bazilian, M., Segerström, R., Alfstad, T., Gielen, D., Rogner, H., Fischer, G., van Velthuizen, H., Wiberg, D., Young, C., Alexander Roehrl, R., Mueller, A., Steduto, P., Ramma, I., 2013. Integrated analysis of climate change, land-use, energy and water strategies. Nat. Clim. Chang. 3. https://doi.org/10.1038/NCLIMATE1789.

Hussey, K., Pittock, J., 2012. The energy-water nexus: managing the links between energy and water for a sustainable future. Ecol. Soc. 17. https://doi.org/10.5751/ES-04641-170131.

IEA, 2012. Water for energy: Is energy becoming a thirstier resource? World Energy Outlook

Inhaber, H., 2004. Water use in renewable and conventional electricity production. Energy Sources 26, 309–322. https://doi.org/10.1080/00908310490266698.

IRENA, 2015. Renewable energy in the water. Energy and Food Nexus.

JISEA, 2015. Concentrating Solar Power and Water Issues in the U.S. Southwest.

Kibaroglu, A., Gürsoy, S.I., 2015. Water–energy–food nexus in a transboundary context: the Euphrates–Tigris river basin as a case study. Water Int. https://doi.org/10.1080/02508060.2015.1078577.

Kohli, A., Frenken, K., 2011. Cooling Water for Energy Generation and its Impact on National-level Water Statistics. FAO, Rome.

Kraucunas, I., Clarke, L., Dirks, J., Hathaway, J., Hejazi, M., Hibbard, K., Huang, M., Jin, C., Kintner-Meyer, M., van Dam, K.K., Leung, R., Li, H.Y., Moss, R., Peterson, M., Rice, J., Scott, M., Thomson, A., Voisin, N., West, T., 2015. Investigating the nexus of climate, energy, water, and land at decision-relevant scales: the Platform for Regional Integrated Modeling and Analysis (PRIMA). Clim. Chang. 129, 573–588. https://doi.org/10.1007/s10584-014-1064-9.

Kurian, M., 2017. The water-energy-food nexus: trade-offs, thresholds and transdisciplinary approaches to sustainable development. Environ. Sci. Policy 68, 97–106. https://doi.org/10.1016/J.ENVSCI.2016.11.006.

Larsen, M.A.D., Drews, M., Rani, R., 2016. Water Consumption in the Energy Sector, DTU Energy Report (chapter 5).

Liu, J., Yang, H., Cudennec, C., Gain, A.K., Hoff, H., Lawford, R., Qi, J., de Strasser, L., Yillia, P.T., Zheng, C., 2017. Challenges in operationalizing the water–energy–food nexus. Hydrol. Sci. J. https://doi.org/10.1080/02626667.2017.1353695.

Macknick, J., Newmark, R., Heath, G., Hallett, K.C., 2012. Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. Environ. Res. Lett. 7, 045802. https://doi.org/10.1088/1748-9326/7/4/045802.

Magagna, D., Uihlein, A., 2015. Ocean energy development in Europe: current status and future perspectives. Int. J. Mar. Energy 11, 84–104. https://doi.org/10.1016/J.IJOME.2015.05.001.

Maupin, M.A., Kenny, J.F., Hutson, S.S., Lovelace, J.K., Barber, N.L., Linsey, K.S., 2014. Estimated Use of Water in the United States in 2010. Reston.

Mayor, B., López-Gunn, E., Villarroya, F.I., Montero, E., 2015. Application of a water–energy–food nexus framework for the Duero river basin in Spain. Water Int. https://doi.org/10.1080/02508060.2015.1071512.

Mekonnen, M.M., Gerbens-Leenes, P.W., Hoekstra, A.Y., 2016. Future electricity: the challenge of reducing both carbon and water footprint. Sci. Total Environ. 569–570. https://doi.org/10.1016/j.scitotenv.2016.06.204.

Mielke, E., Diaz Anadon, L., Narayanamurti, V., 2010. Water Consumption of Energy Resource Extraction, Processing, and Conversion. Energy Technol. Innov. Policy Discuss (https://doi.org/Discussion Paper No. 2010-15).

Miralles-Wilhelm, F., 2016. Development and application of integrative modeling tools in support of food-energy-water nexus planning—a research agenda. J. Environ. Stud. Sci. 6, 3–10. https://doi.org/10.1007/s13412-016-0361-1.

NETL, 2010. Estimating freshwater needs to meet future thermoelectric generation requirements: 2010 update. Natl. Energy Technol. Lab. 109 (https://doi.org/DOE/NETL-400/2010/1339).

NREL, 2015. Concentrating Solar Power and Water Issues in the U.S. Southwest NREL/TP-6A50-61376. https://doi.org/10.2172/1176743.

Rothausen, S.G.S., Conway, D., 2011. Greenhouse-gas emissions from energy use in the water sector. Nat. Clim. Chang. 1. https://doi.org/10.1038/nclimate1147.

Sanders, K.T., Blackhurst, M.F., King, C.W., Webber, M.E., 2014. The impact of water use fees on dispatching and water requirements for water-cooled power plants in Texas. Environ. Sci. Technol. 48, 7128–7134. https://doi.org/10.1021/es500469q.

Scott, C.A., Pierce, S.A., Pasqualetti, M.J., Jones, A.L., Montz, B.E., Hoover, J.H., 2011. Policy and institutional dimensions of the water–energy nexus. Energy Policy 39, 6622–6630. https://doi.org/10.1016/j.enpol.2011.08.013.

Shift Project Data Portal, 2018. Historical Electricity Generation Statistics | The Shift Project Data Portal [WWW Document]. URL. http://www.tsp-data-portal.org/Historical-Electricity-Generation-Statistics#tspQvChart, Accessed date: 20 June 2018.

Simoes, S., Nijs, W., Ruiz, P., Sgobbi, A., Radu, D., Bolat, P., Thiel, C., Peteves, S., 2013. The JRC-EU-TIMES model. Assessing the Long-term Role of the SET Plan Energy Technologies, EUR – Scientific and Technical Research Series https://doi.org/10.2790/97596.

SolarPower Europe, 2017. Global Market Outlook for Solar Power 2017-2021. SolarPower Eur.

Spang, E.S., Moomaw, W.R., Gallagher, K.S., Kirshen, P.H., Marks, D.H., 2014. The water consumption of energy production: an international comparison. Environ. Res. Lett. 9, 105002. https://doi.org/10.1088/1748-9326/9/10/105002.

U.S. Dept. of Energy, 2006. Energy Demands on Water Resources Report to Congress on the Interdependency of Energy and Water. Power.

United Nations, 2017. World Population Prospects The 2017 Revision Key Findings and Advance Tables, World Population Prospects The 2017. https://doi.org/10.1017/CBO9781107415324.004.

United Nations General Assembly, 2015. Transforming our World: The 2030 Agenda for Sustainable Development, Transforming our World: The 2030 Agenda for Sustainable Development. https://doi.org/10.1007/s13398-014-0173-7.2.

Voisin, N., Liu, L., Hejazi, M., Tesfa, T., Li, H., Huang, M., Liu, Y., Leung, L.R., 2013. One-way coupling of an integrated assessment model and a water resources model: evaluation and implications of future changes over the US Midwest. Hydrol. Earth Syst. Sci. 17, 4555–4575. https://doi.org/10.5194/hess-17-4555-2013.

WWAP, 2014. The United Nations World Water Development Report 2014: Water and Energy. Paris.

Zhang, C., Zhong, L., Fu, X., Wang, J., Wu, Z., 2016. Revealing water stress by the thermal power industry in China based on a high spatial resolution water withdrawal and consumption inventory. Environ. Sci. Technol. 50, 1642–1652. https://doi.org/10.1021/acs.est.5b05374.