

Challenges of data availability: Analysing the water-energy nexus in electricity generation

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ABSTRACT

Water is paramount for the operation of energy systems, for securing food supply and for the industry and municipalities. Intersectoral competition for water resources can negatively affect water scarce regions by e.g. power plants shutdowns, poor agricultural yields, and lack of potable water. Future economic and population growth as well as climate change is likely to exacerbate these patterns. However, models used for energy system management and planning in general do not properly include water availability which can lead to improper representations of water-energy interlinkages.

The paper initially highlights the water usage rates of current technologies within electricity generation and technologies with a potential to reduce water usage, electricity consumption or GHG emissions. Secondly, the paper presents currently available data on current and future projected water resources as well as data on energy statistics relevant to water-energy nexus studies. Thirdly, implementation cases are presented showing examples of water-energy nexus studies for the data presented. Finally, the paper highlights main challenges in studying the linkage between water and energy. We find a substantial gap in the general availability and quality of regional and global data for detailed quantitative analyses and also identify a need for standardization of formats and data collection methodologies across data and disciplines. An effort towards a coordinated, and sustained open-access data framework with energy sector water usage at fine spatio-temporal scales alongside hydro-climatic observation and model data using common forcings and scenarios for future projections (of climate, socio-economy and technology) is therefore recommended for future water-energy nexus studies.

1. Introduction

Resolving the highly interlinked and interdependent nexus of water, energy and food systems presents a formidable challenge for sustainable development [1]. The importance of taking a nexus approach in policy and planning is highlighted globally in the UN 2030 agenda and its 17 Sustainable Development Goals (SDGs) [2,3] and regionally in the EU Water Framework Directive [4]. To properly analyse the coherence and competing demands of this nexus, not only at different temporal and spatial scales but also across sectors and climatic conditions, integrated, systematic approaches and tools are needed [5,6].

Water, as a part of the nexus, is an integral part of resource extraction, production, distribution, and use of energy. However, 90% of the world's electricity and fuel production relies on non-sustainable water

sources with regards to either quantity or quality, and overall electricity and fuel production accounts for about 15% of global water withdrawals [1]. Conversely, the extraction, treatment, transport, and cleaning of water and waste water requires notable amounts of energy on their own amounting to, e.g., 4% of the total energy usage (transport and treatment alone) and 5% of total greenhouse gas (GHG) emissions in the US [7].

The demand for water, energy, and food is increasing, driven by a growth in population and economies and consumer behaviour [8] and demands are likely to be geographically redistributed due to migration [9]. Global water withdrawal demands are expected to increase by 55% in 2050 [1] and 48% for global energy consumption by 2014 [10]. Moreover, in many places these increasing demands will induce intensified pressures on natural resources and ecosystems [11,12]. Climate

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change is likely to increase the frequency and magnitude of water scarcity on a general global level [13]. However, the human impact on global water resources has been shown to greatly surpass the impacts of climate change for irrigated river basins [14–16]. The latter finds 62–76% of the global river basin areas will experience increased water stress by 2050 (depending on scenario) and the main cause is attributed to income growth (more so than population growth). Along with changes in the distribution and demand-supply of water resources, land use patterns are also likely to change significantly due to population growth and the associated increased demand for natural resources, commodities, and food, including expansion of agricultural, industrial, and urban areas [17]. Changes to the energy mix also affect the land use by introduction of new and expansion of existing energy technologies such as wind power, solar photovoltaic system (solar PV), hydropower and biofuels.

Projected future increases in energy demand are currently expected to be driven, in particular, by developing countries having the highest rates of economic and population growth [1,18]. Increased global deployment of renewable energy technologies of which many are less water intensive than, e.g., existing thermal power generation from fossil sources has the potential to decrease water stresses and GHG emissions. However, the intermittent nature of renewable electricity generation such as solar PV, wind, and run-of-river hydro can result in a mismatch between energy supply and energy demand and thus entails a need for energy storage. Advances within plant efficiencies, decreased costs of electricity and fuel production, clean technologies, and storage/utilisation is likely to aid in meeting future energy demands [19,20].

In general, water and energy systems are managed and monitored, and therefore the availability of proper data sources in support of sustainable management of the water-energy part of the nexus should in principle be ensured. However, while adequate data exist on water resources and electricity generation respectively, data on, e.g., water usages related to electricity generation remain much more limited. The same applies to information on the cooling technologies used in electricity generation, which may influence estimates of water use as much as the generation technology itself. Not to mention that for hydropower and bioenergy the relation of water use to electricity and fuel production depends on how to address the evaporative shares. In this context reviews by Refs. [21–23] have previously addressed the operational water consumption and withdrawals (volume of water use per unit of electricity or fuel produced). Other studies have linked geographically distributed electricity generation and water resources globally [24,25] and regionally [26]. The availability of consistent data sets presents a significant challenge. Detailed analyses along the water-energy nexus require spatio-temporal information on the water usage and electricity generation technologies. But the nature of these data is multiplex and no coherent database exists holding this information at a level of detail adequate for supporting potential analyses of, e.g., achievable electricity generation pathways for water sustainability and future GHG reduction scenarios [27]. Further, currently available data coming from a range of sources, research communities and institutes lack a shared format, can be software specific [28], are often not publicly and/or freely available [29] or might include too vast a number of assumptions, and quality issues making them unsuitable without proper experience.

Optimally, specific knowledge on the amount of water withdrawn and consumed for each use category should be employed. For reasons such as lack of control and bookkeeping [30], commercial interests [7, 31], imprecision in registered values [32] or even expensive paywalls [33] these water usage levels are rarely comprehensive and assumptions and estimations therefore have to be made. One approach is to assess the specific technologies in question for the plants and facilities (without directly available data) and estimate water usages based on comparable plants operating under similar conditions although with a loss of detail as a result, as e.g. seen in Ref. [34]. Depending on the application, water usage estimates can be combined with facility locations from sub-basin scales, including information on water source, to country-level scales as

typically used in larger scale studies. Finally, temporal scales could range from sub-daily data to account for market and pricing influences production up to yearly averaged data for larger scale studies.

In this paper we highlight some of the critical interlinkages mentioned above, including requirements and data availability for specifically analysing the nexus between water and electricity generation. For comparative purposes and to highlight technologies which are emerging and have the potential to shift the generation of electricity in a more sustainable direction aspects not directly related to the nexus have been included (e.g. biomass, CO₂ capture/storage, and energy storage). Initially, we address current estimates (ranges as well median values) of operational water usage in electricity and fuel production (consumption and withdrawals) and resource extraction for different energy technologies. Secondly, we summarize relevant examples of available data on large scale water resources (current and future) as well as energy statistics data relevant to water-energy nexus studies at different spatial scales. We then, present three implementation examples using some of the presented data to reflect potential uses in assessing the nexus between electricity generation and water (and climate conditions). Finally, we discuss some of the present limitations, uncertainties and associated implications in linking water resources in terms of quantity (availability), quality and variability with ongoing efforts in energy system modelling and resulting policy recommendations in the context of the water-energy nexus in a projected future of further carbon- and water constraints.

2. Water use in energy production and resource extraction

In the following, the term is used to denote freshwater. Thus, the usage of sea water for, e.g., power plant cooling is not addressed. Water withdrawal is defined as the total extracted and diverted water including the share eventually returned back into the source whereas water consumption is the net balance, including only evapotranspired water and water stored in crops and/or other products. Water consumption therefore becomes a subset of water withdrawals and differences between withdrawals and consumption can be substantial (see Fig. 1). Jointly, water withdrawals and consumption are referred to as water usage.

Other than being dependent on energy source, type of plant/generation technology and cooling technology, the water availability, and therefore water usage, in electricity generation is highly dependent on the geographical location and thereby the hydro-climatic conditions in question. Estimates of water use from the US, and to some extent the EU, dominate the picture as corresponding estimates from other regions of the world are in general not easily obtainable, which may introduce uncertainties due to geographical differences in water usages between countries or regions [35]. Environmental concerns, jurisdiction, policies and end-user water-energy interactions are also outside the scope of this paper. Due to limitations in addressing water quantity issues in the water-energy nexus, remote sensing/satellite data are also not taken into account here despite obvious benefits with regards to measuring at larger geographical scales.

Figs. 2 and 3 collate the water withdrawal and consumption associated with currently common or prospected future energy technologies based on a comprehensive literature study of previous publications including both peer-reviewed and grey literature.

2.1. Non-renewable sources

2.1.1. Power generation from thermal plants

Thermal power plants currently make up approx. 80% of the global electricity generation [1] and share many characteristics, including the processes related to water usage, independent of the fuel used (coal, nuclear and, to some degree, gas). For these plants, cooling accounts for the bulk share of total water usage. For thermal power plants, the closed water loop driving the turbine requires only limited amounts of make-up

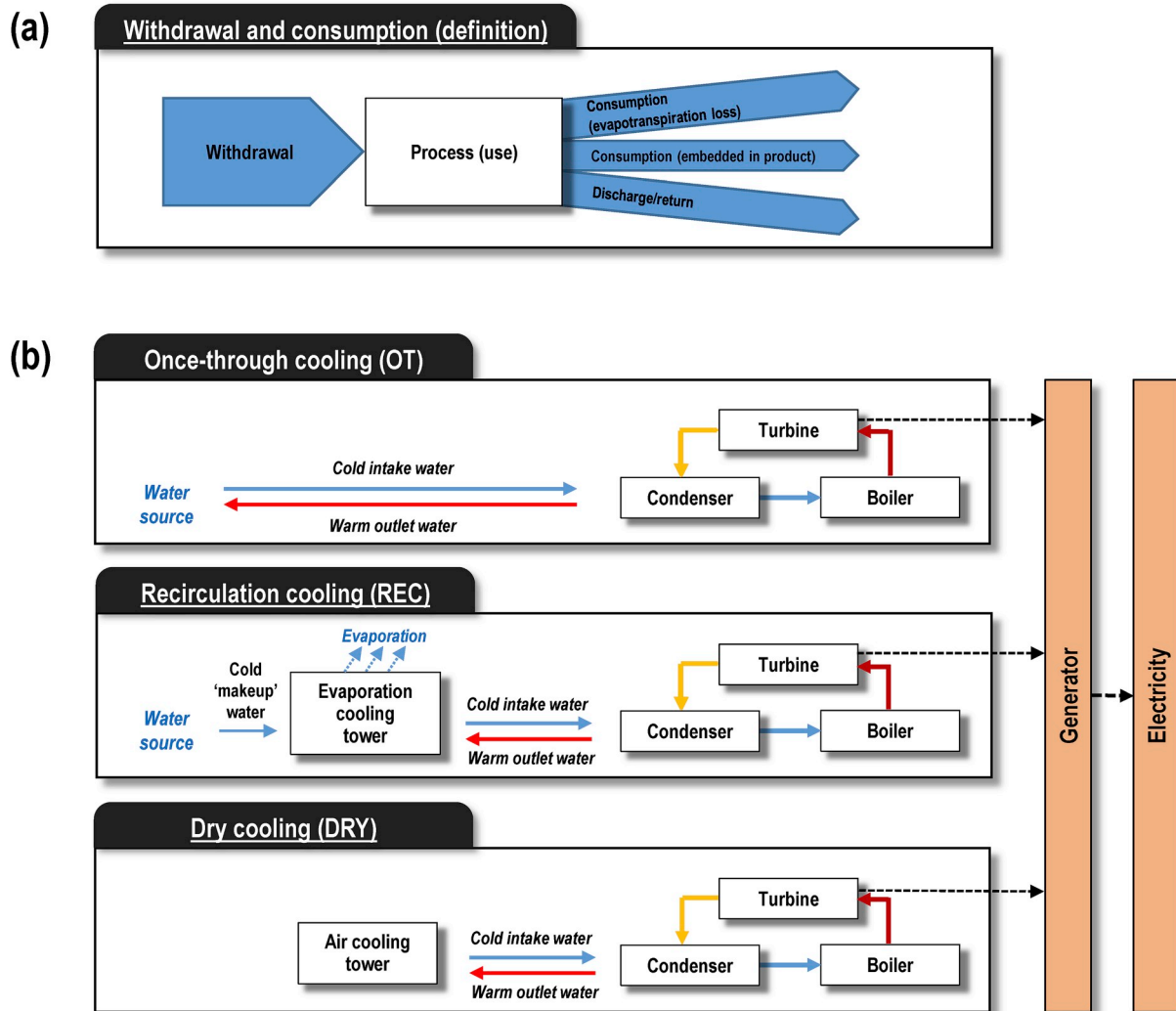


Fig. 1. Water withdrawal and consumption definition (a) and cooling technologies in thermal power plants (b).

water. Cooling of the closed loop on the other hand is very water intensive but also highly variable. In general the cooling of thermal power plant may be divided into four categories (Fig. 1): I) Once-Through cooling (OT), II) Recirculation/tower/pond cooling (REC), III) Dry cooling (DRY) and hybrid cooling (not depicted). The relative share of the different technologies is distinctly related to the availability of water resources and associated legislations. For example in the US the relative share of these different cooling technologies amounts to 43%, 56% (thereof 15% using cooling ponds) and 1% respectively [36]. OT plants generally employ water from adjacent sources such as rivers, groundwater, lakes (or the sea) and returns cooling water to its source (in a warmer state). Correspondingly, the withdrawal rate is immense for all energy sources (25,000–225,000 L/MWh) (Fig. 2) whereas the consumption rate is considerably less (50–2300 L/MWh) (Fig. 3). Newer plants rarely employ OT cooling. REC based plants where water is reused in a loop, and where cooling is employed by evaporation have considerably lower withdrawal rates of 550–10,000 L/MWh for tower based plants and 1100–91,000 L/MWh for pond based plants. Consumption rates on the other hand are found to be slightly higher than for OT based plants for all energy sources and towers/ponds combined due to the evaporation loss (360–3300 L/MWh). DRY based plants constitute a negligible share of the current global electricity generation (although on the rise with implementation examples from USA and South Africa) and use no water for cooling purposes, which is counterbalanced by lowered efficiencies

(2–5%) and higher costs (3–8%) depending on the local climate. Hybrid plants, combining cooling technologies, consume only about 20–80% of water volumes required by REC plants [28] and are seen as fundamental for reducing plant water consumption within currently available methods. Nuclear plants in general have lower efficiencies and therefore have the highest consumption and withdrawal rates for thermal plants but are also more flexible in the choice of location due to the higher energy density in the fuel and can therefore more often use sea water cooling. Secondary water usages vary between thermal plants and include, e.g., pollution/dust control, cleaning and staff usage. In general, coal plants have the highest secondary usage levels (approx. 350 L/MWh) [28].

2.1.2. Oil, gas and coal extraction

The water consumption in oil, gas and coal extraction vary in relation to mainly geology, type of recovery and state of the reservoir. The main consumption share relates to secondary and tertiary oil recovery. For secondary recovery, water is injected below the surface to boost the extraction rate and the level of depletion. For tertiary recovery (often called EOR), various techniques are employed to enhance extraction by reduced oil viscosities by, e.g., steam injection from a co-generation power plant. Secondary extraction (80% of oil production in the US) consume 802 L/MWh, whereas tertiary extraction (almost the remaining 20% of oil production in the US) consumes 505–1215 L/MWh [37]. Oil extractions in shallow oil sands generate consumption rates of 180–425

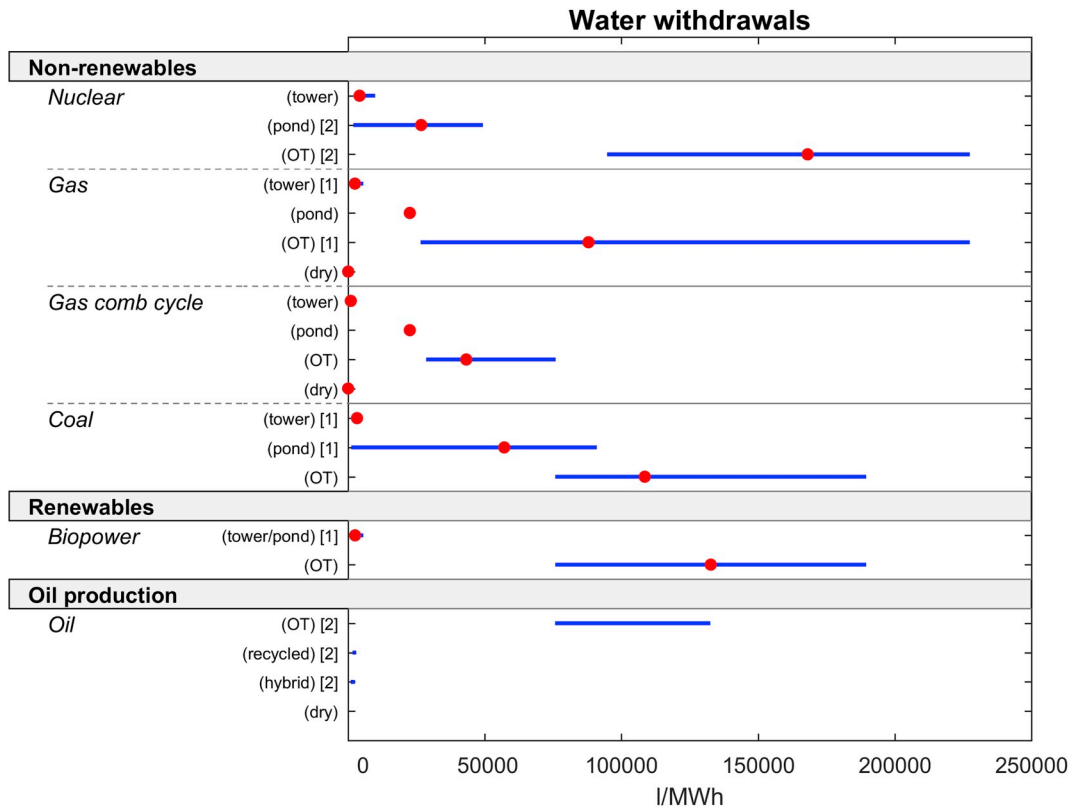


Fig. 2. Operational water withdrawal ranges (median (where available), min and max) from common or prospected future energy technologies based on a review of both peer-reviewed and grey literature. The references for Figs. 2 and 3 include: [1,21–24,28,34,35,37,46,51,102–110].

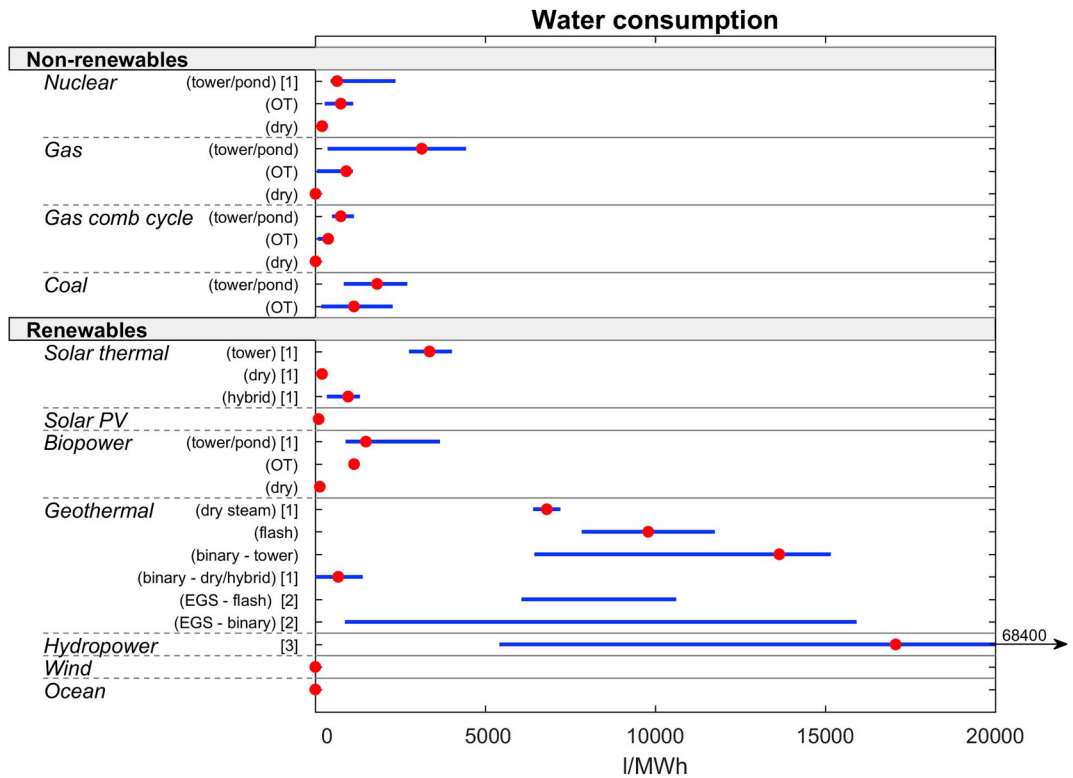


Fig. 3. As for Fig. 2, but for operational water consumption.

L/MWh (both mining and upgrading) [37]. Deeper deposits involve on-site upgrading with consumption rates of 25–210 L/MWh and is dependent on oil product and local geology. Water consumption from conventional natural gas extraction is negligible. Shale gas hydraulic fracturing has a limited water use of 17 L/MWh, but is applied very locally both spatially and temporally and is the subject of considerable environmental concerns [38]. Coal extraction involves consumption rates of 14–105 L/MWh for mining and washing and an added 43–90 L/MWh if transported by slurry pipeline [37].

2.2. Renewable sources

2.2.1. Biomass

Biomass used for liquid fuels in transportation and energy products is considered one of the key renewable energy sources to reduce the use of fossil fuels [39] while requiring minimal changes to current infrastructure and vehicles [40]. The true net biomass carbon footprint is however debated and dependent on the way it is implemented into the energy system [41]. An estimated 32 EJ (10^{18} J) of biofuels will be required globally by 2050 (27% of the envisioned world transport fuel) to reach the global energy-related CO₂ target of 50% below current levels [40]. A substantial amount of water is required in the cultivation of biomass, varying greatly with crop and region [42]. As an example, the volume ratio between water and ethanol produced from sugarcane in Brazil is 90:1, whereas the corresponding ratio is 3500:1 in India [43]. The water use can however vary substantially depending mainly on irrigation demands and corresponding evapotranspiration [44]. The water consumption in biofuel production is typically small compared to the consumption used for cultivation. More recently, second generation biofuels have been introduced, utilizing biomass otherwise not well-suited for food or feed or biomass from (upgraded) residues and/or waste. Second generation biofuels therefore support rather than compete with potential scarce future resources and food supplies and accordingly do not include equally high water usage levels, i.e. as they do not require the same degree of irrigation.

2.2.2. Geothermal electricity generation

Geothermal water consumption varies greatly with the type of facility. In general, there are three types of geothermal designs for steam resource locations at depths in a typical range of 50–3000 m [45,46]. I) The operation of dry steam plants employs hydrothermal fluids primarily in the form of steam directly connected to a turbine omitting only excess steam. II) Flash steam plants, which are more common, operate by ejecting hot (>180 °C) and pressurized steam into the turbine, sometimes followed by a second lower pressure turbine. These plants consume the largest amounts of water. Since the exploited water contains non-potable minerals, it can be debated whether the water consumption can be compared one-to-one with other electricity generation technologies. III) Binary cycle geothermal plants are of newer origin and operate by letting lower temperature water (below 200 °C) pass through a heat exchanger holding a fluid with a much lower boiling point (Organic Rankine Cycle). Here the geothermal water is reinjected, thus resulting in a much lower water consumption although tower based systems still require high amounts of cooling water (Fig. 3). For well depths of 3–10 km enhanced geothermal systems (EGS) are capable of exploiting the energy in some regions where hot water does not reach the ground surface. EGS operate by ejecting hot water at great depths, returning to the surface as steam powering turbines of either flash or binary type. For flash EGS, cooling water consumption is comparable to other flash usages. For binary EGS, the water temperature affects the water consumption as lower temperatures require higher flow rates, which is the reason for larger spread in consumption rates for binary EGS (Fig. 3). Thermal exploitation examples beyond geothermal energy include co-produced electricity generation (or direct heating indirectly facilitating energy savings) from oil and gas wells and lower-temperature thermal energy. For these technologies, the use of

binary techniques will contribute to lower water consumption rates.

2.2.3. Power generation from renewables

Water usage in hydropower electricity generation varies immensely and is highly dependent on the local climate, as the consumption is directly related to evaporation from the water reservoir storage and potentially net seepage, as opposed to direct turbine usage (5.400–68.000 L/MWh). The higher end of this range decisively constitutes the highest levels for all electricity generation technologies. Some studies [35] argue for neglecting the water consumption from hydropower due to the additional societal purposes of reservoirs such as flood control, leisure, irrigation and water supply. Wind, marine technologies, and solar PV have little or no direct water consumption related to electricity generation. They constitute a negligible fraction of the total water use compared to other energy sources, especially with regards to wind energy and ocean based technologies. The projection of ocean-based technologies vary between literature: 0.15%–0.5% of consumption/capacity in the EU by 2020 [47,48]. Solar PV electricity generation incurs a small water consumption used primarily for the cleaning of surfaces and panels (0–125 L/MWh). For comparison concentrating solar power (CSP) technologies with cooling have a substantial consumption (2800–4000 L/MWh), whereas dry cooling CSP consume much less (100–300 L/MWh). Hybrid CSP plants fall here in between. For water cooled CSP, a spatial mismatch between high incoming solar radiation (typically desert locations) and water availability is often seen. Further, CSP water is used for reflection mirror cleaning (75–150 L/MWh).

2.2.4. CO₂ capture, storage, and utilisation

CO₂ capture, storage, and utilisation technologies in combination with, e.g. conventional fossil electricity generation, represents a more recent development towards climate change mitigation in order to reduce the emission rates of GHG, whose main sources include electricity and heat generation, agriculture, industry, and transportation [18]. In general terms, the extraction of CO₂ emitted from electricity generation, the industry etc., is separable in two categories of either Carbon Capture and Storage (CCS) and Carbon Capture and Utilisation (CCU) - in combined terms referred to as CCSU. Considerable development is still needed for these technologies to be readily applicable [49]. With regards to water consumption, CCSU involves a range of processes and technologies where the capture share (as opposed to storage and utilisation) accounts for approx. 80% of the total CCSU water consumption [50]. Also, adding CCS increases cooling demands by approx. 25–140% per power plant [51].

2.2.5. Water recycling and waste water treatment

Employing recycling and waste treatment within water usages can offer savings in both water extractions and financially due to decreased pumping and distribution demands, although not directly linked to electricity generation. In general, the added energy required for waste water reuse is considerably smaller compared to the added energy related to extracting the same amount of water from other sources [52]. The extent and nature of water treatment depends on the proposed water usages. As an example, irrigation water could require lower mineral and biochemical standards than drinking water. Examples where water recycling could be implemented more comprehensively include electricity generation cooling, irrigation (agriculture and landscape), processing water in the industry, toilet flushing, construction, etc. Greywater has been mentioned as a potential source for recycling applicable for purposes of irrigation, indoor applications (toilet flushing), and heat reclamation (through household heat exchangers). Savings are very site- and application specific. A quantitative example include predicted energy savings of 0.8–1.3 kWh per m³ saved water and water savings of 220,000 m³ annually per plant (soft drink production in North America and Europe) after integrating recycling loops [52]. Desalination has been reported financially competitive in some regions,

and can become increasingly relevant with increasing water prices [53].

2.2.6. Emerging technologies and storage solutions

Energy storage has the potential to facilitate water savings by offering a higher degree of power system flexibility and therefore a better implementation of renewables into the energy system. Examples of potential larger-scale energy storage technologies include: I) Chemical storage of energy in the form of hydrogen and methane from excess wind and solar electricity generation, adding to a more efficient use of non-water consuming energy technologies (albeit using water for energy conversion). II) Compressed air energy storage (CAES) in e.g. salt caverns (sealing cracks and fissures) to produce turbine generated electricity in periods of high demands likewise adding to the energy system flexibility [54]. III) Pumped hydropower, involving pumping (using e.g. wind and solar energy in locations of abundant supply) of water to higher altitude reservoirs and utilizing a reverse release through turbines on demand [55]. IV) Thermal energy storage (TES) potentials are currently counterbalanced by high costs, material property and utilisation research but are regarded promising by implementation in CSP plants through molten salt and industrial waste heat [56]. These storage technologies are however immature and costs would need to decrease before a more full implementation.

3. Water resource data for water-energy nexus studies

Examples of freely available water resource data relevant for global and regional scale energy nexus studies is described below and summarized in Table 1.

Several data sets on river discharges exist on a global level. The **Global Runoff Data Centre (GRDC)** [29] holds data on river discharge on a global scale from an approximate 9000 stations dating back to 1806 down to daily resolution. **FRIEND** is another river flow database operated by UNESCO [57] consisting currently of 162 countries divided into

eight regional sub-sections such as “EURO FRIEND”. In FRIEND, a certain overlap of data with GRDC and EWA (addressed below) is seen. **RivDis** is a global and long-term (1807–1991) river discharge database worth mentioning however with no continuous updating [58]. The **European Water Archive (EWA)** on river flow and catchment characteristics exemplifies a regional/continental scale data set, which has now been fully integrated into GRDC [59]. The **HCDN** data set, holds information on US streamflow from 1659 sites for the years 1874–1988 [60]. The **GTN-H** initiative aims at linking existing networks and data centres providing data and information on hydrology on a global level [61]. This includes for example hydrological data from the GRDC. **CORDEX** (The Coordinated regional climate downscaling experiment) offers access to regional climate model data output on a global level, based on 14 sub-domains, for historical and future periods [62]. **CORDEX** data resolutions are 12.5–50 km, in time steps down to 3-hourly. Relevant data for water-energy nexus studies include basic water balance variables such as precipitation, evaporation/transpiration, runoff components as well as wind, temperature, radiation (e.g. for solar energy potentials) etc. (see Fig. 4). The **Aqueduct** dataset holds 12 global indicators of water quantity, water variability, water quality, public awareness of water issues, access to water, and ecosystem vulnerability as well as grouped risks and scores based on these [63]. The data are based on basins (as opposed to e.g. gridded data) and holds 25010 basins and sub-basins in its current database (shape-file). The **GEOSS Portal** is an initiative with data from multiple provider institutions and affiliations on a global level maintained by the European Space Agency with the aim of a user-friendly map-based GUI and data portal [64].

On a European level, the **European Environment agency (EEA)** provide open data on a range of water resource related variables and indicators [65], including on the use of freshwater resources (previously; the water exploitation index) accounting for both the level of renewable water supply and exploitation on a monthly basis since 2002. The EEA database also holds water related information on pollutants,

Table 1
Examples of larger scale water resource data.

	Name	Association	Content	Temporal information	Reference	Data availability*
Global	GRDC/ FRIEND	WMO/UNESCO	Discharge, 9252 stations (2016)	1806–2016 (61% daily) 162 countries	[29,57]	Free
	RIVDIS	Supplied by Oak Ridge National Laboratory	1018 stations	1807–1991, monthly	[58]	Free
	GTN-H	WMO/Global Climate Observing System (GCOS)	Network of hydro-data, observations and products. Data: Precipitation, river discharge, water quality, groundwater etc.	Varies	[61]	Network dependent on other databases
	CORDEX	World Climate Research Program (WCRP) project supported by WMO, UNESCO, etc.	Regional climate model output (14 domains). Historical and future (RCPs). Variables: Precipitation, evapotranspiration, runoff, etc.	3hourly-monthly	[62]	Free
	AQUEDUCT	World Recourses Institute (WRI)	Indicators of water characteristics (basin based)	Historical and future (decadal, RCP based)	[63]	Free
	GEOSS Portal	Maintained by European Space agency (ESA)	Numerous data sets and providers User-friendly map based GUI	Several sources	[64]	Free
	WATCH	EU project (many partners)	Multiple global hydrology forcing and output data	1901-2100 3hourly-monthly	[67]	Free
Regional/ continental	EWA	Non-governmental and non-profit organization with member organizations	Discharge, 4093 stations (2014), closed hereafter. Suppliers urged to support GRDC instead	99% of records are daily	[29]	Free to use (through GRDC)
	EU water framework	European Environment Agency (EEA)	Water stress conditions across EU (indicator based). Topics include e.g. quality, quantities, emissions, floods, wastewater, groundwater, management, abstraction, hydropower, catchments/rivers (ECRINS).	2002–2014 (monthly)	[59]	Free
	EUROSTAT	The European commission	Freshwater data on e.g. wastewater, infrastructure, sewage, pollution, treatment.	Varying periods (often yearly resolution)	[66]	Free
	HCDN	US Geological Survey (USGS)	Discharge	1874–1988 (daily)	[60]	Free

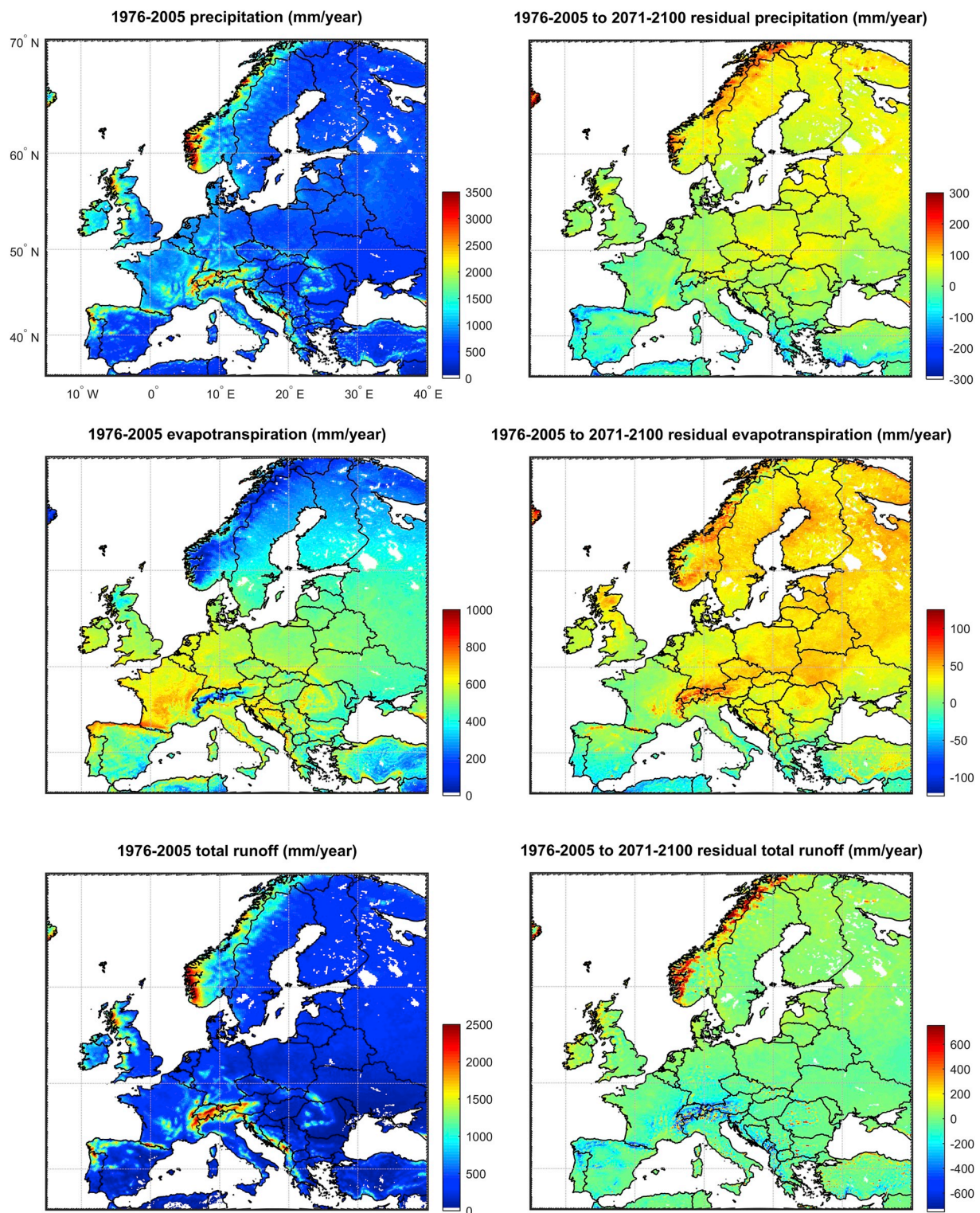


Fig. 4. Historical and projected future water (and climate) data from the CORDEX database [62]. See the Application section for description.

quality, quantity, emissions (to surface waters), historical floods, wastewater, groundwater/aquifers, management plans, abstraction, hydropower, catchment and rivers (ECRINS) and ecology (regions). Also on a European level, the EUROSTAT database includes a combination of water and energy information [66]. For the former these include water resources, (per year, long-term average), abstractions by origin (fresh surface water & groundwater, other sources) and purpose, water use by supply scheme and by economic activity group, connection rates to

wastewater treatment by type and level of treatment, wastewater treatment infrastructure, sewage sludge and aquatic pollution by source and discharge by type of treatment.

In addition to the abovementioned (longer lived) initiatives and data centres the collection, creation, and distribution of water resource data have also been a core part of several research projects like the WATCH project [67]. WATCH comprises a relevant water resource database to be employed in water-energy nexus studies under climate change

conditions as the data include both meteorological forcing data for hydrological model applications as well as model output. The forcing data include both a 20th century data set (ERA-40 reanalysis forcing, [68]), a 1979–2012 data set (ERA-Interim forcing [69]), and a projected 21st century data set based on three global climate models (GCMs) and the IPCC climate scenarios B1 and A2. The model output data include 20th century hydrology model/land surface model output for nine models and nine variables and 21st century output where each hydrology model is driven by future scenarios.

4. Electricity and energy statistics for water-energy nexus studies

Data from the energy domain that are relevant for water-energy nexus studies at a global or regional level are listed below and summarized in Table 2. As indicated, most data sources are freely available.

International Energy Statistics published by USEIA (U.S. Energy Information Administration) [70] has a global coverage with a detailed division of electricity generation technologies. The data includes export, import, domestic consumption and losses, the temporal aggregation is yearly (from 1980) while the smallest geographical entity is country level. The Renewable Energy Source of Information (Resource) platform [71] published and maintained by IRENA (International Renewable Energy Agency) provides global annual electricity generation from renewable sources (from 1980) aggregated into 6 technological types (hydro, bioenergy, geothermal, marine, solar, wind). The data can be aggregated into regions (continents, Eurasia, Middle East and Central America and the Caribbean). **DataBank** [72] published and maintained by the World Bank is an analysis and visualization tool containing compilations of time series data on a variety of topics there among electricity generation data based on the World Development Indicators database. The data are a national level, in yearly resolution (from 1967), and aggregated according to input fuel (hydro, natural gas, nuclear, oil, coal and renewables without hydro). Countries can be aggregated according to geography, income, size, etc. The **International Energy Agency's** (IEA) Monthly Electricity Statistics [73] holds electricity generation and trade data for member countries of OECD aiming to report up-to-date and consistent information from recent months. It also provides annual data (from 1973) for previous years and year-to-date indicators at a country level as well as in organizational and regional groupings. For a paid subscription, the amount of available data on a country-level basis increases significantly. **OECD Data** [74] published and maintained by OECD contains annual electricity generation for OECD countries. The only differentiation is between nuclear and not-nuclear technologies. The historical values start in 1973. **Global Energy Statistical Yearbook** by energy consulting company Enerdata [75] is a free online application, holding annual electricity generation, consumption, trade and share of renewables in electricity generation for 186 countries (2000–2015) however with no information on electricity generation technologies.

A few databases have a global coverage of detailed geographical and techno-economic data on specific power plants. An example includes the **World Electric Power Plants Database** by Platts [76] providing detailed technical boiler type, generator type, temperature at the turbine, and geographical coordinates of plant locations etc. The **Power Plant Tracker** by Enerdata [77] contains annual performance indicators such as electricity generation and efficiency. Both of these two databases require membership. **Power Plants registered at Enipedia** [78] represents an open-source version of a global power plant register containing location and technical data on individual plants such as capacity, fuel used, cooling method, efficiency although data are often missing or incomplete.

An example of regional level energy data includes the **Environmental Statistics and Indicators database** [79] by the Economic Commission for Latin American and the Caribbean holding annual primary and secondary energy for the 29 countries of the region (1970 and

2014). At smaller geographical scales data are often available with finer geographical and temporal aggregation. For example, the **ENTSO-E Transparency Platform** (European Network of Transmission System Operators for Electricity) [80] holds data on e.g. hydropower reservoir filling rates, hydro plants, aggregated hourly production rates, and hourly generation for specific units (country, control area, and bidding zone level for EU and 13 neighboring countries from 2014). The “**Renewables.ninja**” web tool [81] provides hourly PV and wind capacity factors for EU-28, Norway and Switzerland for the period 1985–2014. **EUROSTAT** offers data on e.g. energy supply, transformation, consumption, imports/exports, market/prices on a monthly basis [66]. The **EMHIRES** (European Meteorological High resolution RES time series) dataset published by the Joint Research Centre [82] contains solar PV and wind data for EU-28, Norway, Switzerland and the non EU countries of the Western Balkans. The time series cover: I) hourly solar power capacity factors at country level, bidding zone level, NUTS 1 and NUTS 2 level, II) onshore and offshore wind power capacity factors at country level and III) wind power capacity factors at bidding zone, NUTS 1 level and NUTS 2 level without aggregation into onshore/offshore (all 1986–2015). **Open Power System data** is an effort towards collecting, processing and holding free energy data from multiple sources of dissimilar nature onto a shared database structure [83]. The data include power plant information, generation capacities, pricing, house hold data etc. at the EU level. At the country level, e.g., energy statistics are generally provided by the national energy authorities and there are datasets which collate such data, e.g. the IEA Energy Statistics and Balances [84]. For example in Denmark, Danish transmission system operator, **Energinet.dk**, publishes hourly electricity generation profiles by type of plant [85]. The Swedish transmission system operator, **Svenska kraftnät**, publishes hourly electricity generation profiles by type of plant [86], while the Norwegian power system operator, **Statt-net**, publishes hourly electricity generation profiles by type of plant for four Nordic (Denmark, Norway, Sweden) and three Baltic (Estonia, Latvia, Lithuania) countries [87].

5. Application

This section presents three examples of how the data presented here can be applied to nexus studies.

5.1. Large-scale hydro-climatological application

This example exhibits the extraction of three main variables from the water balance from a mini-ensemble of regional climate models (RCM) from the CORDEX database [62] over Europe in 12.5 km resolution (Fig. 4). The variables include precipitation, evapotranspiration and total runoff and are plotted as yearly mean levels for the historical period of 1976–2005 and as residuals between the historical period and 2071–2100 based on the RCP4.5 scenario. The models are driven by global climate models (GCM) at the domain boundary and include the MPI-ESM-LR/CCLM4, EC-Earth/RCA4 and EC-Earth/RACMO22 models. This type of data is relevant to larger-scale water-energy nexus studies by providing a robust realisation of future trends for hydrological and meteorological variables with a high influence to the energy system. At the scales shown, a projection on the direction of trends, their magnitude and timing can be estimated. For more local predictions on e.g. stream flow, groundwater levels or water temperatures, smaller scales hydrological models need to be applied.

5.2. Water use by electricity generation plants

For this example, the electricity generated in EU28 is extracted per energy source from Ref. [66] (Fig. 5, left). Then, by using knowledge on the water withdrawal rates for each energy source, cooling technology (and their distribution), and the estimated freshwater/sea water shares on a EU28 level the corresponding freshwater withdrawals rates were

Table 2

Examples on major energy statistics databases organized according to geographical coverage, geographical aggregation, temporal aggregation, and/or fuel/technology aggregation.

	Name	Association	Content	Temporal information	Reference	Data availability*	Link to water
Global	International Energy Statistics	U.S. Energy Information Administration (US EIA)	Electricity generation per technology type and fuel and power plant data	Annual (1980–2015)	[70]	Free to use	Electricity generation from thermal and hydropower plants
	Resource (Renewable Energy Source of Information) DataBank	IRENA	Electricity generation per technology type	Annual	[71]	Free to use	Electricity generation from thermal and hydropower plants
		World Bank	Electricity generation by fuel	Annual (from 1967)	[72]	Free to use	Electricity generation from thermal and hydropower plants
	IEA - Statistics	International Energy Agency	Electricity generation by fuel	Monthly	[84]	Some is free - elaborate data upon subscription	Electricity generation from thermal and hydropower plants but also technical and economic data and annual electricity generation
	OECD Data	OECD	Electricity generation divided into nuclear and non-nuclear	Annual	[74]	Free to use	Electricity generation from nuclear plants
	Global Energy Statistical Yearbook	Enerdata	Gross annual electricity generation	Annual	[75]	Free to use	No
	The World Electric Power Plant Database	PLATTS	Technical data and geographical coordinates for specific production units	Updated quarterly	[76]	Paid subscription	Technical data
	Power Plant Tracker	Enerdata	Technical data and geographical coordinates for specific production units	Annual	[77]	Paid subscription	Technical and economic data and annual electricity generation
	Power Plants register	Enipedia	Annual electricity generation and geographical coordinates for specific production units	Annual	[78]	Free to use	Technical and annual electricity generation
	Energydata.info	World Bank Group and partners	Primarily geographical data on transmission grid expansion, power plant location, renewable energy potential and population demographics	Varying Hourly to annual	[100]	Free to use	Varying
Global power watch	World Resources Institute (WRI) and partners	Under development data platform with georeferenced powerplant specific data	Likely annual	[101]	Free to use	Geo-referenced electricity generation that can enable linking to cooling water bodies and similar	
Global Energy Observatory	Open community, lead by Los Alamos National Laboratory	Annual electricity generation by plant, country and fuel type. Covers 40–95% of installed EU capacity	Annual	[88]	Free to use	Water withdrawals and consumption possible to fill in, but are often left blank.	
Regional	Environmental Statistics and Indicators	Economic Commission for Latin America and the Caribbean's (ECLAC)	Water use for electricity generation and total electricity generation per country	Annual	[79]	Free to use	Hydroelectricity generation
	ENTSO-E	ENTSO-E Transparency Platform	Electricity generation and hydro reservoir inflow on country, control area and bidding zone levels	Hourly/weekly	[80]	Registration required	Electricity generation aggregated into 20 technology types and hydro reservoir inflow
	Renewables.ninja	Renewables.ninja web tool	Solar and wind capacity factors	hourly	[81]	Free to use	Only if cooling of PVs is considered
	EUROSTAT	The European Commission	Energy supply, transformation, consumption, imports/exports, market/prices etc.	Monthly	[66]	Free to use	Electricity generation per fuel source
	EMHIRES	EC JRC	Solar and wind capacity factors	hourly	[82]	Free to use	Only if cooling of PVs is considered
Open Power System Data	Several partners and original data sources	Conventional and renewable power plants, generation capacities and pricing	From 15min	[83]	Free to use	Indirectly only (by technology based assumptions)	
Country level (examples)	Energy data	Energinet.dk	Electricity generation by plant type	Hourly	[85]	Free to use	Electricity generation from thermal and hydropower plants
	Production statistics	Svenska kraftnät	Electricity generation by plant type	Hourly	[86]	Free to use	Electricity generation from thermal and hydropower plants
	Nordic power balance	Stattnet	Electricity generation by plant type	Hourly	[87]	Free to use	Electricity generation from thermal and hydropower plants

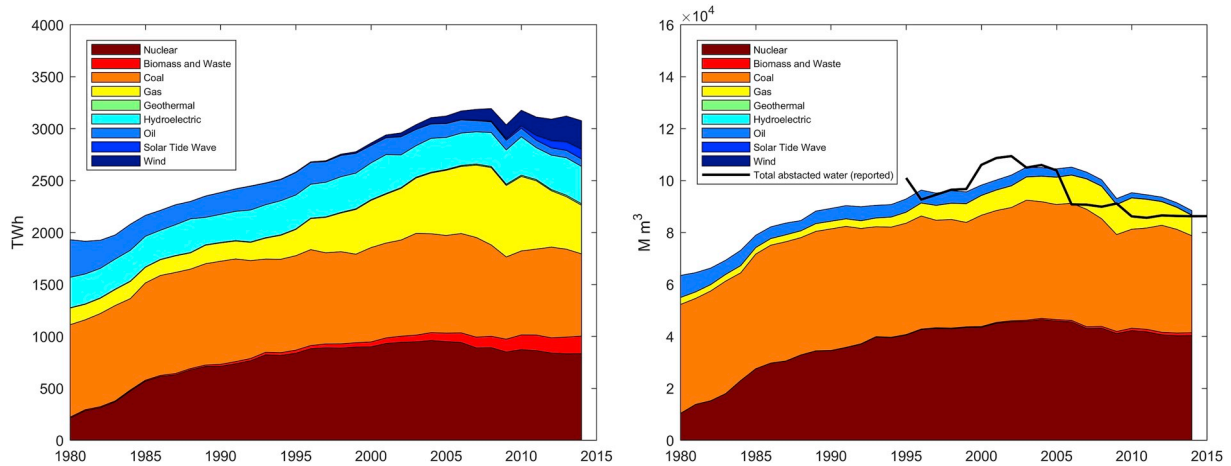


Fig. 5. Left: The total generated electricity (TWh) for all EU28 countries for different fuel sources for 1980–2014 [66]. Right: The estimated water withdrawals rates per energy source calculated by using the generated electricity per energy (shown left) and literature estimates on median water withdrawal rates (Fig. 2) for each energy source and (cooling) sub-technology as well as the estimated freshwater/sea water shares. Also shown is the reported freshwater abstractions here acting as validation data. See the Application section for a description of calculation steps.

then calculated (Fig. 5, right). This was particularly interesting since the reported freshwater abstractions were publically available [66] acting as a validation of the method and showing highly similar results. The amount of gap filling needed for reported abstractions (using running means) increases for earlier data, and levels prior to 1980 is therefore now shown here (some countries have data from 1970). The data on the distribution of cooling technologies and freshwater/sea water usage were estimated from Refs. [78,88]. The same calculations could have been done for water consumption, as shown in Fig. 3, although a similar dataset of reported consumption rates (which likewise could act as validation data) was not found available in the process of conducting this study.

5.3. Detailed water usage at plant level

At a very local scale, the final example highlights a step towards the level of detail in water-energy nexus data as urged by the authors of this study. Here more detailed monthly withdrawal and consumption rates for a range of selected US power plants are visualized (Fig. 6) for the 2014–2015 period as available from Ref. [70]. The plants have been

selected to reflect a range of energy sources (coal, nuclear, gas, wood/waste/biomass, and municipal solid waste), and cooling types (OT/REC etc.). From the figure it can be seen that the plants in relation to their cooling technology exhibit a water use similar to the levels in Figs. 2 and 3, but also that there is a high temporal variation and seasonality and which therefore supports the argument of employing a high detail in the spatio-temporal linkages to water and meteorology data in nexus studies.

6. Discussion

In the preceding sections we present current estimates of operational water usage in electricity and fuel production, and we have summarized some of the key data sources that currently describe water resources and electricity and fuel production. What is evident is that the combined domains of water and energy, at least at the spatial scales we address above, are poorly covered by the data sources that are currently available for analyses of the water-energy nexus. This includes lack of detailed data sets describing, e.g., the water use by the energy sector in a spatio-temporal resolution adequate for linkages to water resource and

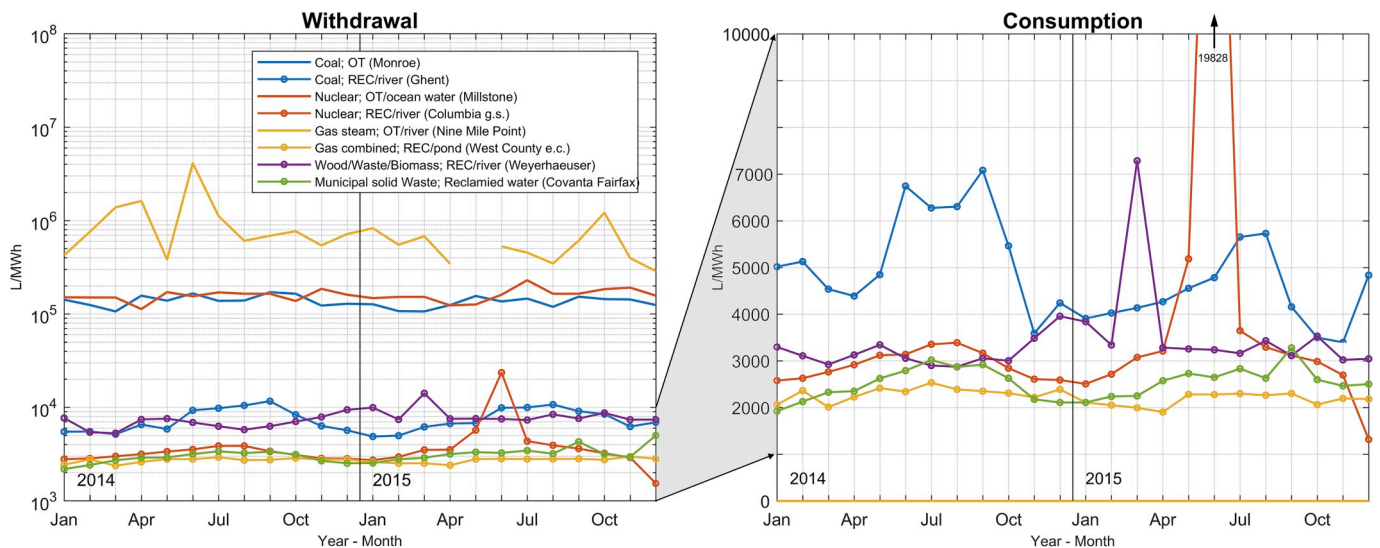


Fig. 6. Withdrawal and consumption rates (L/MWh) for selected US power plants of varying fuel sources (coal, nuclear, gas, wood/waste/biomass and municipal solid waste) and cooling types (OT/REC etc.) for 2014–2015 [70].

energy system models. Thus, most energy data of high temporal resolution omit water use linkages entirely, whereas those that include information on water uses tend to be aggregated at annual scales and therefore do not capture spatio-temporal details, e.g. seasonal variations, which are important for managing most water/hydrology systems. Ideally, such details would encompass information at the plant level such as the intake/re-ejection amounts, time/space information, quality (temperature/chemistry), source (river name, location, and aquifer depth etc.). With the notable exception of the aggregated annual data collected by the EEA and EUROSTAT, water uses by the energy sector are also not generally included in most of the readily available data on water resources (cf. Table 1). A key reason for the success in collecting data within the hydrological discipline such as WATCH [67] and especially within the climate disciplines such as CMIP5 [89] and CORDEX [62] is likely related to incentives: These efforts are mainly related to research on model development, climate change and/or impacts and there are few arguments towards not participating apart from lack of funding to do so. And since these efforts are based upon research, no commercial interests are at stake: Properly obtaining information from the database requires a high degree of specialised knowledge. Within energy data, multiple commercial interests are involved and the total turnover within the energy sector is estimated to equal 2e12 EUR [90] in the EU alone. Legislation or funding from central bodies could push efforts towards more, free and aligned data but politics and finance are beyond the scope of the present study. Parallel to the need for more detailed water use-energy sector data, is the need for an updated and sustained hydro-climatic framework facilitating open access data from large-scale hydro- and climate models (separately and combined), where existing models are driven by the same forcings, historically and for future scenarios. The framework and available data may well be much along the lines of e.g. CORDEX [62] and WATCH [67] initiatives although with a more sustained effort than the latter and with more recent future scenarios. This would enable reasonable comparison grounds and hydro-climatic ensemble studies much along the lines of what is often seen in climate model research [91] thereby allowing for a range of research aspects covering hydrological variability and extremes, and to obtain more trust in future projections.

The alternative to detailed in situ data on water usages in electricity and fuel production is to use values based on current estimates (see above) of operational water usages as a means to bridge the gap between water and energy systems. For quantitative nexus studies however, this approach is likely to introduce considerable uncertainties due to the large spans in, e.g., recorded water usages for individual power plants (see Figs. 2 and 3), as caused by not only variations in technology usages but also dependence on regional hydro-climatic conditions, local regulations, plant optimization, incorrect/inconsistent reporting, etc. Likewise, data of adequate quality are found to be plentiful for some electricity generation technologies, whereas in other cases such data are scarce, such as for several technologies that are currently considered as part of shifting from more traditional fossil GHG emitting electricity generation technologies to other more sustainable forms [23].

Another challenge is seen in the conditions for the collection and availability of data on water use by the energy sector which differ immensely between countries and regions, which can constrain the applicability and comparability of estimated water uses. As an example, historical records from the US has significant gaps in terms of missing information related to critical energy technologies (e.g. nuclear and gas combined cycle) despite otherwise adequate data availability [23]. Historically, the lack of reliable water use data in reviewed sources may even reflect the general challenge of water being an undervalued resource [92].

On top of the spread in estimates of the water use in electricity and fuel production, as introduced by natural, geographical, technological and hydro-climatic variations, discrepancies in definitions and calculation/measurement methods can also constitute a significant challenge for data collection in the context of nexus studies. As mentioned above,

assessments of water use in hydropower production can, depending on its definition, range from negligible to exceeding that of all other electricity generation technologies. This depends in part on how water evaporation is shared among multiple uses of a reservoir and also on how evaporation is calculated ranging from simply dividing the total reservoir evaporation with electricity generation to only accounting for net evaporation (i.e. compared to the water balance prior to reservoir construction) [93]. Across different fuel types the differences in water footprint definitions in general make reported estimates/water consumption rates even less comparable. This is particularly evident when comparing the generally reported water footprint of electricity generation with the footprint from the production of liquid biofuels. These are some of the most well studied fuels in the water-for-energy literature, yet they are typically not reported in a consistent way, which is comparable and ready to be incorporated in an energy systems analysis. In summary, the development of methodologies for comparing different types of reported water use factors should be in high demand and is poorly covered by the existing scientific and technical literature.

So far we have only addressed the challenges of carrying out water-energy nexus from a general perspective of quality and representability. However, integrated assessments of the water-energy (and food) nexus, including connections to eco-systems, livelihood, security, etc. [94,95] range from pieces of policy discussion [11,96] to complex quantitative modelling of management and policy scenarios at different scales [5] using a variety of methodologies and tools as highlighted by Ref. [97]. This means that the data requirements for different kinds of assessments also vary extensively. Thus, for many real-life applications the estimated water uses and data sources discussed above could be entirely adequate for mostly qualitative and/or semi-quantitative nexus assessments. For national policymaking, the values of taking an integrated approach has been demonstrated by e.g. Ref. [5] Regional cases of stakeholder conflicts across the water-energy nexus has been addressed in Ref. [98] while [95] outline a methodology for stakeholder participation in assessments of transboundary nexus challenges.

Conversely, recent developments in integrated assessment type modelling [5] represent the entire water-energy nexus chain as a series of highly complex and interlinked numerical processes, prescribing information on human and natural systems and their interactions, which requires or even supersedes the level of detail and/or precision mentioned above. This is especially true at the regional and/or basin scale, which is often the natural focus of water and energy systems management, and consequently also in the centre of deliberations towards ensuring the sustainable use of resources across the water-energy (and food) nexus. Modelling the dynamic linkages between water and energy at this scale evidently requires combining fully distributed spatio-temporal models of both water and energy systems, potentially addressing both present and future climatic and socio-economic conditions. For water alone, this would require modelling of water flows and storages in spatio-temporally distributed sub-components of both surface- and groundwater, involving aspects of vegetation from land surface models, forced by data from, e.g., atmospheric or ocean models or even dynamically coupled climate-hydrology models [99]. For energy, this would encompass integrated spatio-temporal modelling of production levels, technologies, markets, trade, and demand. Further, linkages to other sectors such as agriculture, food, industry, cities, etc. would need to be accounted for. Presently, there are few if any models, which represent the water-energy nexus at the very high resolution and complexity suggested here. However, there is no doubt that ongoing research efforts within numerical modelling of both physical, economic, and social science dynamics, the increasing computational resources available and the demand for reliable simulation tools for testing management scenarios and policy initiatives will continue to advance the field of numerical water-energy nexus studies. Hence still more (complex) processes will be added to the model systems either through 'hard' or 'soft' linking to represent the different nexus systems and their broader context. Also, for this aim it is imperative that improved data

sources are collected and shared. Already a decade ago [31] highlighted this importance and proposed efforts to facilitate such data sharing. As the need and value for such data, e.g. in terms of integrated planning and tool development has only increased since then, the need to overcome data sharing obstacles such as proprietary, business or security concerns is likely even more important today, and in itself present a major challenge in terms of studying the intricacies of the water-energy nexus in a changing world.

7. Conclusions and recommendations

In this paper we highlight some of the main challenges related to data availability when analyzing the water-energy nexus. For this aim we have assessed current estimates of operational water usage in electricity and fuel production for different energy technologies, and we have also considered the currently available data on the state of water resources (present and future) and electricity and fuel production at different scales. In general we find that there is a substantial gap in the availability, access and quality of proper regional and global data in order to facilitate detailed quantitative analyses within the water-energy nexus. Thus, there is a great need for improving the current quality and availability of historical water use data (withdrawals and consumption, or stocks and flows depending on terminology) for virtually all major sectors and sub-sectors related to the water-energy nexus, including at matching spatio-temporal scales relevant for linking water and energy systems. In addition there is also an urgent need for improved standardization of formats and data collection methodologies across different uses of the data (research, operations, planning, etc.), which in most cases presently are incompatible. Advances in this regard would immensely aid not just the validation of methods and models but would also contribute to an improved confidence in nexus assessments in support of management procedures and policy goals related both to current and future conditions. On top of the above, the standardization should also encompass future projections and scenarios for highest possible consistency similar to those of other multidisciplinary studies.

Author contributions

M.A.D.L. conceived the idea, processed the data and led the study and writing. S.P. and R.E.E. contributed to data synthesizing. All authors contributed to discussions and the writing of the paper.

Declaration of competing interest

The authors declare no competing interests.

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