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Troubled waters: Estimating the role of the power sector in future water scarcity crises

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ABSTRACT

One of the effects of climate change is on freshwater availability. The widespread drought in the summer of 2022 impeded access to freshwater, putting into question the reliability of the current and future energy generation and evoking concerns of competition of different industries for water. In response to climate change, energy transition scenarios represent pathways to a more sustainable energy system, but often overlook the water footprint of the energy sector. Therefore, this study uses machine learning for the identification of thermal power plants' cooling systems to estimate the water footprint of the current and future energy system using six energy transition scenarios. It is built on published data on thermal power plants announced globally, with a total capacity of 3277 GW, which are planned to be installed between 2020 and 2050. The results demonstrate that the water consumption of the global power sector may increase by up to 50% until 2050, compared to the 2020 level. The findings also emphasize that every new thermal power plant installed in the future will be associated with a higher average water demand per unit of generated electricity. Hence, the rising stress on water systems becomes another argument supporting the transition towards renewables.

1. Introduction

Climate change is also a water change, because the effects of climate change are strongly felt through changes in freshwater availability, its disrupted supplies, and exacerbated water scarcity [1,2]. Since 2012, "water crisis" was constantly included in the Top-5 Global Risks by Impact in the yearly Global Risks Report released by the World Economic Forum (WEF) [3]. Even according to very modest estimates, already in 2017 about 47% of the global population (or 3.6 billion) lived in areas that suffer from water scarcity at least one month every year [4]. This is the result of a constantly increasing demand for water, food, and energy of a growing population as well as the economy, and the depletion of water resources [5]. The global power sector is currently the second largest consumer of freshwater resources after agriculture. In particular, a considerable amount of water is consumed (evaporated) in hydropower generation, and in thermal power plants (coal-, gas-, oil-fired and nuclear) for cooling. According to some estimates, the energy-related water demand can reach a level as high as 40% of the total water demand in a country [6].

Despite the environmental concerns reflected in various reports and countries' obligations to reduce carbon emissions in the power sector to tackle climate change, according to the information provided in the GlobalData dataset there are plans to commission at least 2.6 TW of new thermal power plant capacities worldwide by 2050 [7]. This projected increase in thermal power capacities globally will result in an increase in water demand for power generation. This may impose an additional pressure on the areas already suffering from high or extremely high water stress and worsen the competition for the already limited freshwater resources with other vital sectors such as agriculture and housing.

Generally, energy transition scenarios aim to demonstrate a pathway towards a more sustainable renewable energy system from a carbon emissions perspective. Yet, the water footprint of the current and future energy system in many transition scenarios is often overlooked [8,9]. Therefore, water scarcity and water demand should be taken into

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account while designing transition scenarios.

Several previous studies have approached this problem from different perspectives, timeframes and geographical scales. A wide range of studies exist for the United States [10], China [11], the United Kingdom [12], South Africa [13] and India [14]. On a regional level, studies exist for the European continent [15] and Middle East and North Africa (MENA region) [16]. A handful of studies project the future water demand on a global scale [17]. Some studies are focused on the estimation of the operational water use in the energy sector (when water is mainly used for cooling purposes or cleaning) [14], other studies [11, 16] employ a lifecycle assessment (LCA) approach which, in addition to the operational water use, considers water use associated with the foreground and background processes of the energy production (e.g., extraction of the fuel). However, the results of this LCA analysis should be treated with caution because an accurate allocation of the calculated water demand to water bodies may be challenging unless the extraction of the fuel, its treatment and its power generation processes are located in the same geographical area.

Studies that aim to predict the future water demand of the energy sector typically use aggregated capacity data for the water footprint projections (for instance, the study by Terrapon-Pfaff et al. [8]). However, this approach has two main drawbacks. First, it is difficult to quantify the uncertainty of the estimated values (due to their aggregated nature). Second, similarly to the results of the LCA approach, the water demand predicted using this method can neither be allocated to a specific power plant nor to a specific water body to analyze the potential consequences of the energy-related water abstractions on the availability of freshwater resources on the local-level.

Thus, the current knowledge gap is the lack of information on the current and future water demand on the individual power plant level and the future water demand on the level of the power sector as a whole. This gap implies that current water footprint analyses may be restricted by impeding the ability to trace the water demand to its origin, to track its development over time (inability to track the operation and decommissioning of power plant units), as well as to capture the uncertainty of the results based on the cooling technology of individual power plants and the estimation model. Apart from that, the availability of information regarding the current water demand of specific power plants is essential for designing future sustainable energy systems, especially in areas with significant water scarcity coupled with elevated power demand.

Hence, to address this information gap, in contrast to previously conducted studies, this study aims to assess the future water demand of the energy sector using the reported data on individual, announced and planned power plants globally. The water demand assessment is conducted from the perspective of water consumption and water withdrawal, with a special emphasis on the freshwater consumption and on the water consumption per unit of generated electricity. The estimates are presented for the time period from 2020 to 2050 for the entire power sector and for the global thermal power plant fleet separately. A focus of this study is on thermal power plants since they, in addition to a high water demand, have a large environmental footprint and, thus, should be phased out in the near future. In the study, we deploy a machine learning algorithm using the available historical power plant data to identify the most probable cooling technology of each individual future power plant unit, and, subsequently, to estimate its future water footprint.

This paper shows that currently planned power plants not only significantly delay a successful low-carbon transition, but they also significantly increase water consumption by the power sector. In addition, taking into consideration the geographically distributed water stress provides a clearer view of the impact of the power sector on the water systems at a local level. Therefore, the results of this study address two areas of research: Firstly, the projections of the total water demand add another dimension to the discussion of the sustainability of the energy transition scenarios. Secondly, they may provide a basis for enabling an effective water policy and planning on a country-level and globally.

The rest of the paper is structured as follows. Chapter 2 goes through the methods deployed over the course of this study, and Chapter 3 presents its' results. The study concludes with the discussion in Chapter 4, which puts the obtained results into the context of the global water crisis, and Chapter 5, where the conclusions are drawn.

2. Methods

2.1. Power plant data

The main source of power plant data for this study was the power plant database obtained from Lohrmann et al. [18]. This database contains information on 13′863 active thermal power plant units (coal, gas, nuclear and oil) exceeding 50 MW, which were installed globally from 1923 to 2015. In order to complement it with power plants that were installed during 2016–2020 and to obtain information concerning future power plants, we used the GlobalData database [7] to add 4′289 "future" power plants, which correspond to 3.3 TW of thermal power capacity. More information regarding the power plant data compilation process is provided in Section A of Supplementary Materials.

Many power plants in the compiled dataset (corresponding to 1.9 TW of thermal capacity) did not have information concerning their future commission year. However, this information is crucial for the assessment of the future water footprint of the thermal power generation. Thus, the next step was to assign commission years to individual power plants for which this information was missing in the initial database [7]. Section B of Supplementary Materials discusses the approach to assign commission years to individual power plants for which this information was missing in the initial database. Sections C and D of Supplementary Materials demonstrate the potential impact of this step on the presented water footprint estimates on the example of the results obtained for the Bloomberg New Energy Finance (Bloomberg NEF) scenario.

2.2. Cooling technologies of announced plants

Since the power plant database did not contain any information concerning the cooling systems installed in the announced power plants, the type of cooling needs to be determined. In this study, the projection of the cooling technologies utilized for individual power plants is based on a method deploying machine learning, which was developed and tested in a previous study [19]. Previous research highlighted the existing wide application of machine learning in water management [20].

The method applied in this study uses information on the technical characteristics of individual power plants to assign the cooling technology to each individual power plant. The variables *"Power plant capacity (total active)", "Fuel used in power plant", "Year Online", "Type of boiler"* are available from the power plant database for each specific power plant, *"Seawater-cooling"* was assigned to each specific unit, as discussed in Section 2.4 and the remaining information was obtained from open sources that corresponds to their specific location (such as "*Freshwater total, per country*", "*Seasonal water variability, per country*", *"Agricultural water withdrawal as percent of total renewable water resources of the country, per country"* – all obtained from Ref. [21], "*Water stress score, province*" from Ref. [22], *"Days of warm weather"* from Ref. [23], and other country-level socio-economic variables, such as the "*Corruption perception index*" – from Ref. [24], "*GDP per capita of the country*" – from Ref. [25], and "*Prices for electricity*" – from Ref. [26]. The selection of these variables for the cooling type assignment was based on a literature review of previous water-energy nexus studies and of reports on local factors influencing the cooling systems selection [32,33]. For example, some previous studies relied on the ratios of cooling system types in the region/country found in various literature sources [27,29]. Other studies identified cooling technologies using satellite images [28].

However, the majority of studies identified the type of installed cooling system based on power plants' proximity to large water bodies: to major rivers [30] and sea/ocean coastline [17,31].

The cooling technology assignment method combines the filter method (Pearson) correlation and the differential evolution feature selection (DEFS) wrapper method [34] to select features that are relevant for the cooling technology identification. It is a sophisticated approach for the selection of relevant variables that has demonstrated high accuracies for the assignment of cooling technologies in the previous study [19]. Next, the selected features are used in a K-nearest neighbor (KNN) classifier to assign cooling technologies to individual power plant units. The classifier was trained and cross-validated using the power plant database [18], which contains information on active thermal power plant units commissioned before the year 2015 globally, and using additional information. The training data was initially divided into a separate data set per fuel type to train fuel-specific models in order to achieve a better classification accuracy. Both the 5-fold cross-validation and the holdout split were applied with stratified random sampling to ensure that the training, validation and test sets all contain similar shares of the cooling technology classes (dry, inlet cooling, once-through cooling, cooling tower and pond cooling). Fig. 1 illustrates the flow chart of the classification model.

The set of features selected by the model for the cooling technology prediction using the KNN classifier as well as the calculated test set accuracies are presented in Section E of Supplementary Materials. The obtained test set accuracies are considerably higher than the reported accuracies of other previously used approaches for the missing value imputation of the cooling technology, which use aggregated capacity data and pre-determined shares of cooling technologies for the water footprint projections [35].

2.3. Type of water for cooling

The selection of cooling technologies (and their optimal design) implemented in individual power plants is influenced by the type of water (freshwater or seawater) available for cooling purposes [32].

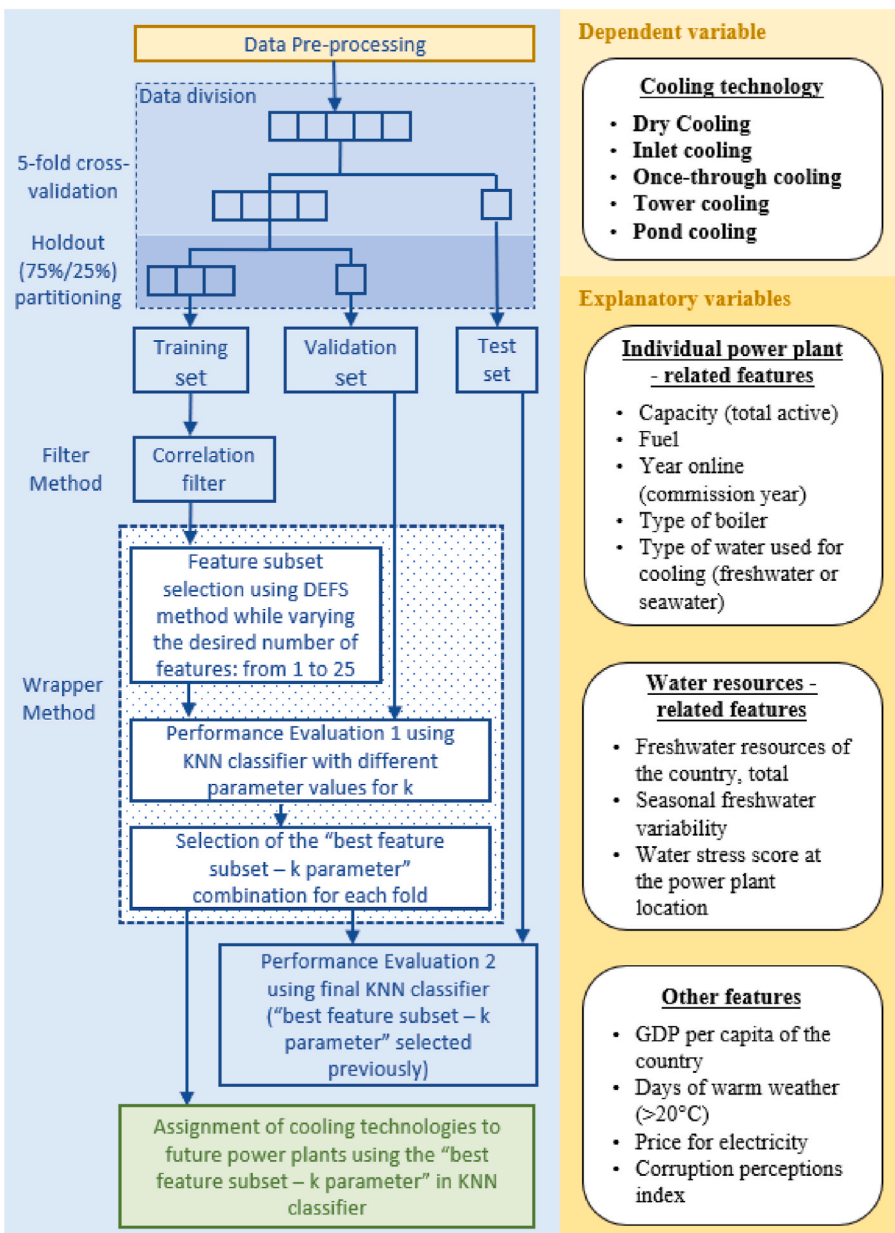

Fig. 1. Model for cooling technology identification using K-nearest neighbor (KNN) classifier, from Ref. [19].

Typically, power plant databases do not contain information concerning the type of water used for cooling. This information is usually available from the reports issued by the power plants operators for individual power plants. However, collecting this information from plant operators, especially for future (planned) power plants and on the global scale, is highly impractical, and for many of the power plants in non-transparent states becomes impossible. The GlobalData dataset [7] contains neither information concerning the type of water used by future (planned) power plants nor their exact location. To overcome this data limitation, in this study, the type of water for cooling was assigned to individual power plants using the current shares of seawater-cooled thermal power capacities obtained from Lohrmann et al. [18]. These shares were calculated using the results of a Geographic Information Systems (GIS) analysis performed in the study and represent the percentage of the country's current active thermal capacity that uses seawater for cooling purposes. Although this approach may add uncertainty to the results of the study, it was selected for several reasons. First, the shares of the seawater-cooled power plants in the generation mix of each specific country will likely remain unchanged in the future. This is based on the fact that thermal power plants are typically closely linked to the population/industrial centers (large power consumers), whose location (in regard to the nearest water bodies) will not considerably change in the next decades. Secondly, previous studies deployed this approach of applying coefficients of the seawater use in thermal power generation (for instance, in Davies et al. [17]).

2.4. Assessment of the water footprint

The water footprint (WF) of individual power plants for each specific year was calculated using Equation (1).

$$WF = WUI \times Cap \times FLH \quad (1)$$

where WUI – water use intensity factor, in m^3 of water per MWh of generated electricity, Cap - active capacity of individual power plants, it is given in megawatts, and FLH – full load hours of power generation in hours. In subsequent steps, the calculated annual water footprint of individual power plants was aggregated on country-, region-, and global-levels.

The assessment of the water footprint of individual power plants was conducted through the calculation of their water withdrawals and water consumption. Water withdrawal refers to the total amount of water that is taken from a water source, and water consumption is the difference between water withdrawal and the amount of water returned to the water source. It is noteworthy that the WUI factors vary for water withdrawal and water consumption.

The use of WUI factors for the water footprint estimation in the power sector is an effective and a widely used approach. For this study, we applied the WUI factors from Macknick et al. [36]. Although these factors were initially derived using empirical data records of the water use in the United States, Macknick et al. [36] suggest that they could also be applied for water demand estimation for power plants located in other geographic regions [36]. Lohrmann et al. [9] demonstrated that these factors can be used for power plants in Europe. The authors of this study, however, acknowledge that any differences in cooling water management in individual power plants across the globe may result in minor variations in the water demand estimates.

The WUI factors are assigned using information concerning the type of fuel used by individual power plant, its generation technology and the installed cooling system. Since the WUI factors are not available for oil-fired power plants [36], we grouped oil and gas power plants at this stage, as it was done in previous studies [28,37]. It is crucial to mention that oil power plants may, in general, have a higher water dependency than gas plants. This assumption, however, will not impact the accuracy of our estimates considerably, since, as mentioned earlier, the share of future oil power plants in the database is negligible and represents only 1.4% of the thermal power capacities with an announced installation year and 2.9% of power capacities with an unknown installation date.

For the full load hours (FLH) of the future thermal power plant generation we used the forecast by the U.S. Energy Information Administration (EIA) annual energy outlook 2021 [38] and Bloomberg NEF 2020 [39]. Specific FLH for a country or region are applied when available. In case no distributed data is available, global averages are applied for the thermal power plants, as is the case in the Bloomberg NEF scenario. Although, in principle it is potentially inaccurate to use global numbers for power plants across regions, this approach has been selected using the following logic. The current variations in the generation behaviors between countries or regions with different energy system compositions will be reduced in the future. This is because regions that currently use controllable generation (such as gas, oil and, to some extent, coal) for the totality or majority of their generation, will be forced to shift from constant generation to balancing of higher shares of renewables, which follow similar patterns across the globe. According to the EIA, by 2050 all scenarios predict between 53% and 58% of generation by renewables, from which up to 76% is expected to come from wind and solar PV, while Bloomberg NEF forecasts 69% generation from renewables. Therefore, thermal generation will have to adapt to more irregular production schemes of fluctuating renewables, which is expected to become the norm.

3. Results

3.1. Water consumption of global energy sector

The water footprint of the global energy system was investigated from the perspective of the water consumption. The results for the years 2020, 2030, 2040 and 2050 are presented in Table 1. The table presents the median water consumption estimates for all six scenarios considered in this study. The table contains both, the projected annual water consumption of the global power sector and the corresponding annual water consumption of the thermal power generation (given in brackets).

In 2020 the median annual water consumption of the global energy sector was estimated at the level of 88 cubic kilometers of water. If the development of the global energy system will follow the scenarios projected by Bloomberg, the water consumption may increase to about 104 cubic kilometers of water annually. When following the EIA scenarios, the annual water footprint ranges from 119 (in EIA Low Oil Price Scenario) to 132 cubic kilometers of water (in EIA High Oil Price Scenario). This implies an increase between 35% and 50% of the annual water consumption, compared to the 2020 level.

While the largest share of the energy-related water consumption is related to hydropower plants, thermal power generation is currently responsible for about 22% of the total water consumption of the global energy sector. Depending on the scenario, by 2050 thermal power generation's share is projected to constitute 20–24% of the total water consumption.

3.2. Water footprint of thermal power plants

In 2020, the total water consumption of the global thermal power plant fleet was estimated between 19.5 cubic kilometers (in EIA scenarios) and 20.8 cubic kilometers (in Bloomberg NEF). The slight difference (of about 6%) between these estimates is caused by the difference in the FLH projections reported by Bloomberg and EIA for 2020. It was estimated that about 78% of the consumed water was taken from local freshwater sources, such as rivers and lakes, while the remaining 22% was seawater.

As shown in Fig. 2, the United States, China, India and Russia had the largest water consumption of the thermal power sector in 2020, consuming annually 5, 4.1, 2.1, 1.4 cubic kilometers of water, respectively. These four countries are currently responsible for about 60% of the water consumed by thermal power plants globally. Aside from the

Table 1
Projections of the annual water consumption of the global power sector, in cubic kilometers. Values in brackets depict the projected values of the water consumption of the global thermal power sector, in cubic kilometers.

Estimate [km^3]	2020		2030		2040		2050	
Bloomberg NEF	87.80	(20.8)	91.99	(19.3)	97.96	(20.1)	104.22	(21.2)
EIA Reference case	88.12	(19.5)	103.16	(19.1)	113.10	(23.9)	124.30	(29.0)
EIA High Oil Price			105.70	(19.8)	117.14	(24.0)	132.07	(29.6)
EIA Low Oil Price			101.52	(18.9)	110.89	(23.2)	118.76	(28.2)
EIA High Economic Growth			105.58	(20.0)	116.89	(24.5)	131.96	(30.0)
EIA Low Economic Growth			101.61	(18.6)	110.90	(23.0)	118.67	(27.8)

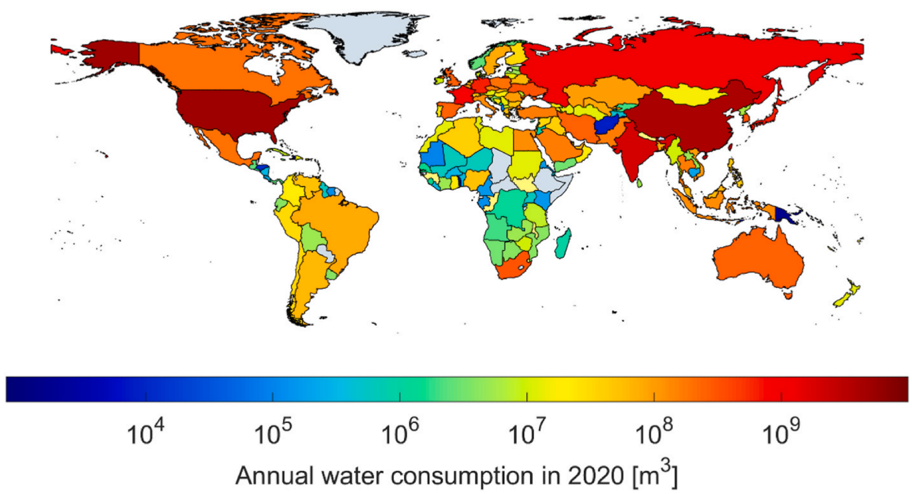

Fig. 2. Annual water consumption of thermal power generation in 2020, per country, in cubic meters. The presented map is for illustrative purposes only and does not imply the expression of any opinion concerning the legal status of any country or territory or concerning the political delimitation of borders.

large thermal power capacities located in these four countries, their high water consumption is influenced by the wide use of cooling towers, which is a prevailing cooling technology in the thermal power sectors of these countries, and which consumes a considerable amount of water per unit of generated electricity, compared to other cooling technologies.

In the same year, the global total water withdrawal of thermal power plants was projected to be between 820.3 cubic kilometers (in the EIA scenarios) and 861.9 cubic kilometers (in Bloomberg NEF). Unsurprisingly, the share of abstracted seawater in the total global water withdrawal is considerable: it constitutes about 57% of the projected global total water withdrawal. This could be explained by the fact that power plants equipped with once-through cooling systems (which withdraw large amounts of water during operation) tend to be located close to the ocean's coastline.

The countries associated with the largest water withdrawal are China

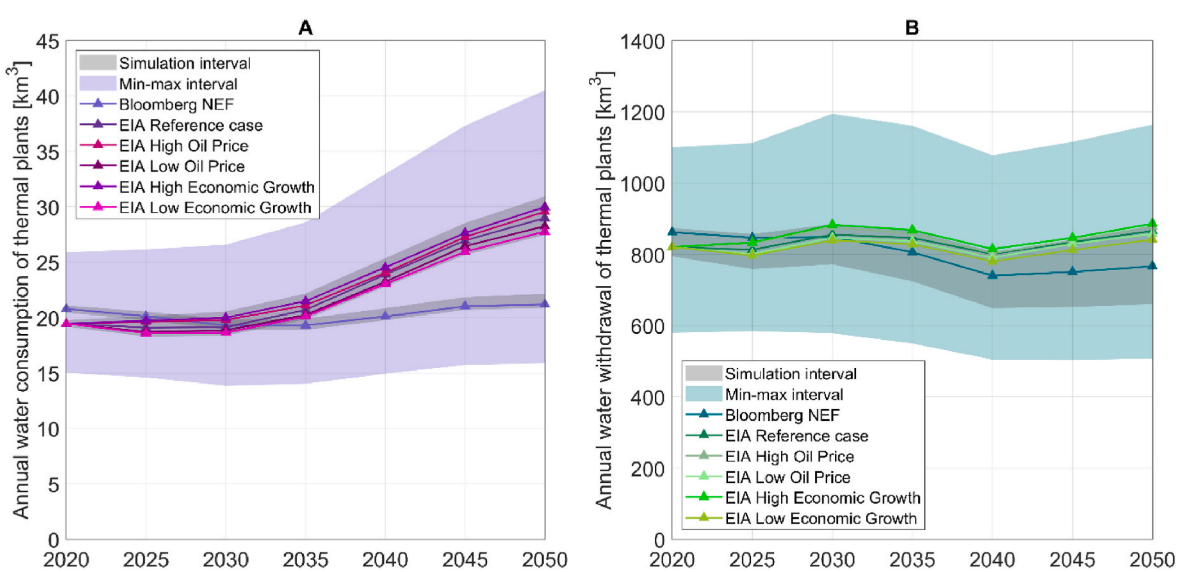

Fig. 3. Projections of annual water consumption (A) and water withdrawal (B) of thermal power plants globally, in cubic kilometers, from 2020 to 2050. The figure presents median estimates for each scenario, min-max interval of these estimates (purple shade in A, green shade in B), based on min-max WUI coefficients – see Macknick et al. [36]. and the simulation interval (grey shade) reflecting the cooling technology classification model's plausible variation of results.

(159.8 cubic kilometers), the United States (152.8 cubic kilometers), Japan (94 cubic kilometers) and Russia (56.8 cubic kilometers). About 95% of Japan's thermal power sector is equipped with once-through cooling systems, which results in the country's high water withdrawals. However, it is worth mentioning that 96% of Japan's thermal capacity is projected to be seawater-cooled, therefore having a rather inconsequential effect on the country's freshwater resources.

The results for both the annual water consumption and water withdrawal for the reference year 2020 and the projections until 2050 are illustrated in Fig. 3. The figure presents the projected median values for the six scenarios and the minimum-maximum interval of these projections. By 2050, the global thermal power sector is projected to consume between 21.2 cubic kilometers of water (according to Bloomberg NEF scenario) and 28.9 cubic kilometers of water (average of EIA scenarios) and withdraw between 507.9 cubic kilometers of water (in Bloomberg NEF scenario) and 865.6 cubic kilometers of water (average of EIA scenarios). It can be noted that in the case of water consumption, the min-max interval for the year 2050 is considerably wider than the min-max interval for 2020, which highlights the difference in the FLH projections for the power generation technologies associated with a high water consumption, such as nuclear power plants.

As depicted in the figure, the projected increase in thermal power capacities from 2020 to 2050 is estimated to result in an average increase of 48% in the total water consumption of the thermal power sector if following EIA scenarios, and a negligible change if Bloomberg NEF scenario will be implemented. Only a minor change in the total water withdrawal is projected in the EIA scenarios: by 2050, median withdrawal values increase by, on average, 6%. In contrast to that, according to Bloomberg NEF scenario, the total water withdrawal will decrease by 11% by 2050, compared to the 2020 level. These projections correspond to the current global trend to increase the installations of tower cooling systems and to decrease the use of once-through cooling systems, which indicates a development towards the reduction of water withdrawals for cooling purposes in power generation.

The lines in Fig. 3 represent the estimate of the median total water consumption and withdrawal of thermal power plants according to the classification models used in this study. Acknowledging the possibility of error for the assignment of the cooling technology for some power plants, the impact of plausible misclassifications on the consumption and withdrawal estimates is presented in Fig. 3 as grey areas. The results are based on a simulation approach (10′000 runs) using the fuel type-specific error rates of the models (see Section E of Supplementary Materials) and the confusion matrices of these models to simulate possible errors in number and type that may occur for the assignment of the cooling technology to each future power plant. The corresponding results show that for consumption the estimates only vary up to 1.8% below (in 2025) and 3.6% above (in 2050) the presented projected median annual water consumption, with most intervals showing variations of less than 3% around the median estimate. For withdrawal, the estimates vary up to 13.5% below (in 2050) but only 1.5% above (in 2020) the projected median annual water withdrawal.

To put the aforementioned findings into perspective, Table SM2 of the Supplementary Materials shows the share of freshwater withdrawals of the power sector in each country to the total freshwater withdrawals in that country, and the corresponding water stress score. Among the countries characterized by high and extremely high water stress, for a few countries the estimated share of the total freshwater withdrawals allocated for the thermal power generation is over 5% (incl. Azerbaijan, Belgium, Italy, Spain and the United States), and for three countries this share even exceeds 10% (China, Israel, and Kuwait). High shares of water withdrawals dedicated to only the thermal power sector (excluding hydropower) in countries with a considerable water stress highlight the need for a careful consideration of the potential increase in the water intensity of thermal power for managing regional water stress.

3.3. Specific water consumption

The specific water demand per unit of generated electricity (in this study – per MWh) describes the influence of the power generation mix on the average water demand of the power sector. This measure is widely used in LCA studies to estimate the energy-related water content of various products [11].

The projected development of the specific water consumption for the global energy sector is presented in Fig. 4A. As illustrated, the projected changes in the power generation mix will lead to a decrease of the specific water consumption: from an average of 3.74 cubic meters per MWh in 2020 to about 3.04 cubic meters per MWh by 2050. Although all scenarios suggest a drastic increase of renewable and low water-demanding capacities such as solar and wind energy (from about 10% of the total generation mix in 2020 to 56.1% by 2050 according to the Bloomberg NEF scenario and to 40.5% in the EIA Reference scenario), it only leads to a 20% decrease of the specific water consumption in the energy sector by 2050. This is because of the hydropower generation, which, due to its high water use intensity, keeps the specific water consumption relatively constant during the investigated time period. This highlights the urge to increase the share of low water-demanding technologies, such as wind and solar PV, in the global power generation mix.

Although the specific water consumption of the entire global energy sector is projected to decline over time, the specific water consumption of thermal power generation is expected increase, as demonstrated in Fig. 4B. According to the results of the analysis, in 2020 the specific water consumption of thermal power plants was at the level of 1.2 cubic meters per MWh. By 2050 it may reach the value of 1.7 cubic meters per MWh.

This increase could be explained by the following consideration. The average size of announced thermal power plants in the database tends to increase over time. In particular, according to the database used in this study, the average size of the power plant in 2020 was about 800 MW, and power plants that are planned for commissioning in 2050 have an average size of about 1700 MW. The size of a power plant is important, as larger power plants can use technologies like super-critical and ultra-critical boilers which have higher fuel efficiency than subcritical boilers, however resulting in an overall reduction of the water efficiency of the system as found by Macknick et al. [36]. Macknick et al. [36] report that super-critical boilers consume about 3% more water than subcritical boilers per MWh of electricity produced, while using the same cooling system. Consequently, as thermal capacities are replaced by more fuel-efficient (and yet more water-demanding) power plants, the overall specific water consumption of the thermal power plant fleet is expected to increase.

In order to restrain the rising water demand of the power sector, the installation of new thermal power plants should be limited in the future. In this regard, there are several strategies, which should be implemented in the future:

(1) to offset the growth of thermal power capacities by more water-efficient technologies,
(2) to increasingly replace future thermal power plants with renewable energy technologies, such as solar PV and wind,
(3) to ensure that water-intensive thermal is done only in areas with abundant water resources (low water stress level).

3.4. Water consumption criticality

The next step is the analysis of the development of the water consumption in different countries to highlight geographical locations that are potentially critical from the perspective of water resource availability for energy-related water consumption. Fig. 5 illustrates the total capacity, freshwater consumption, specific water consumption and water stress score in 2020 and their corresponding projected change

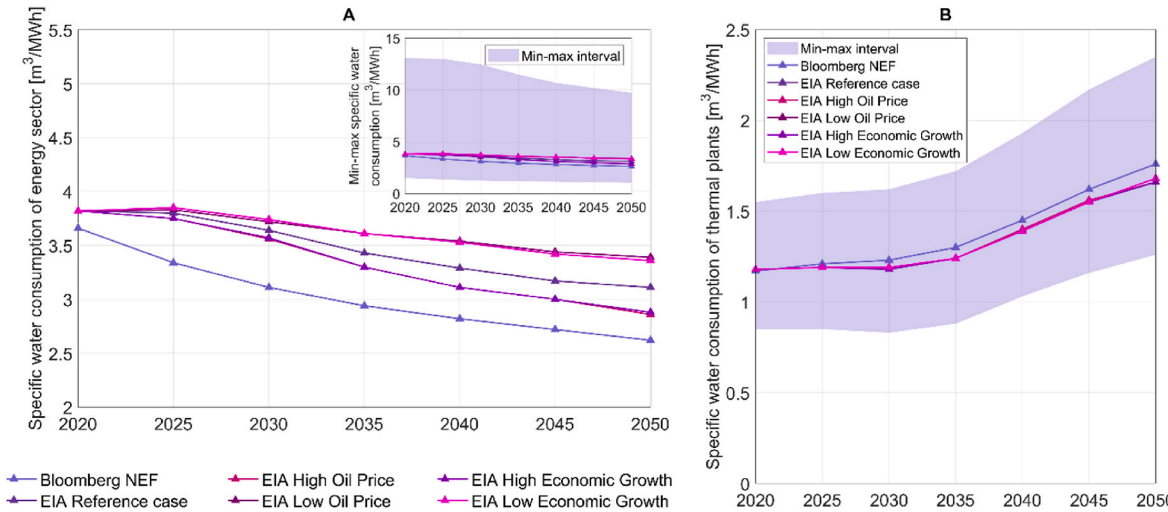

Fig. 4. Projections of the specific water consumption of the global energy sector (A) and of the global thermal power plants (B), in cubic meters per MWh of generated electricity, from 2020 to 2050. The shaded area presents median values and min-max interval (based on min-max WUI coefficients – see Macknick et al. [36]). More information concerning this min-max interval is given in Section F of Supplementary Materials.

(relative and absolute) until 2040.

To examine potential implications of the projected development for the global thermal power sector, we introduce and deployed the water consumption criticality (WCC) matrix. WCC matrix considers in the X-axis each country's specific water consumption of the thermal power plants (which, in turn, takes into account the types of cooling technologies used in the country), on the Y-axis the freshwater consumption for the thermal power sector, and whether this freshwater consumption is projected to increase by 2040 (arrow). In this study, the WCC analysis includes only power plants with known geographical location that are currently active and which are announced by the authorities to be commissioned in the upcoming decades. In future studies, the analysis of WCC can also include other forms of power generation, such as hydropower plants, if the exact location of the future hydropower capacities is known.

Fig. 6 displays the WCC matrix for the year 2020. The figure contains only countries, which are characterized by high and extremely high water stress in 2020, which indicates a high competition for freshwater resources [22]. Hence, although some countries were assigned to the group of Low WCC (green color in Fig. 6), in this classification they represent the countries of high concern.

According to our estimates, Kazakhstan, Pakistan, Syria, Uzbekistan, India, Belgium and Australia are assigned to the extremely high WCC category since these countries have a high specific water consumption, a high freshwater consumption and were in 2020 considered countries with already high to extremely high water stress. Saudi Arabia, Iran, Turkey, Greece, Spain, Mexico, China, the United States, Armenia, North Macedonia, Mongolia and Peru are characterized by high WCC. Large thermal power capacities, which are located in these countries, and which have a high freshwater dependence, should be monitored closely. Among the above-mentioned countries, Armenia was estimated to have a considerably high specific water consumption for the thermal power generation in 2020 (about 2.3 cubic meters per MWh in 2020, which is considerably higher than the estimated global average of 1.2 cubic meters per MWh – as shown in Fig. 4A).

The ongoing climate change and the extensive water use by other sectors of the economy as well as the growing population are estimated to reduce the availability of water resources in the future, compared to the current levels [1]. As demonstrated in Fig. 5H, the water stress level is projected to worsen in most countries of the world over the upcoming decades. For some countries (for instance, Saudi Arabia, Oman, Yemen, Libya, Kazakhstan, etc.), the water stress score remains unchanged due to the fact that these countries are already facing the highest level of water stress.

In this regard, Turkey embodies a country of growing concern. First, the country's water stress is predicted to worsen from high to extremely high by 2040. Second, based on our results, the water consumption of Turkey's thermal power sector is projected to increase by 130% by 2040, compared to the 2020 level, and the specific water consumption of the country's thermal power plant fleet is projected to grow during the investigated time period. Taking into account the plans of the country to install more hydropower capacities in the near future [40], the sustainable use of freshwater resources by the energy sector in Turkey might be compromised. A similar situation is expected in Pakistan and India, both characterized by a high competition for water resources, where the water consumption of thermal plants is projected to increase by about 61% and 84%, respectively, and the specific water consumption is expected to grow as well. This increased water demand for the energy generation may put an additional strain on the local freshwater resources and, simultaneously, may reduce the freshwater availability for the energy sector of these countries, as it has already happened before in several countries in the world [41].

In general, the effects of climate change will be different across the globe. WRI investigates these effects from the perspective of seasonal variability, which describes variation in water supply between months of the year, flood occurrence, which reflects the number of floods, and drought severity, which indicates the average length of droughts and the dryness of the droughts around the globe [22]. In this regard, using a water stress score as the only indication of the effects of climate change might appear as a simplification of a more complex phenomenon.

The results presented for 2040 in this section should be viewed as an optimistic scenario since they were only based on the information that is currently available in the GlobalData dataset, which, in turn, may not contain all power plants that will be installed globally by 2040.

4. Discussion

The relationship between water and energy is not new, and the term "water–energy nexus" has been in use for more than a decade [16,42]. However, this relationship and its implications are rather complex and constantly evolving along with the development of technologies for electricity production and storage, as well as developments in other sectors such as agriculture and urban infrastructure, and different approaches to the study of this relationship are constantly being developed. For example, one study [43] investigated several individual energy–water nexus links between rural, urban and infrastructure

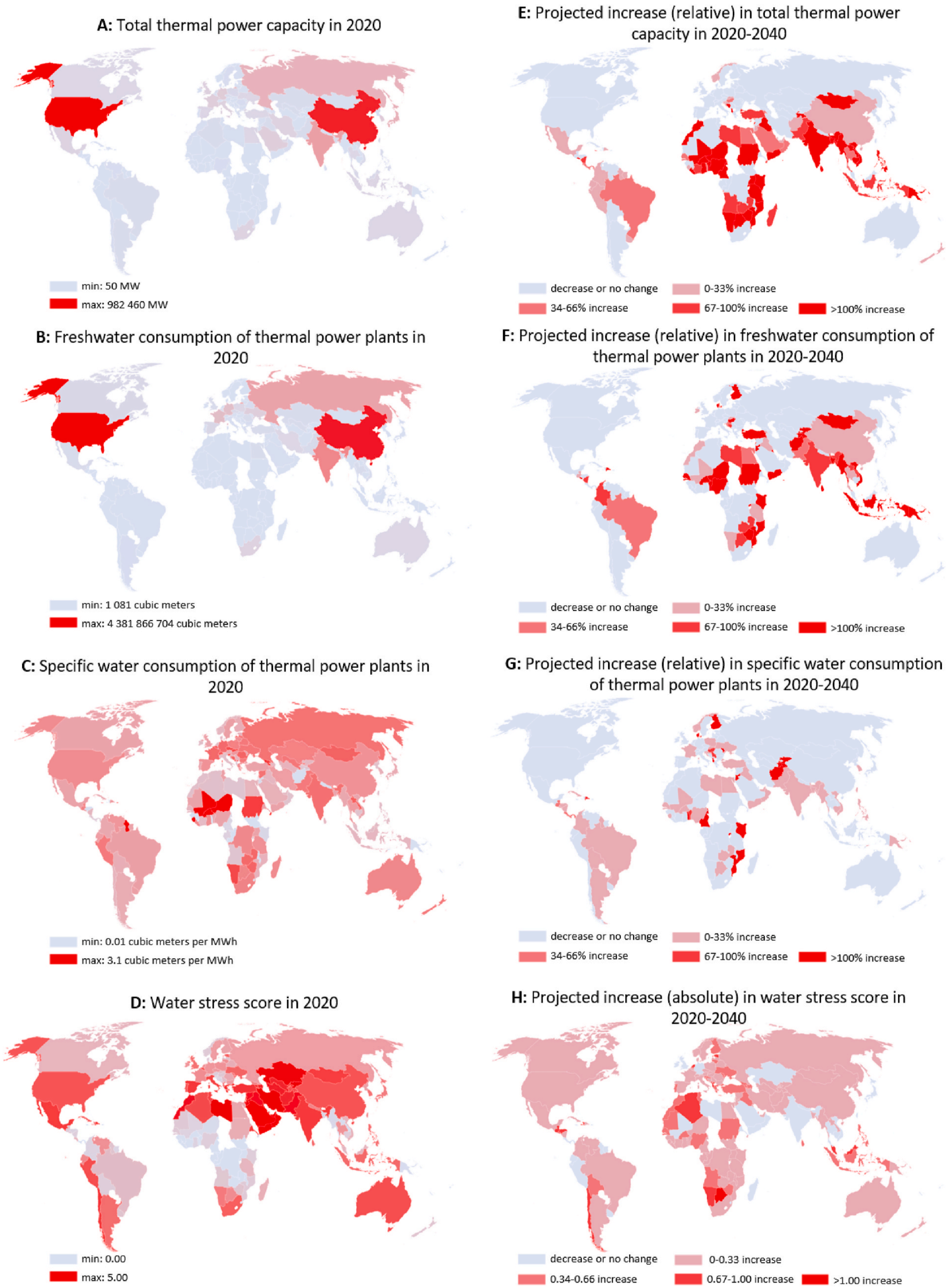

Fig. 5. Components of the water consumption criticality in 2020 (A–D) and their corresponding projected increase (relative and absolute) until 2040 (E–H). A, E: total thermal power capacity. B, F: freshwater consumption of thermal power plants. C, G: specific water consumption of thermal power plants. D, H: water stress score (as reported by Ref. [22]). The presented map is for illustrative purposes only and does not imply the expression of any opinion concerning the legal status of any country or territory or concerning the political delimitation of borders.

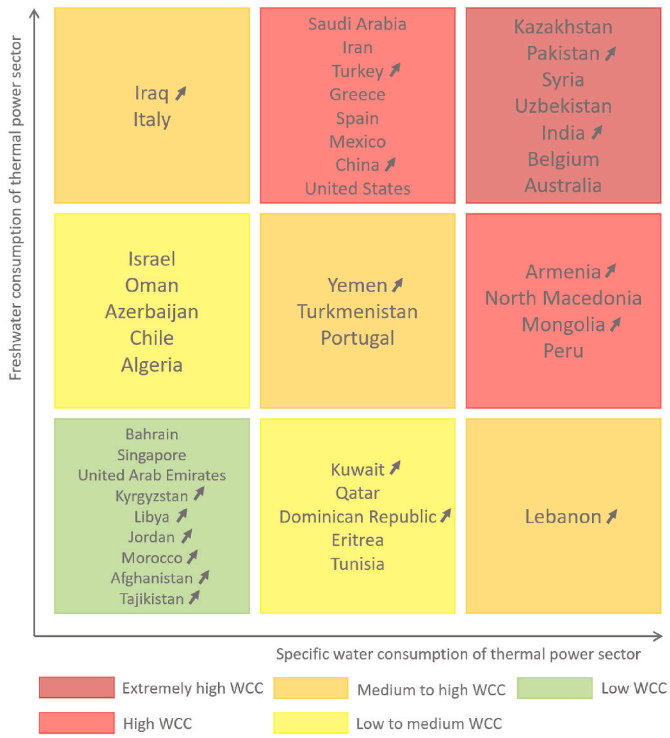

Fig. 6. Water consumption criticality (WCC) in 2020. The countries are arranged in descending order based on their water stress score. The arrows indicate that the freshwater consumption of the country will increase by 2040, compared to 2020 level (based on the data on the planned and announced thermal power plants).

settings around some of the most populated and economically active regions of China; Beijing, Hebei and Tianjin. Another example, also in China, investigates the water–energy–carbon nexus at the delta of the Yangtze River and populations surrounding it [44]. Similarly, very geographically specific studies have recently been conducted for Romania [45] and India [46], addressing also the connections of water and energy with land and food respectively. However, to the best of the authors' knowledge, there has been no study that, at a global level, takes into account the currently announced–future energy developments as well as the specific geographical water stress. The contribution of this study is to present estimates for the water demand of the future power sector according to several energy transition scenarios.

Climate change is making water resources increasingly unreliable, contributing to the need and utility of estimates for the water demand of the future power sector as an instrument for water planning and policy. To illustrate the depth of the issue, just during the summer of 2022, the water levels of the main European tributaries such as the Rhine, Rhône and Garonne rivers have been severely affected by drought, lowering their levels to the point where their transport and cooling capabilities for power plants are being thwarted, and it can still get worse [47,48]. A considerable increase in drought intensity was reported during the last decades in France [49]. This has caused a decrease in the cooling power of rivers (low river flows and increased temperature of water), which has resulted in interruptions in the power generation process [50] and has affected electricity prices [51]. In the middle of an ongoing energy crisis, France is being forced to take water out of hydroelectric reservoirs to maintain other economic activities in the Garonne River basin, at the cost of millions of euros and for the first time in over 30 years [48]. Severe droughts like the currently ongoing one, are more likely to become increasingly common, due to climate change. Considering the ongoing scenarios, research has been performed that proposes the reduction of water use for other economic activities, for example agriculture [52] and mining [53], in order to have more water available for the electricity production.

However, the increasing uncertainty of water resources should be taken into account when designing the future global power system, and a low water–dependence for the electricity production may prove to be the best strategy going forward. For example, the abovementioned case of hydropower reservoirs being drained in order to keep river flows in France is only one side of the story. Just as other economic sectors are competing for water, thermal power production is also struggling to keep operating, as nuclear power plants are forced to reduce their output due to water shortages for cooling [54].

In view of recent energy and water crises, it becomes clear that water–resiliency should become one of the deciding factors for the planning and management of the current and future power infrastructure. It appears that politicians, decision-makers, energy system planners and modelers are currently disregarding the impact that the power sector has on water resources (and vice versa) while focusing on emissions, as even the most optimistic or realistic scenarios implies higher water consumption in comparison to today's level. A failure to carefully account for the future water demand and future potential water availability variations could prove to be catastrophic. Thus, it becomes another solid argument for the acceleration of a transition to a power system deeply based on, or entirely constituted by, renewable energy such and wind and solar. In this regard, knowledge on the impact of the current power sector on water availability is vital for moving forward toward sustainability.

5. Conclusions

Energy transition scenarios typically overlook the water footprint of the future energy system. As shown in this study, the water consumption of the power sector will continue to grow, despite the expected increase of "water-free" solar and wind installations. As estimated in this study, the global energy sector in 2050 will consume at a minimum around 102 km^3 of freshwater (coming from the more progressive Bloomberg NEF scenario), out of which 16.5 km^3 are freshwater commitments to thermal power plants not yet in operation today. Problematically, an increase in freshwater consumption associated with the planned and announced thermal power generation is projected to occur in at least 39% of the countries that have already high or extremely high water stress by 2040, suggesting that energy policy in those countries is neglecting water demand aspects.

While the specific water demand per unit of generated electricity of the global power sector is projected to decline (due to the higher shares of solar and wind in the power generation mix), the specific water consumption of thermal power plants is going to increase from 1.2 cubic meters per MWh in 2020 to 1.7 cubic meters per MWh in 2050. Hence, in order to ensure a (more) sustainable use of water resources in the future, both, the total capacity of highly water-dependent thermal power generation and its share in the global power generation mix, should decrease.

In 2020 Iran, India, Saudi Arabia, Ukraine, Kazakhstan, China, United States, South Africa, Pakistan, France, Armenia, Australia and Mexico are associated with a very high WCC. The water demand of the local energy systems of these countries may become an additional factor contributing to the already existing water stress. By 2040, Turkey, Pakistan and India embody countries of increasing concern due to the estimated considerable growth of energy-related water demand. The potential consequences of this projected growth and its impact on the local water systems should be studied in a greater detail within a specific geographical context.

From the analyzed energy transition scenarios, it is shown that Bloomberg NEF strikes a better balance of water resource use and emissions. According to the Bloomberg NEF 2020 scenario, a reduction by more than 40% of the emissions from the power sector is expected by 2050. However, the freshwater demand during the same period is increasing by almost 20%. Other, more progressive energy transition scenarios are occasionally presented in the academic literature (for instance Ref. [55]), which could potentially further decrease the water consumption of the power sector. However, these scenarios were not considered for this study, as they do not take into account the thermal power plants that are currently announced, planned and under construction.

Code availability

Matlab scripts used in the production of this analysis are available from the corresponding author upon request.

CRediT authorship contribution statement

Alena Lohrmann: Conceptualization, Resources, Methodology, Software, Investigation, Visualization, Validation, Writing – original draft. **Javier Farfan:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing. **Christoph Lohrmann:** Methodology, Software, Visualization, Investigation, Writing – original draft, Writing – review & editing. **Julian Fritz Kölbel:** Resources, Writing – review & editing. **Frank Pettersson:** Investigation, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Alena Lohrmann reports financial support was provided by Kone Foundation. Alena Lohrmann reports financial support was provided by Finnish Academy of Science and Letters.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2023.128820

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