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Assessment of the water footprint for the European power sector during the transition towards a 100% renewable energy system

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ABSTRACT

The transition towards a 100% renewable energy system may be an opportunity to resolve the water-energy nexus. However, deployment of some technologies might impose additional strain on water ecosystems. An energy-system-wide analysis of water demand in Europe was performed for the period 2015–2050 using the LUT Energy System Transition model for two scenarios: Area (with electricity interconnections) and Regions (without). For fossil-fuelled power plants, the water footprint in 20 European regions may decrease considerably until 2050, by 28.3% in the 'Area scenario' and 24.2% in the 'Regions scenario'. However, total water demand in the Area scenario increases in 5 regions on average by 14%, from 7% (Balkan-West countries) to 24% (Sweden). Further, Turkey, Norway and Sweden may have the largest water demands in Europe due to the commissioning of new hydropower plants. Results indicate discussions on the sustainability of energy transition scenarios should be expanded to include water footprint.

1. Introduction

Currently, a large share of Europe's power generation relies heavily on water availability. Considerable amounts of water are used in hydropower generation, and thermal power plants require water for cooling purposes. The electricity sector of the European Union is on average responsible for approximately 55% of the total water withdrawal [1]. The researchers note that without a radical improvement of the water resource management in the power sector, the power plants' demand for water might surge considerably in the future [2]. This rising water demand might lead to a further depletion of water resources and aggravation of water-related risks, especially in regions which are already suffering severely from water stress [2].

In the annual report released by the World Economic Forum [3], "water crisis" is listed in the top-10 global risks in terms of both likelihood and impact for the year 2020. According to the data presented in the Water Resources Institute (WRI) Aqueduct Atlas, about 142 million Europeans are currently living in areas exposed to high or extremely high baseline water stress [4]. The river Danube, which flows through 19 European countries and passes 47 cities and 4 national capitals, was listed by the World Wide Fund for Nature (WWF) as one of the ten rivers at risk in the world [5].

Water constraints, droughts and heatwaves have already compromised power generation in Europe [2]. For instance, the heatwave of 2015 induced a reduction of coal power generation in Germany and Poland [6,7]. Previously in 2006, the temperature rise in river water forced French, German and Spanish nuclear plants to reduce or even halt power generation [8]. According to the European Environment Agency report [9], water availability is projected to further decrease as a side effect of climate change [10]. This holds especially true in southern parts of Europe, affecting thermal power plants, hydropower, bioenergy potential and fuel transport on rivers.

The adaptation to climate change represents challenges and opportunities for the implementation of a defossilised energy system in Europe [9]. In general, renewable energy technologies are known to consume considerably less water compared to conventional fossil-nuclear fuelled power plants. For instance, solar PV and wind generation require only marginal quantities of water (if any) for occasional cleaning of PV modules and wind turbine blades [11]. However, some other types of renewable energy technologies (for instance, hydropower and bioenergy) could consume water more

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intensively than the fossil-based systems they replace [12,13]. Thus, a more careful assessment of energy-based water consumption will add another layer in the discussion of the sustainability of 100% renewable energy systems, which are extensively discussed in recent years, in particular, for the case of Europe [14–17].

Studies of the water-energy nexus exist for several regions of the world, such as the Middle East and North Africa [18], China [19], the UK [20], as well as globally [21]. However, studies on Europe as a whole are lacking in the literature. In addition, water-energy nexus studies have not been completed on a European level that account for projections of the transition towards higher shares of renewable energy in the future. Furthermore, the European Council has set a target to strengthen the energy interconnection between the countries [22] in order to increase the European Union's security of electricity supply and to achieve higher penetration of renewable energy technologies into its energy markets. The economic consequences of establishing such interconnections have been the focus of recent research articles [16,23]. However, there is a lack of research analysing the potential changes in water usage in electricity production. Given that Europe is reported to have the highest energy-related water footprint in the world [24], projections of future water use in the energy sector can provide a basis for effective water policy and planning.

To address the above-mentioned concerns, this study aims to: (1) assess the current water demand of Europe's power sector from the perspective of water consumption, (2) evaluate the potential impact of establishing high voltage power transmission interconnections between the regions of Europe on the water demand estimates, (3) project the development of water consumption until 2050 for the example case of two energy transition scenarios, and (3) identify potential bottlenecks on the pathway towards a zero greenhouse gas (GHG) emission renewable energy system when conducting the comparison of the two scenarios.

2. Methods

2.1. Data gathering and database compilation

2.1.1. Compilation of the power plant dataset

The main source of power plant data for the research was the GlobalData dataset [25]. The dataset was later complemented and corrected with the information presented in other databases [26–28], and the results of the global power plant structure were published by Farfan and Breyer [29]. The presented dataset provides comprehensive information on existing power plants (name, capacity, type of generator, fuel type, commission date, country and region, etc. were reported for each specific power plant). However, the dataset did not include the locations in high spatial resolution of the power plants, or the source and the amount of water used for power generation, which are required for the water footprint determination and analysis.

The aim of this study was to put an emphasis on the European energy system-wide analysis. Therefore, the initial dataset was narrowed down to contain only active power plant units exceeding 50 MW located in Europe. Countries presented as part of the analysis are the EU-27 member states, Albania, Bosnia and Herzegovina, Iceland, Kosovo, Macedonia, Moldova, Norway, Serbia, Switzerland, Turkey, Ukraine and the United Kingdom.

The limitation of 50 MW originates from the inability to identify the location and the cooling system of such power plants using satellite imagery. This selected cut-off seems appropriate for the study due to the following reasons: (1) thermal power plants of low capacity require a relatively low amount of water for cooling purposes due to their small size; (2) thermal power plants of low capacity are typically equipped with dry cooling systems, which demand less water than other cooling systems [13]; (3) thermal power plants of low capacity are often combined heat and power (CHP) plants, which have relatively low water abstractions for waste heat discharge [30]. As for renewable energy technologies, it is challenging to identify the location of small-scale generation units since the names of such units are typically not available in the commonly used power plants databases.

In contrast to the previous study by Lohrmann at al. [31], which was focused only on thermal power plants, this research aims to assess the water footprint of other water-intensive non-thermal power technologies. As a result, 3276 power plants with a total active power plant capacity of 845 GW were presented for the analysis, of which 895 units (27.3%) are gas power plants, 852 (26.0%) are coal-fired, 835 (25.5%) are hydropower, 302 (9.2%) are oil-fired, and 150 (4.6%) are nuclear power plants. Other technologies, such as biomass and biogas power plants, solar photovoltaic (PV) and concentrated solar thermal power (CSP) plants, together account for less than 7.4% of the total amount of the units presented for the analysis.

This research does not encompass the assessment of geothermal plants since their share in the current European energy system is negligible (less than 0.3% of the total energy generated in 2015). However, it is important to remark that geothermal power plants, depending on the cooling type, might be the second most water demanding power generation technology (after hydropower), consuming up to 19.48 m^3 per MWh [13]. This extensive water consumption might have a considerable impact on the local water systems. In contrast to geothermal technology, the share of wind power in the current energy system is high (16% of the total installed capacity higher than 50 MW). In addition, according to both scenarios considered in this study, this share is projected to increase by 2050. However, no water is being abstracted in the process of wind power generation. Thus, the water footprint of wind power generation was not assessed in this study. In addition, pumped hydro energy storage technology was left out of the scope of the research since no water footprint factors were available in Macknick et al. [13].

2.1.2. Identification of location and coupling power plants with water bodies

To estimate the type of water used for cooling purposes (sea or freshwater), the exact location of individual power plants needs to be pinpointed. The exact geographical coordinates of thermal power plants were previously identified and reported by Lohrmann et al. [31]. For this study, the locations of other types of power plants presented for the analysis (hydropower, biomass, CSP) were identified based on the information presented in the initial database (name of the specific power plant, fuel type and capacity, region and town of its location) using satellite imagery in Google Earth, Bing and Yandex.Maps. Fig. 1 presents the location of water-intensive power generation facilities identified for this study, thus, excluding solar PV power plants.

To link individual power plants with water bodies, the method of Geographic Information System (GIS) analysis was implemented. The Global Self-consistent, Hierarchical, High-resolution Geography Database (GSHHG) [32] was used as a source of a high-resolution data for ocean coastlines, lakes and rivers. Power plants were assumed to have a direct freshwater cooling source if they are located within 5 km of rivers and lakes. In contrast to that, power plants located within 20 km of the ocean coastline, were assumed to use seawater for cooling purposes, as it was shown by Biesheuvel et al. [33] and later implemented and validated on global level by Lohrmann et al. [31], where power units with unknown water source were assumed to use underground freshwater for cooling.

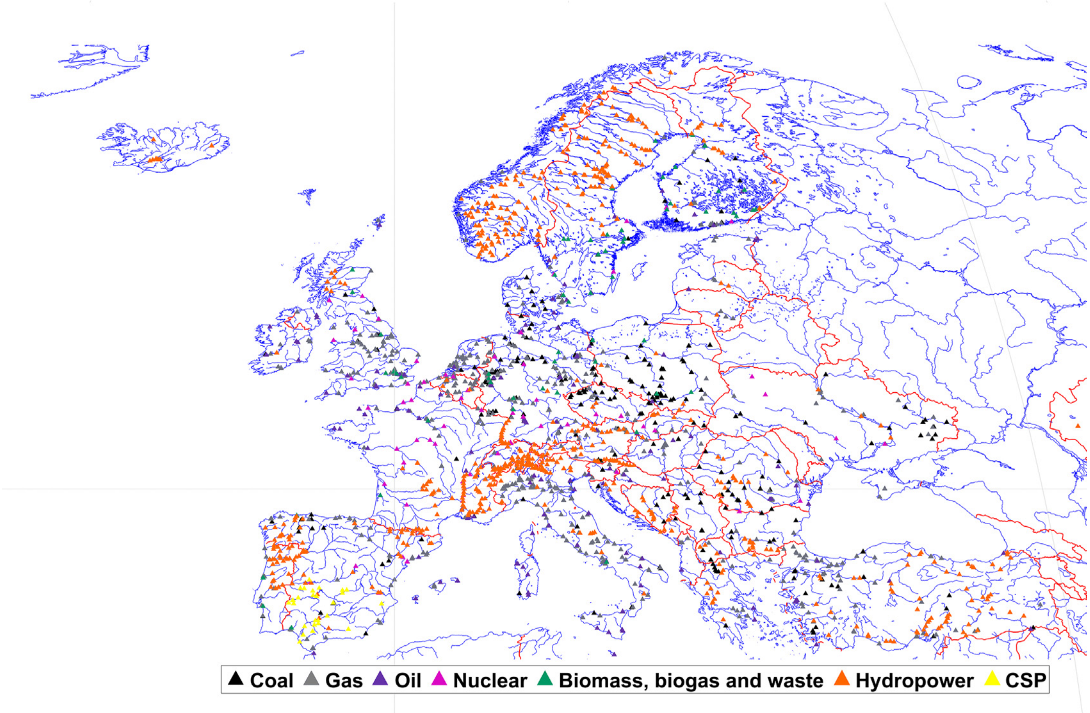

Fig. 1. Identification of the exact location of power plants exceeding 50 MW in Europe. The blue lines on the map represent water bodies: rivers, lakes, ponds, channels, and coastlines. The borders of the countries are marked in red colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.1.3. Cooling system identification

Knowing the cooling system of individual thermal power plants is crucial for the assessment of their water footprint on river ecosystems. However, the initial dataset provided by GlobalData [25] contained almost no information on the installed cooling technology at an individual power plant level. Therefore, the subset of the European power plants used in this research was complemented with the cooling technology data gathered and reported by Lohrmann et al. [31] for the case of coal, gas, nuclear and oil power plants. In subsequent steps, the type of cooling technology was identified for individual CSP, biomass and biogas power plants.

The method of cooling system identification in biomass and biogas power plants applied in this research was previously reported by U.S. Geological Survey [34] and Luo et al. [35] and tested on a global level by Lohrmann et al. [31]. For the case of the US power plant fleet, Luo et al. [35] achieved a precision level of 90% for the cooling technology identification. Their method is based on the manual identification of the cooling technologies of individual thermal power plants using satellite imagery provided by Google Earth, Bing and Yandex.Maps. In total, five types of cooling technologies were considered: dry cooling (or so-called air cooling, direct and indirect), once-through cooling (or open loop cooling), recirculating tower cooling systems (which is typically subdivided into natural draft towers, mechanical induced-draft towers and mechanical forced-draft towers), recirculating pond cooling and inlet cooling systems of gas power plants.

The main limitations of the applied method were discussed by Luo et al. [35]. In this research, the cooling system identification method did not allow identification of the cooling technology in several cases. Firstly, the method appeared to be ineffective for biomass power plants that were located within large industrial complexes (e.g. pulp and paper facilities) where several types of cooling technologies were utilised. In this case, the allocation of cooling technology should be performed by specialists familiar with the particular industrial complex. Secondly, the identification of several once-through power plants was not feasible using satellite imagery due to the fact that their intake or outlet facilities were submerged. Thirdly, in many cases, it was not possible to identify the cooling system of low-capacity power plants due to their small size. Thus, the size emerged as the primary reason for selecting a 50 MW capacity as the limit for this study. Moreover, the precision of cooling system identification appeared to be strongly dependent on the image resolution and timing of the satellite shot. Finally, the assignment of cooling technology was not possible for power plants belonging to the category “aggregated capacities”. This category was added to the initial GlobalData database [25] by Farfan and Breyer [29] to match the capacities presented in the database with the statistical information on power generation provided by governmental institutions and international organisations for all countries in the world. These capacities cannot be assigned to specific power plants or units. Therefore, by definition, this method applied in the research cannot be used for their cooling system identification. The amount of thermal power plants which cannot be assigned any cooling technology using this method is rather low (for instance, the “aggregated capacities” represent 135 entries in the database, which account for about 4.1% of all power units presented for the analysis). They represent only 16.1% of the total power plant capacity in the database. Thus, the choice of missing value treatment for the cooling technology is crucial for the analysis of local freshwater-deficit regions.

In order to “fill in the gaps” in the cooling technology data, a simple statistical analysis was performed. The analysis was based on historical data (year, capacity, fuel and combination of the generator type and cooling technology of individual power plants) available in the database. The selected method of missing value imputation might impact the water consumption estimates. In order to assess the variability of the water consumption estimates resulting from the choice of the cooling technology for the "aggregated capacities", a sensitivity analysis was performed. The results of the sensitivity analysis are discussed in the Supplementary Materials (Note 1).

2.2. Analytical approach for the assessment of the current water footprint

2.2.1. Individual power plant – level

Typically, the assessment of the energy-based water footprint is conducted from the perspective of water withdrawal and water consumption. Water withdrawal is defined as the total amount of water taken from the water source to meet the demand of the power generation process. In contrast to that, water consumption represents the difference between water withdrawal and the amount of water returned to the source. From another viewpoint, if water is seen as a common good for industrial, agricultural and domestic use, then water withdrawal can be treated as the amount of water "used" by the economy. In contrast to that, water consumption can be defined as the amount of water "used" by the technological process since it describes how much water is "lost" during the process of power generation. The focus of this study is on water consumption since it illustrates the direct impact of power generation on water availability. In particular, this water is disposed from the immediate water environment, for instance, by means of evaporation.

Water consumption (or so-called "water footprint") of power plants was calculated using Equation (1) presented below.

$$\text{Water footprint } = \text{Active capacity} \times FLH \times WUI \tag{1}$$

where the *Active capacity* is given in MW; *FLH* – full load hours of power generation – in hours; *WUI* – water use intensity factor – in m^3 per MWh. For the assessment of the current (2015) water footprint, the FLH were obtained from the International Energy Agency (IEA) statistics [36]. The FLHs were assigned to individual power plants according to their generation type (coal, gas, hydropower, solar PV, etc.) and location (country).

Table 1 in the Supplementary Material contains information concerning the WUI factors used in this study, which were derived by Macknick et al. [13]. For different types of power plants, depending on the installed generator type and cooling technology, different WUI factors were applied. As highlighted in Table 1 of the Supplementary Material, a few types of power plants do not require cooling for the process of power generation (solar PV and hydropower). In the case of solar PV, the WUI factors were available only for utility-scale plants. This is one of the limitations of this study, and residential solar PV plants were left out of the scope. For hydropower plants, the WUI factors were only reported for in-stream plants and reservoirs, thus, the other types (e.g. pumped hydro energy storage) were filtered out from the final database. A discussion concerning the selection of the WUI factors for CHP power plants is presented in Note 2 of the Supplementary Material.

Although the approach of using WUI factors is an effective and widely applied method for water demand estimations in the power generation sector, it is associated with uncertainty (since different factors will lead to different estimates). As mentioned previously, for this study, the values of water use intensities were derived from Macknick et al. [13]. Whilst these factors were reported for the United States, Macknick et al. suggest that they can also be used for water demand estimations for other geographic regions (including Europe) [13]. Consequently, many studies which focused on water demand estimations for European power plants (e.g. Ref. [37]) have reported using WUI factors from Macknick et al. [13]. However, any variations in water management and cooling technology utilization between the United States and Europe might result in differences in the water consumption estimates [38]. In order to address this concern, the WUI factors (median values and min-max intervals), which were applied in this study [13], were compared to the WUI factors that were used in other studies on Europe (see Note 3 of the Supplementary Material).

2.2.2. Region- and country – level

The country-specific total water consumption was calculated as the sum of the water consumption of all power generation facilities located in these countries. In addition, the aggregated water footprint was calculated for all Europe's twenty sub-regions presented in the LUT Energy System Transition model [16,39]. The LUT Energy System Transition model optimises the projected energy systems in full hourly resolution. The dataset of the real weather conditions, which is implemented in the model, has a $0.45^\circ \times 0.45^\circ$ spatial and hourly temporal resolution. Hence, the (local) variability of renewables and their impact on the future energy system design is considered in greater detail, compared to other studies. This step was taken in order to match and compare the estimated current water footprint with the projected values by the 'Regions scenario' and the 'Area scenario' until 2050. These twenty regions, their location and specifications are presented in Fig. 2. Additional information concerning the countries assigned to each specific region is provided in Table 1.

2.3. Scenarios

The Regions scenario assumes that each of the defined 20 regions of Europe is an independent energy system with no exchange of electricity. At the same time, it was recognised in Ref. [16] that some natural areas of energy cooperation exist within the European context while constructing the individual regions. In most cases, regions are national energy systems. However, many regions are combinations of national systems that have shown high levels of energy cooperation in the past, especially the exchange of electricity. The Area scenario establishes high voltage power transmission interconnections between the regions of Europe. The basis of the scenario is established by known capacities of HVAC and HVDC connections in winter 2010/2011 as developed by ENTSO-E [40] and supplemented by further information from Refs. [41–43]. Interconnections were determined on an individual basis between each region and observed known border crossing points as well as routes of undersea cables. To account for varying topography, an additional 10% was added to interconnection distances. In some cases where accurate information could not be found, straight lines between the main centres of electricity demand were drawn. New undersea cables were assumed to be HVDC cables, as is the norm in Europe. New additions on land were assumed to be comprised of 70% underground cables and 30% overhead lines to account for possible social resistance to visible lines overhead. In both scenarios, no analysis of transmission or distribution infrastructure within regions was attempted, although internal transmission line losses were accounted as a function of electricity consumed, as documented in Ref. [44]. A full description of scenario parameters and methods is found in Ref. [16].

2.4. Estimation of the power sector's water footprint in 2016–2050

The results of the Regions and Area scenarios determine the power capacities that should be commissioned during the transition period from 2016 to 2050. However, since the location of these new power capacities was not defined, this study assumes that all new thermal capacities will consume freshwater for cooling purposes.

The scenarios were applied to project the development of the

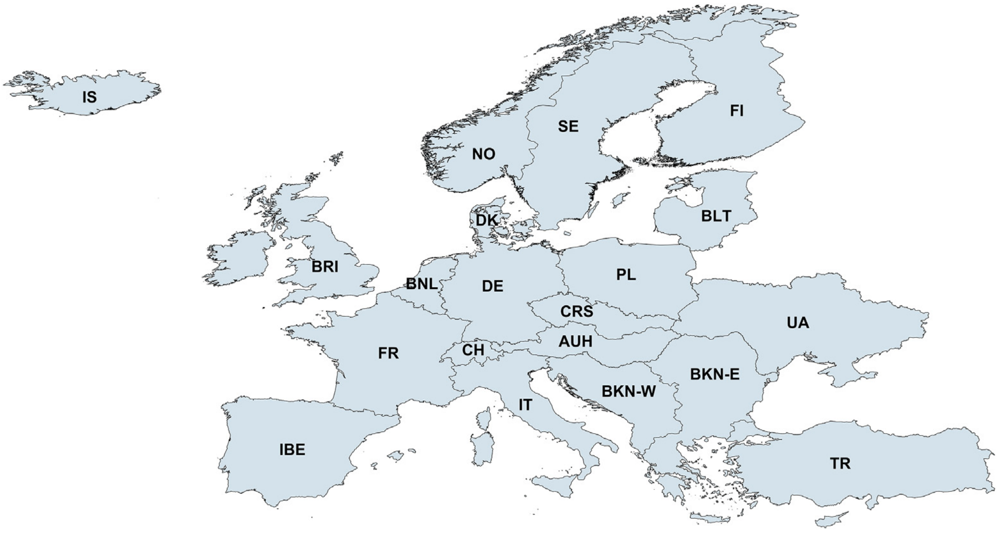

Fig. 2. Geographical regions used in this study [39].

Table 1
Median, minimum and maximum values of water consumption estimates and specific water consumption per region in 2015.

Region	Countries	Median, [km^3]	Minimum, [km^3]	Maximum, [km^3]	Specific water consumption, m^3/MWh (based on median values)
NO	Norway	1.89	0.60	7.56	15.47
DK	Denmark	0.02	0.01	0.02	0.55
SE	Sweden	1.20	0.41	4.49	7.66
FI	Finland	0.32	0.13	1.07	4.22
BLT	Baltic: Estonia, Latvia, Lithuania	0.05	0.02	0.14	1.74
PL	Poland	0.32	0.26	0.57	2.07
IBE	Iberia: Portugal, Spain, Gibraltar	1.34	0.70	4.13	3.74
FR	France, Monaco, Andorra	2.40	1.79	4.81	4.23
BNL	Belgium, Netherlands, Luxembourg	0.28	0.22	0.33	1.31
BRI	British Isles: Ireland, United Kingdom, Isle of Man, Guernsey, Jersey	0.52	0.36	0.98	1.33
DE	Germany	1.13	0.95	1.99	2.04
CRS	Czech Republic, Slovakia	0.42	0.29	0.71	3.70
AUH	Austria, Hungary	0.80	0.34	3.11	8.55
BKN-W	Balkan-West: Slovenia, Croatia, Bosnia & Herzegovina, Serbia, Kosovo, Montenegro, Macedonia, Albania	0.69	0.29	2.41	6.94
BKN-E	Balkan-East: Romania, Bulgaria, Greece	0.62	0.30	1.95	3.87
IT	Italy, San Marino, Vatican	0.43	0.17	1.50	1.40
CH	Switzerland, Liechtenstein	0.67	0.26	2.42	10.24
TR	Turkey, Cyprus	1.71	0.69	6.12	5.41
UA	Ukraine, Moldova	0.46	0.31	0.92	2.79
IS	Iceland	0.23	0.07	0.93	13.19

water footprint of Europe's power sector from 2016 to 2050. Equation (2) below was used to estimate the Aggregated water consumption (AWC) of the power sector in each of the twenty regions presented for the analysis. The results were obtained for 5-year intervals and cover water consumption of fossil-based, nuclear and renewable energy technologies.

$$\mathrm{AWC}_t=\sum_{i=1}^{n}(Previously installed capacity_{i,t}\times ProjectedFLH_{i,t}\times WUI_i)+\sum_{i=1}^{n}(Projected new capacity_{i,t}\times ProjectedFLH_{i,t}\times WUInew_i) \tag{2}$$

where i denotes the specific type of power generation (coal, gas, hydropower, solar PV, etc.), t the analysed year. *Projected new capacity* (in MW) and *Projected FLH* (in hours) were obtained from Ref. [16] as part of the results of the simulation of the Regions scenario and the Area scenario.

'*Previously installed capacity*' was calculated as the difference between active power plants in 2015 and power plants that are scheduled for decommissioning by the year t. The projected lifetime for different types of power plants was obtained from Farfan and Breyer [45], who report on the average technical lifetime of 40 years for coal and nuclear power plants, 34 years for gas and oil, and 100 years for hydropower plants.

To compute the water footprint of newly installed thermal power plants, a simple statistical analysis was performed. We determined the most common generator type during the last 15 years for all twenty regions and assigned it to the new capacities in these regions. The cooling technology was selected premised on a similar logic used in the section 'Cooling system identification', which also considers that the cooling system technology should correspond to the generator type and the fuel used at the power plant. Using this approach, *WUI new* factors were assigned.

3. Results

3.1. Current water consumption of the Europe's power sector

In 2015, the total water consumption of Europe's power plant fleet was estimated at a level of 15.54 km^3. The highest amount of water was consumed by hydropower plants (in-stream and reservoirs), which accounted for 61.5% or 9.55 km^3 of the annual water loss. Nuclear and coal-fired power plants consumed 19.4% and 15.5%, respectively. Other technologies (gas-, oil-, biomass- and biogas-fired power plants, CSP and solar PV plants) together were responsible for less than 3.6% of the total water consumption.

According to the IEA statistics [36], the share of hydropower plants in European power generation was about 13.9% in 2015. As mentioned previously, the estimated share of consumed water by hydropower plants is much higher (61.5%). This difference can be explained by the fact that hydropower plants have the largest reported water consumption factors among all power technologies, which, according to Macknick et al. [13], can be up to 68 m^3 per MWh. This value represents the higher limit of the minimum—maximum (min—max) interval for water consumption estimates, which is 21 times higher than the corresponding value for nuclear power plants equipped with cooling towers. Thus, hydropower plants consume up to 21 times more than nuclear plants with cooling towers for the generation of the same amount of electricity.

In contrast to that, gas-fired power plant contribution to the Europe's generation mix was 15.4% in 2015, while their share in the total water consumption was estimated at 2.5%. Compared to other technologies (hydropower, nuclear and other fossil-based plants), Europe's gas power plants have a relatively low water consumption per unit of generated energy. These “water savings” are mostly caused by the commonly used dry cooling systems, which, according to the findings of this study, equip up to 21% of the Europe's gas power plants that exceed 50 MW.

In this study, all hydropower plants, CSP and solar PV plants were assigned to freshwater sources. Thus, the GIS analysis was conducted for thermal power plants presented in the database. The results of the GIS analysis highlighted that about 37.6% of the total active thermal capacity is located within 20 km of the sea coastline. Thus, following the approach described in the study by Biesheuvel et al. [33] and also implemented by Lohrmann et al. [31], it was assumed that these power plants might use seawater for cooling purposes. The use of seawater for cooling represents a “more sustainable” solution, especially for coastal regions with high freshwater scarcity. The share of the assumed seawater-cooled capacities varies in different regions. The results show that regions with the highest shares are Norway, Denmark and Sweden, where the proportion of potentially seawater-cooled thermal capacities was higher than 93%.

As illustrated in Fig. 3, the water consumption for electricity generation is not distributed evenly in Europe either. The “leader” in total (sea- and fresh-) water consumption was France, consuming about 2.39 km^3 annually. Nuclear power plants (mostly equipped with cooling towers), which contributed as much as 77.5% to the final generation mix in 2015 [36], accounted for 64.5% of the total water consumption. Hydropower, the second-largest power generation technology in France in 2015, consumed about 33% of water related to the country's power sector. About 32.4% of the thermal capacity exceeding 50 MW was assumed to be potentially seawater-cooled, thus, freshwater consumption of the country was estimated at the level of 1.83 km^3 annually.

In 2015, the second place of total water consumption was taken by Norway with 1.89 km^3 of water “loss” annually, of which 99.7% was consumed by hydropower. Water consumption of thermal power plants was dominated by gas power plants located at the coastline. Thus, the above-mentioned water consumption value represents losses of freshwater. Therefore, Norway had the largest consumption of freshwater for power generation in Europe.

The results of the analysis highlight that Europe's region with the lowest water demand was Denmark. Total water consumption was 0.02 km^3, of which only 16% was abstracted from freshwater sources (i.e. rivers and lakes).

The specific water demand per 1 MWh of generated electricity reflects the influence of the power generation mix on the average water consumption. The analysis shows that Europe's “leader” was Norway with estimated 15.5 m^3/MWh. The lowest specific water consumption was in Denmark with 0.6 m^3/MWh. Information about other regions presented for the analysis is given in Table 1. This table also includes median, minimum and maximum estimates of water consumption per region.

Figs. 3 and 4 depict the values of the total water consumption in all twenty regions selected for the analysis. The values presented are the estimated median values and min-max intervals for the year 2015. It is crucial to remark that the presented values for Iceland's total water consumption might appear lower than its actual water consumption in 2015. This difference can be explained by the fact that geothermal technology, which represents the second main power generation technology of the country and is contributing 28.8% to the generation mix, was left out of the scope of this research.

3.2. Projected water consumption in 2050

In the case that the Area scenario is implemented, the annual total water consumption is estimated at the level of 11.14 km^3 in 2050. Thus, the total water consumption was projected to decrease by about 28.3% by 2050, compared to the 2015 level. In contrast to that, if the Regions scenario is pursued, the annual total water consumption in Europe will decrease to 11.77 km^3 by the end of 2050. Compared to the 2015 level, this will result in a 24.2% decrease in water consumption. Fig. 5 illustrates the projected annual water consumption on a regional level for both scenarios. As highlighted in the figure, the projected “leaders” in total water consumption are Turkey, Norway and Sweden due to their high shares of hydropower in the final generation mix. In 2050, these three countries are projected to be responsible for about 47.5% of Europe's total water consumption according to the Area scenario, and for 44.8% according to the Regions scenario, respectively. Both scenarios project Turkey's power sector to have the highest water demand in Europe in 2050 with 1.91 km^3 of water consumed annually.

As shown in Fig. 6A, the largest decrease in annual water consumption is projected during the period from 2015 to 2030. This decrease can be explained by the large defossilisation of the power sector, which, according to these scenarios, is scheduled during 2015—2030 [16]. In particular, fossil-fuel power plants are projected to consume about 35.3% of the total amount of water used by the Europe's power sector in 2020. According to the Area scenario, this share is estimated to consistently decrease to 13.9% in 2030, to 4.5% in 2040 and to about 1.6% in 2050. In contrast to that, the Regions scenario projects a slightly higher share of 2.0% for fossil-fuel power plants in the total water consumption by the end of 2050. Thus, both scenarios project an almost full elimination of the water footprint of fossil-fuelled power plants.

3.3. Comparison of the Area and Regions scenarios

A suitable scenario should ensure better mitigation strategies for water use in the power generation sector during the whole

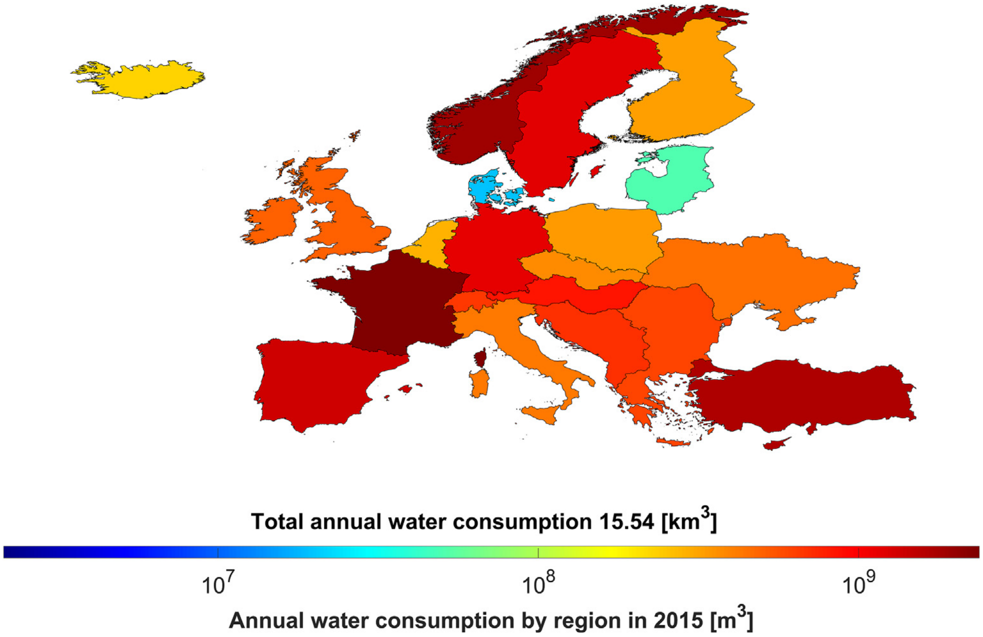

Fig. 3. Total water consumption (median values) of the Europe's power sector in 2015, in m^3.

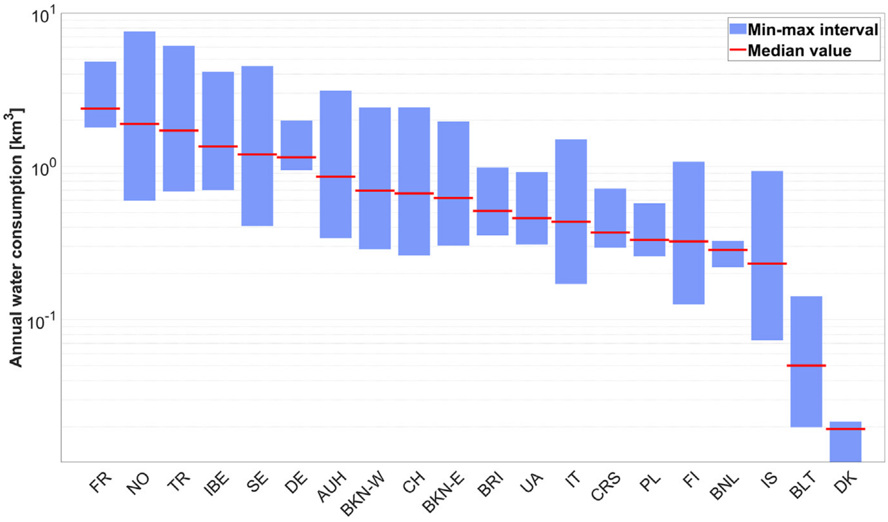

Fig. 4. Total water consumption of power sector in 2015, per region. Y-axis is given in logarithmic scale.

transition period. The results of the study show that the total annual water consumption projected for both scenarios in 2050 differs only marginally (0.64 km^3 per year or 5.4%). Another way to evaluate and compare the scenarios is to use the metric of cumulative difference introduced by Lohrmann et al. [31].

The cumulative difference represents the amount of water that could be excluded from power generation in the case that the Area scenario is implemented instead of the Regions scenario. In other words, the cumulative difference illustrates the “savings” of water, which are aggregated for the entire transition period from 2015 to 2050.

In this study, the cumulative difference was calculated using Equation (3). This equation determines the area between the curves in Fig. 6A, which represents the annual water consumption for both scenarios.

$$\text{Cumulative diff} = \int_{2015}^{2050} \left(AWC(t)_{Regions} - AWC(t)_{Area}\right) dt \qquad (3)$$

where *AWC* denotes the Aggregated water consumption of the power sector, in m^3, and *t* the analysed year.

The results of the calculations are illustrated in Fig. 6B, which illustrates that the Area scenario allows to gradually save up to 18.09 km^3 of water during the 35-year transition period, compared to the situation when the Regions scenario is selected for implementation.

3.4. Identification of potential bottlenecks of the energy transition

The next step of the study was to evaluate the potential impact

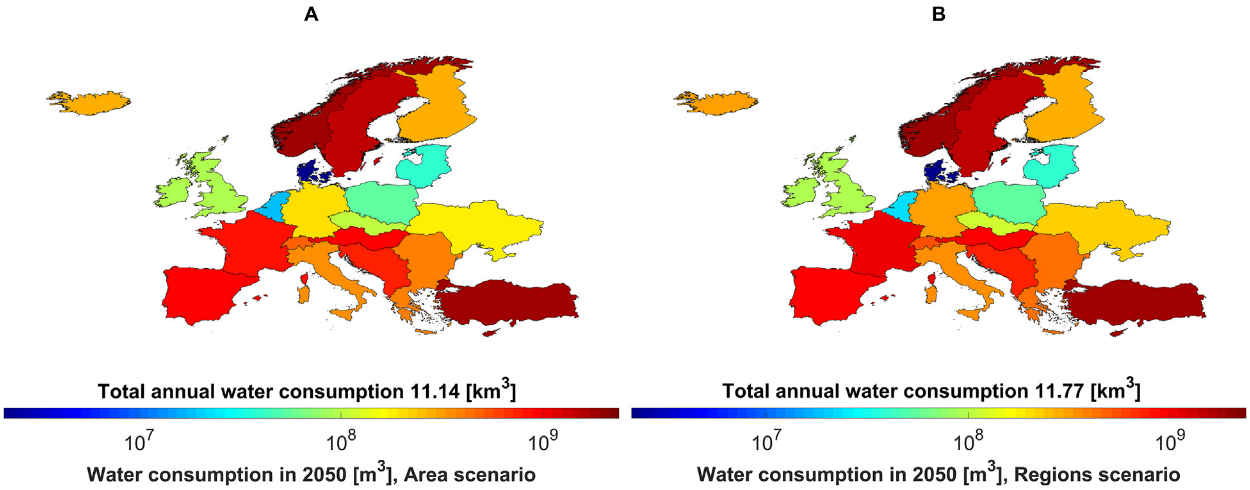

Fig. 5. Projected total water consumption (median values) of Europe's power sector in 2050, in m^3, according to the Area scenario (A) and the Regions scenario (B).

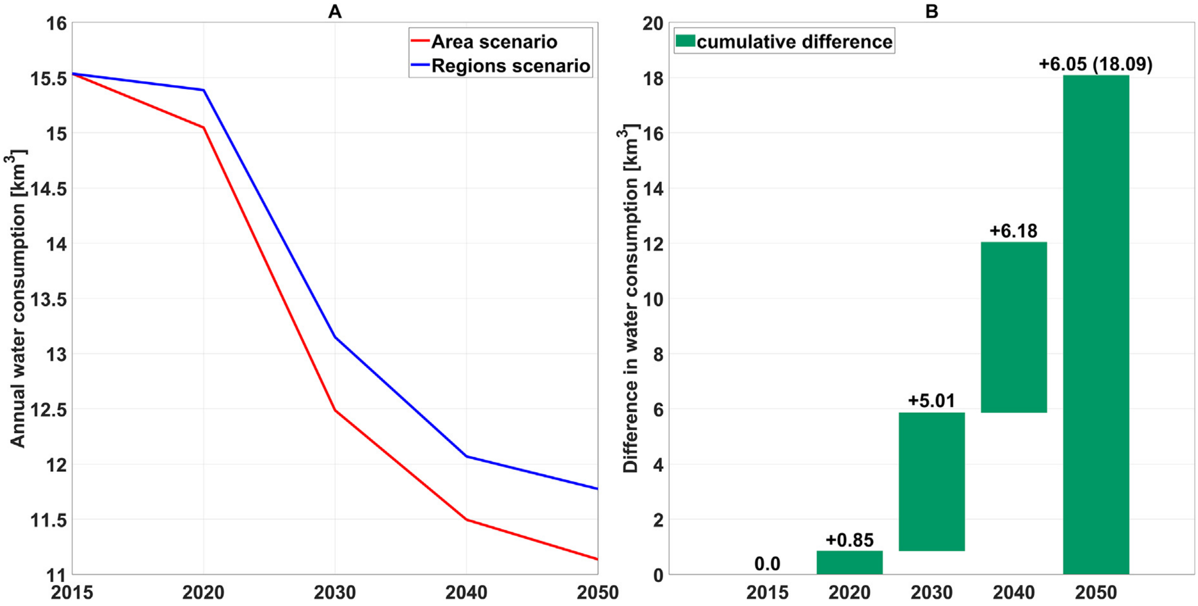

Fig. 6. Comparison of the Area and Regions scenario. Changes in total annual water consumption from 2015 to 2050, in m^3, according to the Area scenario and the Regions scenario (A). Cumulative difference in water consumption (B).

of the energy transition on the regional level. Fig. 7 highlights the development of the water consumption in 2015–2050 on the regional level for the Area scenario (Fig. 7A) and the Regions scenario (Fig. 7B). As shown in the figure, in Europe as a whole as well as in most of Europe's regions, the total water consumption of the power sector is projected to decrease by the end of 2050 (marked in green colour). This projected decrease in the annual total water consumption reflects the projected decommissioning of old fossil-fired power plants and their replacement by less water consuming renewable energy technologies [16].

However, in five out of twenty regions an increase in the annual total water consumption of up to 24% is projected during 2015–2050. In Fig. 7, these regions are marked with red colour.

The results show that an increase of 7% is projected in Austria and Hungary (AUH region), another 7% in the Balkan-West countries, 11% in Turkey, 21% in Iceland and 24% in Sweden. Thus, the estimated average increase for these regions is 14%. According to the Area scenario, during the transition period 2015–2050, the commissioning of new hydropower plants or expansion of capacity is projected in 19 of Europe's regions (with the exception of Finland) presented for the analysis. However, in the case of the five above-mentioned regions, the share of these new hydro capacities is high: compared to 2015, on average, an increase of 29.4% of the hydropower capacities is projected in 2050. Thus, the “savings” of water achieved by the decommissioning of old thermal power plants could not compensate for the “additional” water consumption of the increased hydropower capacities.

4. Discussion

Sustainability aspects of the Area and Regions scenarios were discussed in previous studies [16,39]. On the one hand, it was shown that both scenarios are consistent with the targets imposed by the Paris Agreement [46]. In particular, Child et al. [16] reported that a complete defossilisation of the European energy system could be achieved by 2035 in the Area, and by 2045 in the Regions

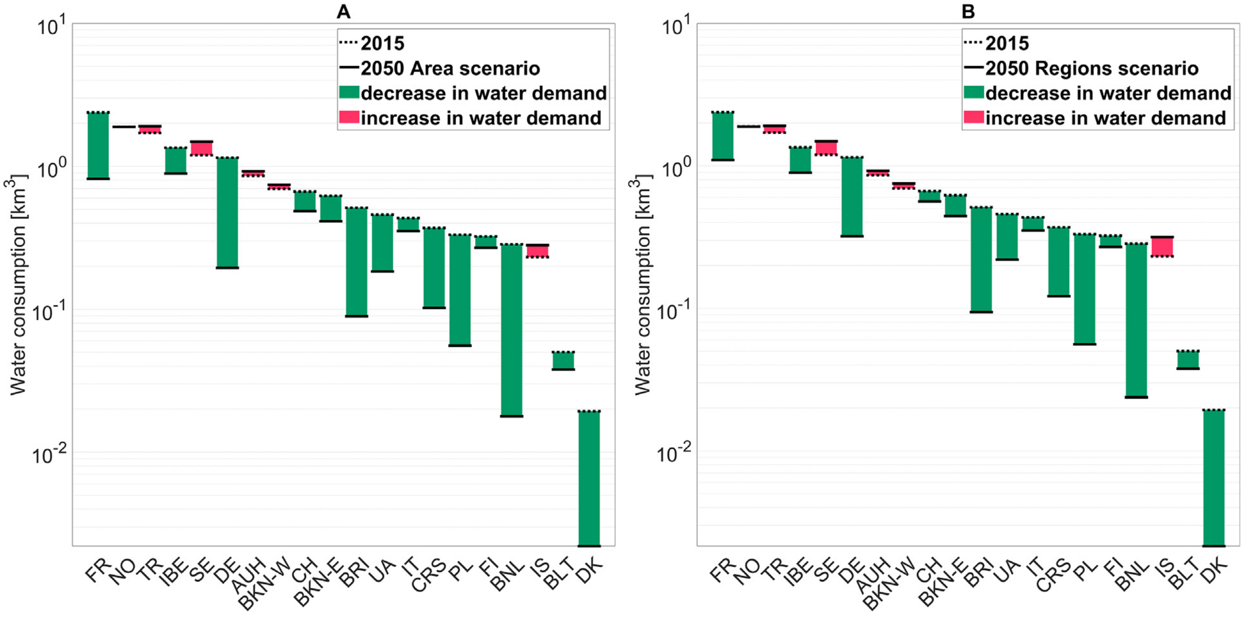

Fig. 7. Changes in total annual water consumption (median values) from 2015 to 2050, in m^3, according to the Area scenario (A) and the Regions scenario (B). The y-axis is given in logarithmic scale.

scenario. On the other hand, the economic feasibility of the presented scenarios was assessed. Child et al. [16] projected the decrease of the levelised cost of electricity (LCOE) from the current 69 €/MWh to 51 €/MWh in the Area scenario and to 56 €/MWh in the Regions scenario. In addition, the technical feasibility and governmental policies were taken into account in their research.

In contrast to that, this study focuses on the assessment of the water footprint of the European power sector, which is not always included in modelling studies. The results of this study indicate that the water demand of power plants should not be neglected in the discussion on the sustainability of energy transition scenarios.

In particular, the results show that in the case that the Area scenario is implemented, the total water demand (of fossil-based and renewable energy technologies) for Europe as a whole can be decreased by up to 28.3% during the transition period until 2050. In eight regions, the implementation of a zero GHG electricity system will lead to a reduction in water consumption in the power sector exceeding 60%. However, in five out of twenty regions the total water demand is projected to increase between 7% (Balkan-West countries) to 24% (Sweden), with an average ascent of 14%, according to the Area scenario. The projected increase in water demand is on account of the extensive implementation of new hydropower capacities, which are scheduled for commissioning during 2015–2050. Thus, even if these regions possess large hydropower potentials, they require a more careful assessment of water resources before the implementation of these scenarios. Such an assessment is pivotal, as the consumed water represents the “lost” water by means of evaporation and, thus, would not return to the local water systems.

The results of this transition show several potential impacts related to water footprints. First, the reduction in thermal power plant capacity can result in an increase in water quality and availability at a local level in some locations, especially for the Area Scenario. Some cooling systems in thermal plants extract water at a lower temperature than it is returned, thereby affecting water quality through thermal pollution [18]. In addition, cooling may result in evaporative losses that displace water over long distances. The reduced water footprint shown in this transition may then contribute to the achievement of the United Nations Sustainable Development Goal (SDG) 6 – Clean Water and Sanitation, which aims to increase water quality and reduce withdrawals as a proportion of the total water resources. In addition, SDG 12 calls for the responsible consumption and production through reductions in materials' footprints (including water). It is estimated that the current increasing trend of water scarcity could lead to the displacement of approximately 700 million people even by 2030 [18].

A diminished need for water in energy systems may increase water security in a broader sense. This may make water available to increase such provisioning services as agriculture. Also, retaining water in ecosystems may sustain various cultural services, such as recreation, spirituality, science and art. A reduction in water scarcity in some regions may also contribute to a decreased potential for conflict as well as reduce inequalities [47]. Failure to establish an effective balance between water and energy security can have potential social, economic and environmental consequences [21]. Also, it has been argued that the nexus can be expanded to include food, land use and climate, suggesting a complex system affecting many areas of life [48].

According to the WRI Aqueduct Atlas [4], four out of five regions with the projected increases in water consumption (except for Turkey) are reported to have low baseline water stress, which is indicative of a high availability of renewable water resources. However, Turkey, which is projected to increase its energy-based water consumption by 11% and, thus, to become the largest water consumer in Europe, is characterised by high baseline water stress [4]. In addition, the agricultural sector of Turkey is reported to dominate the country's water demand with a 75% share of the total water consumption [49] (compared to an average of 44% for Europe [50]). It is projected that all larger regions of Turkey even require access to desalination to guarantee freshwater supply [51], which is also driven by demand for irrigation [52]. Thus, the projected implementation of a high share of hydropower might impose an additional stress on Turkey's water resources and create a higher competition for water resources with the pivotal agricultural sector. Therefore, a further systematic analysis is required to evaluate the effect of the implementation of these scenarios for the case of Turkey.

According to Gleick [53], losses from hydropower plants vary greatly and are affected by such factors as regional climate, average annual flow of the water body, dam height, gross static head, reservoir area and volume, drainage area characteristics, installed capacity of the hydropower plant, type of power plant and average annual energy production. The authors conclude that the relationship between gross static head and dam height may be better indicators of evaporative water loss and other sustainability concerns than power production. This may be particularly important when considering the difference between run-of-river hydropower and large dams. In addition, many large dams and reservoirs have been constructed for multiple purposes that may result in larger reservoirs than would otherwise be needed for electricity generation. This could exaggerate statistics related to evaporative losses for hydropower in some cases and Gleick [53] recommends that this key distinction be taken into account in any overall environmental assessment. Likewise, Torcellini et al. [54] also indicate that there is no easy way to disaggregate the end uses of hydropower dams and reservoirs, which makes an assessment of evaporative losses per unit of electricity generated problematic. For the case of Turkey, the rather high level of estimated consumption from hydropower may produce benefits greater than those measured by electricity generation alone (e.g. flood control, consistent water supply for irrigation and recreational use).

Therefore, the provided values of specific water consumption per 1 MWh of generated electricity represent rough estimates that may even seem “ambiguously formulated” for the case of hydropower in certain cases according to Gleick [53]. Given the wide-ranging geography of different parts of Europe, appropriate caution in interpreting results is advised. In order to obtain more accurate projections, a life-cycle assessment of the entire energy system should be conducted.

The choice of 2015 as a representative year for this analysis merits further comments. As stated previously, heatwaves in parts of Europe caused temporary reductions in coal power generation [6,7]. In addition, 2015 was at the end of a 5-year trend of decreasing wholesale electricity prices in Europe. Some regions of Europe even saw the lowest wholesale electricity prices in more than a decade [55]. As thermal power plant operation is related to wholesale prices, one could surmise that thermal plant full load hours may have been lower than normal during 2015. This could mean that initial estimations of water consumption for power production in Europe (15.5 km^3) may have been somewhat lower than a truly representative year, making projections of water savings presented here rather conservative. At the same time, changes in European electricity generation sources due to increasing impacts of variable renewable energy had already resulted in a decreasing trend in full load hours for thermal power plants over the preceding decade [56]. Therefore, selection of a representative year for comparisons within such a context of change is inherently problematic.

5. Conclusions

The study addresses the problem of extensive energy-based water use in Europe. In particular, the current water footprint of 3276 power generation units exceeding 50 MW was estimated and aggregated on a per region and country level.

Using the results of the Area and Regions scenarios computed with the LUT Energy System Transition model, the water demand of the European power sector was projected for the time period from 2015 to 2050. The results of the study reveal that the transition to a 100% renewable electricity system might lead to a decrease of up to 28.3% for Europe's energy-based water consumption by 2050, compared to the 2015 level. As the result of defossilisation, the water footprint of thermal power plants is projected to decrease to the negligible amount of 1.6% in 2050 according to the Area scenario. In addition, the study highlights the potential bottlenecks of the future energy transition, where the change of the energy system might lead to an increase in energy-based water consumption. As a consequence, this change of the energy system can become an additional factor contributing to the already existing water stress in a region. The impacts of new hydropower capacity in particular should be viewed within specific geographical and operational contexts to best determine if related consumption would contribute to greater water stress or other environmental harm.

The results of the study demonstrate water-related benefits of establishing power transmission interconnections between the regions of Europe. During the investigated period from 2015 to 2050, the additional savings of water (due to power interconnections) are estimated to reach 18.09 km^3 of water.

Therefore, the results of the study could potentially support Europe-wide and regional policymaking by providing another dimension to the discussion of the sustainability of the energy transition scenarios.

Non-English speaking authorsfinalization of the manuscript

The second author, Michael Child, who is a native English speaker, has conducted proofreading of the article.

Data availability

The data that support the findings of this study are available from GlobalData [25].

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Declaration of competing interest

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

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Author contributions

Alena Lohrmann: Conceptualization, Methodology, Software, Investigation, Writing - Original Draft. **Michael Child:** Resources, Validation, Writing - Review & Editing. **Christian Breyer:** Writing - Review & Editing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2021.121098.

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