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Gone with the clouds: Estimating the electricity and water footprint of digital data services in Europe

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ABSTRACT

Cloud and data services have experienced a constant increase in demand ever since their availability. Whether for computing of complex models, digital data storage, blockchain transactions or digital service hosting, digital data is having an increasingly important role in society. However, with the increasing presence of data centers, not only the availability and quality of cloud and data services increases, but also the demand for electricity and water by the digital services industry. This work aims to provide an estimation for the current and future water consumption of digital data services in Europe from 2022 to 2030. The projection considers European trends for population, data services consumption, technological development, data transmission and energy consumption among other factors. Publicly available data was combined with literature research to extrapolate the development of digital data usage in Europe until 2030. The results demonstrate that from 273.4 to 820.1 million cubic meters of water and from 56.3 to 169 Terawatt-hour of electricity will be consumed yearly in Europe in 2030 for internet usage.

1. Introduction

The world is experiencing the continuous digitalization of the everyday life. From the expanding "*smartification*" of home appliances and the increasing capabilities of communication devices, to the growing availability of streaming services, cloud storage, cryptocurrency transactions and cloud processing services. It is estimated that the average European citizen used around 187.3 Gigabytes (GB) of data yearly in 2020 numbers [1]. This represents an increase of 32.4% from the previous year, and a 286% increase compared to 5 years ago [1].

The constant expansion of the demand for data services and digital transformation has become a multi-trillion euro business globally, in which both tech giants (Microsoft, Meta, Amazon and Google) and smaller players compete [2]. COVID-19 related lockdowns have further pushed Europeans towards digital services, as remote learning, working, shopping and gathering became the new rule [3].

However, the aforementioned data consumption comes at an environmental cost. Data centers are linked to high water [4] and electricity consumption [4]. The energy efficiency of data centers is constantly increasing, to the point that an increase in computing workload of 550% from 2010 to 2018 has resulted only in an increase of energy demand of 6% [5]. Although the capacity over electricity consumption continues to decrease [4] large computing centers still consume the electricity equivalent to that of small cities [6]. Moreover, along with the water consumption related to the electricity consumption, the immense amount of heat generated by the computing centers requires additional on-site water cooling, further increasing the water footprint of the computing centers [7]. The abovementioned "double water impact" of data centers goes beyond the widely studied energy-water nexus, with studies identifying the ties of water and energy to combined heat and power [8], hydropower [9], mining [10] and energy systems [11], to name some.

Despite the large electricity and water consumption incurred by computing centers, there is the challenge of lack of transparency on behalf of the main providers of computing services; Google, Meta, Microsoft and Amazon [4]. This lack of transparency makes it difficult for governments and decision makers to deal with electricity and water management in the zones where computing centers operate or may be commissioned.

Although the literature on the topic is relatively limited, analysis of the environmental effects of data centers has been studied in the past, and indicators for data center performance are still being developed [15]. Particularly when addressing the system's electricity consumption

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Nomenclature

EU	European Union
EU27	European Union, includes Austria, Belgium, Bulgaria, Croatia, Republic of Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden
EU28	European Union, includes EU27 countries and the United Kingdom
EB	Exabyte
GB	Gigabyte
IEA	International Energy Agency
kWh	Kilowatt hour
OECD	Organization for Economic Cooperation and Development
PV	Photovoltaic
mln	Million
MW	Megawatt
MWh	Megawatt-hour
TWh	Terawatt-hour
UK	United Kingdom
AVG_{DUXY}	Average monthly data usage per subscription per country
DPC_{XY}	Data volume generated in country X in year Y
DtT	Data center-to-data transmission network ratio
DV_{CXY}	Data volume generated per capita in country X in year Y
e_{GB}	Energy consumption per GB of data usage
e_{CXY}	Energy consumption of data centers per capita in country X in year Y
es_{XY}	Sensitivity of energy in country X in year Y
F_{BSXY}	Number of fixed broadband subscriptions per hundred inhabitants in country X in year Y
IWC_X	Indirect water consumption of electricity sector in country X
M_{BSXY}	Number of mobile broadband subscriptions per hundred inhabitants in country X in year Y
P_{CXY}	Population of country X in year Y
Te_C	Total energy consumption rate
Te_{CXY}	Total energy consumption by data centers in country X in year Y
$TIWC_{XY}$	Total indirect water consumption at data centers in country X in year Y
$TDWC_{XY}$	Total indirect water consumption at data centers in country X in year Y
$TTWC_{XY}$	Total transmission water consumption in country X in year Y
TWC	Total water consumption rate
TWC_{XY}	Total water consumption for data usage in country X in year Y
Tt_{CXY}	Total energy consumption for data transmission in country X in year Y
WCC	Water consumption per MWh used for cooling in data centers
SW_{XY}	Sensitivity of water in country X in year Y
X	Country
Y	Year

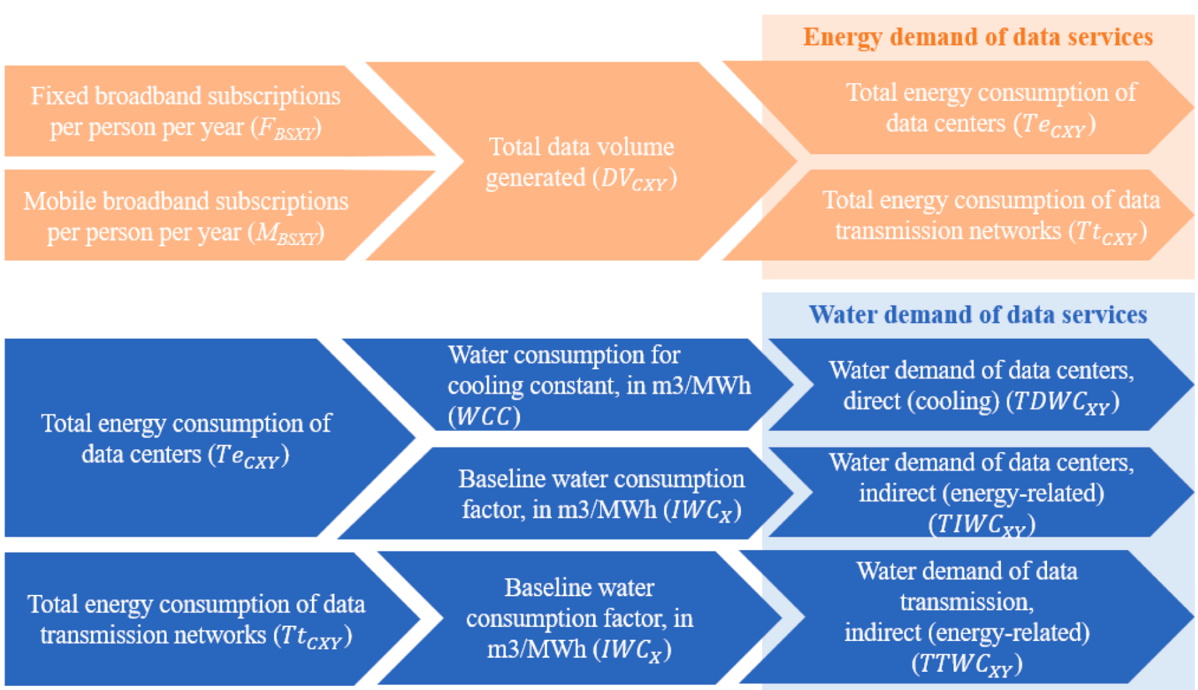

Fig. 1. Methodological scheme for the estimation of energy consumption (top, in orange) and water consumption (bottom, in blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

[16], as well as how external factors affect the operation of the data centers [17] including weather conditions as discussed by [18] and [19]. However, optimization for energy and water use can be a trade-off, in some cases reducing the processing performance of data centers [20]. This issue is particularly relevant in areas of high water stress. Facing scrutiny for this issue, service providers have pledged to reduce their water and energy impact (for example Google [12], Amazon [13] and Microsoft [14]). However, to date providers have not released a detailed

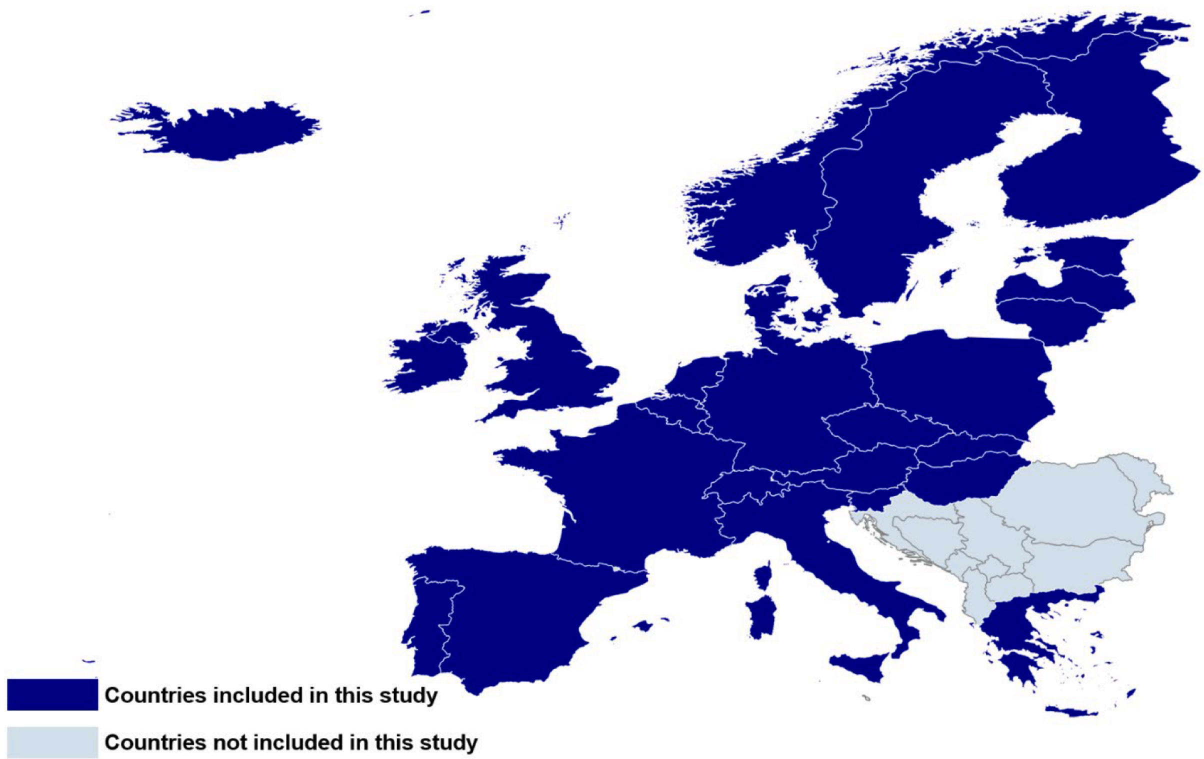

Fig. 2. OECD-Europe countries, included in the scope.

strategy to achieve this goal.

Water consumption by data centers is a constantly developing field of research. From attempts to estimate the state-of-the-art water consumption of data centers [4], to proposing improvements to the water efficiency of cooling systems to data centers [18]. For example, deploying an alternating cooling strategy [21], novel evaporative condensers [22], installation of redundant multi-chillers [23], introduction of hybrid (water–air) cooling systems [24], etc. Alternatives to freshwater for cooling are also being explored, such as sea water for cooling [25] but are not yet the norm. Another approach has been to explore the potential utilization of the waste heat generated by data centers [26].

In general, assessments at a national or regional level for the electricity and water consumption for digital data services have not been carried out, thus presenting the research gap explored in this work. Therefore, this research aims to estimate and make a projection of the yearly electricity and water consumption incurred by the currently operating and planned computing centers and data transmission in Europe until 2030. The estimates may then be used to support water and energy management at the computing centers' host regions.

2. Methods

This section presents the scope, methods and assumptions employed in this study to estimate the electricity and water consumption of each

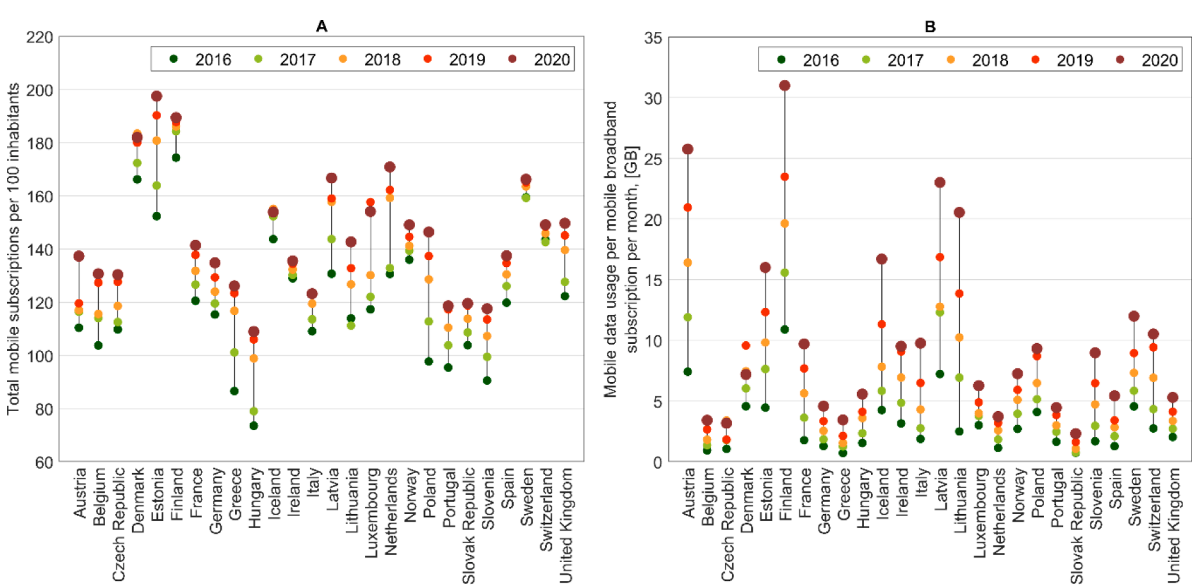

Fig. 3. Reported development of the subscription (A) and data usage (B) behaviors in OECD-Europe from 2016 to 2020. Source OECD [1].

component for data usage. Shown in Fig. 1 shows a scheme for how each component of the water and electricity impact of the digital service industry is calculated, with further explanations on each term in the subsequent subsections.

2.1. The scope (geography of study)

Due to data availability, the scope of the study considers countries in the European continent that are also part of the Organization for Economic Cooperation and Development (OECD). Therefore, the countries included are the European Union (EU27) excluding Bulgaria, Croatia, Cyprus, Malta and Romania, but including Iceland, Norway, Switzerland and the United Kingdom (UK) [1], for a total of 26 countries as shown in Fig. 2. In order to use a unified reliable source for the countries within the scope, having the OECD report data subscriptions and data usage was the deciding factor for the delimitation of the scope. Complementing the OECD data on broadband usage, the population metrics and projections produced by [27] were selected. The presented geographic scope was chosen exclusively due to data availability. The policies within and without the analyzed countries (individually and collectively) are not part of the scope of the study.

2.2. Projections for data usage until 2030

In order to understand the water and energy demand by data centers, the volume of data circulating in the countries analyzed had to be calculated, as well as the development trends. The OECD reports number of fixed and mobile broadband subscriptions per hundred inhabitants per country and per year (F_{BSXY} and M_{BSXY} respectively), as well as the average monthly data usage per subscription per country (AVG_{DUXY}), as shown in Fig. 3. Therefore, the data volume generated is calculated by Equation (1).

$$DV_{CXY} = \frac{(F_{BSXY} + M_{BSXY})}{100} \times AVG_{DUXY} \times 12 \times P_{CXY} \quad (1)$$

From Equation (1), DV_{CXY} and P_{CXY} stand for data volume of country “X” in year “Y” and population of country “X” in year “Y”, respectively. The constants of 100 and 12 are included due to the variables F_{BSXY} and M_{BSX} being reported by OECD in subscriptions per hundred inhabitants, and AVG_{DUXY} being reported monthly, respectively. From Equation (1), it can also be inferred the data volume per capita for each country and year (DPC_{XY}), and it can be calculated as shown in Equation (2).

$$DPC_{XY} = \frac{DV_{CXY}}{P_{CXY}} \quad (2)$$

Since the OECD [1] reports numbers for subscriptions and data usage only for the year range of 2016–2020, a projection was made for F_{BSXY}, M_{BSXY} and AVG_{DUXY}. Considering that the slope of the curve from 2016 to 2020 for each of these variables was close to linear for the majority of the countries studied, linear extrapolation was used to forecast the values for each of these variables from 2021 to 2030. In the case of the population, the forecast from The World Bank was used. However, in the case of a handful of countries, the variable M_{BSXY} exceeded two mobile subscriptions per capita. In these cases, the limit was set to a maximum of two mobile subscriptions per capita. The reasoning for the two mobile subscriptions per capita is that, for once, having two subscriptions per individual (for example a work subscription and a personal subscription) seemed sufficient. This is also considering that each of those subscription could be used across multiple devices simultaneously, so a need for more subscriptions per capita became unfathomable. On another hand, even if more than two mobile subscriptions per capita would happen, it is likely that it would not increase the data usage correspondingly, as intensive data traffic (viewing videos, browsing and uploading to social media, listening to music, etc.) requires usually full user attention. Therefore, the assumption was that additional mobile subscriptions could only divide the data generated, but not necessarily generate more data traffic. The number of total subscriptions per capita, after adding the fixed subscriptions, still exceeded two subscriptions per capita in 11 out of the 26 countries by 2030, but this was allowed.

2.3. Estimation of energy consumption of data centers

Next step was to estimate the water and energy footprints corresponding to the volume of data. Pihkola et al. [28] estimated a ratio of 0.3 kW-hour (kWh) per GB of processed data in 2018. This is a steep increase in electric efficiency by data centers, since in 2012 the energy consumption was estimated to be from 4.5 kWh [16] to 5.1 kWh [29] and as high as 7 kWh per GB [30]. However, as Mytton [4] points out, there is a limit to how much this number can be reduced. Although this limit is not yet known, 0.3 kWh/GB was assumed as maximum energy consumption, and 0.1 kWh/GB as minimum limit for energy consumption.

After defining the limits for energy consumption per unit of data, the total energy consumption per country and energy consumption per capita per country by data centers are calculated using Equations (3) and (4) respectively. In Equation (3), the total energy consumption by data centers of a given country “X” in a given year “Y” is expressed by the term Te_{CXY}. Likewise, in Equation (4) the energy consumption by data centers per capita in a given country “X” in a given year “Y” is expressed by e_{CXY}. In both equations the term e_{GB} represents the energy consumption per GB of data usage, set to either 0.3 kWh per GB or 0.1 kWh per GB for maximum and minimum limits respectively.

$$Te_{CXY} = DV_{CXY} \times e_{GB} \quad (3)$$

$$e_{CXY} = DPC_{XY} \times e_{GB} \quad (4)$$

2.4. Estimation of energy consumption of data transmission networks

In addition to data processing at the data center site, there is a data transmission component to the water and energy impact of data usage. As estimated by the International Energy Agency (IEA) [31], data transmission networks alone consumed 30% to 36% more electricity than data centers in 2020. Together, data centers and data transmission networks consume globally 2.1% to 2.4% of the global final electricity demand [19]. Despite the constant increase in data traffic, technological advances have kept the energy consumption of data transmission networks relatively constant globally since 2010 [31]. Moreover, electricity consumption varies according to the media and technology of transmission [31], with wireless having currently a higher energy intensity than wired media. It is estimated that in 2021 around 40% of the electricity consumed by data transmission networks corresponded to wired media, with the remaining being wireless media [32]. In order to estimate the electricity consumption of the data transmission networks, the data center-to-data transmission network ratio (DtT), reported by [31], is used as shown in Equation (5). In Equation (5), Tt_{CXY} represents the energy consumption for data transmission in country “X” in year “Y”, while the constant DtT is at a value of 1.33, obtained from IEA [31] as the electricity consumption ratio of data transmission over data center per GB.

$$Tt_{CXY} = Te_{CXY} \times DtT \quad (5)$$

2.5. Estimation of water demand of data centers

Finally, after the volumes of data and energy had been calculated, it became possible to estimate the water impact. According to [4], there are two components to the water consumption of data centers. First, an indirect water consumption component (IWC_X), which derives from their high electricity consumption and affects data transmission and data center operation. Depending on the electricity source, the water consumption for electricity production can vary greatly, where thermal

Table 1
Baseline water consumption factors per unit of electric energy per country, from Lohrmann et al. [36].

ISO Country code	Country	IWC_x, m^3/MWh
AUT	Austria	8.55
BEL	Belgium	1.31
CZE	Czech Republic	3.7
DNK	Denmark	0.55
EST	Estonia	1.74
FIN	Finland	4.22
FRA	France	4.23
DEU	Germany	2.04
GRC	Greece	3.87
HUN	Hungary	8.55
ISL	Iceland	13.19
IRL	Ireland	1.33
ITA	Italy	1.4
LVA	Latvia	1.74
LTU	Lithuania	1.74
LUX	Luxembourg	1.31
NLD	Netherlands	1.31
NOR	Norway	15.47
POL	Poland	2.07
PRT	Portugal	3.74
SVK	Slovak Republic	3.7
SVN	Slovenia	6.94
ESP	Spain	3.74
SWE	Sweden	7.66
CHE	Switzerland	10.24
GBR	United Kingdom	1.33
	Average	4.45

power plants and hydropower plants have considerably higher water consumption than renewables like solar photovoltaic (PV) and wind as found by several authors like Lohrmann et al. [33], Pan et al. [34] and Zhang et al. [35]. In order to accurately account for this component, the geographically distributed water consumption by the energy sector, as estimated in Lohrmann et al. [36], is considered for each specific country. These water consumption factors per unit of energy, obtained from [36] are presented in Table 1. These factors are considered constant for the period 2020–2030, due to the unlikeliness of dramatic changes in the power sector in any of the presented countries within the next eight years.

The second component is the direct water consumption used for cooling of the data center. This component has proven to be more controversial (although historically more water has been consumed indirectly) as new data centers open in areas of high water stress, with the typical data center using the water equivalent of a city of 30,000 to 40,000 inhabitants [37]. Mytton [4] estimates that a 1 Megawatt (MW) data center uses 25.5 million liters of water per year for cooling, however water consumption takes place in relation to energy use rather than capacity. Based on this information, it was assumed that a 1 MW data center that operates without interruption, consumes 8670 Megawatt-hours (MWh) of electricity per year, which was considered being constant for the period 2020–2030. Therefore, the components of water consumption at the data center are calculated according to Equations (6), (7) and (8) for indirect, direct and data transmission water consumption respectively.

$$TIWC_{XY} = Te_{CXY} \times IWC_X \tag{6}$$

$$TDWC_{XY} = Te_{CXY} \times WCC \tag{7}$$

$$TTWC_{XY} = Tt_{CXY} \times IWC_X \tag{8}$$

$$TWC_{XY} = TIWC_{XY} + TDWC_{XY} + TTWC_{XY} \tag{9}$$

In Equation (6), $TIWC_{XY}$ stands for the total indirect water consumption at data centers of country "X" in year "Y", while Te_{CXY} is obtained from Equation (3) and IWC_X is as presented in Table 1. In Equation (7), $TDWC_{xy}$ stands for total direct water consumption at the data center site (for cooling) and *WCC* stands for the water consumption for cooling constant, calculated as 2.94 m^3 of water per MWh of electricity used in the data center, obtained from [4]. Besides the direct and indirect water consumption at the data center site, Equation (8) presents the indirect water consumption derived from data transmission networks. In Equation (8), $TTWC_{XY}$ represents the total transmission water consumption of country "X" on year "Y", estimated using the same geographically distributed water intensity per unit of energy, IWC_X as in Equation (6). Finally, the term TWC_{XY} in Equation (9) represents the

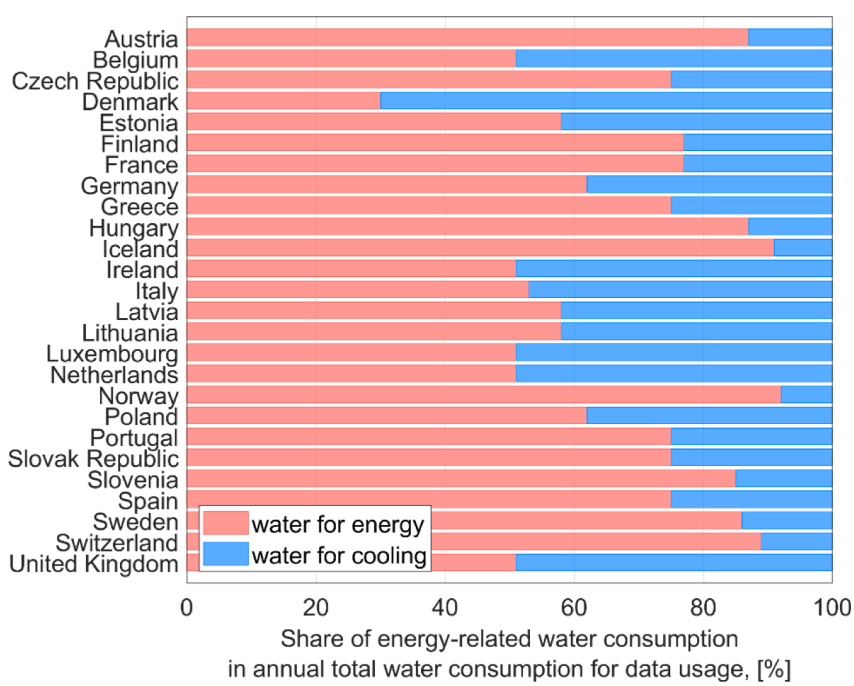

Fig. 4. Distribution of the direct (blue) and indirect (red) components of water consumption for data usage for all OECD-Europe countries. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

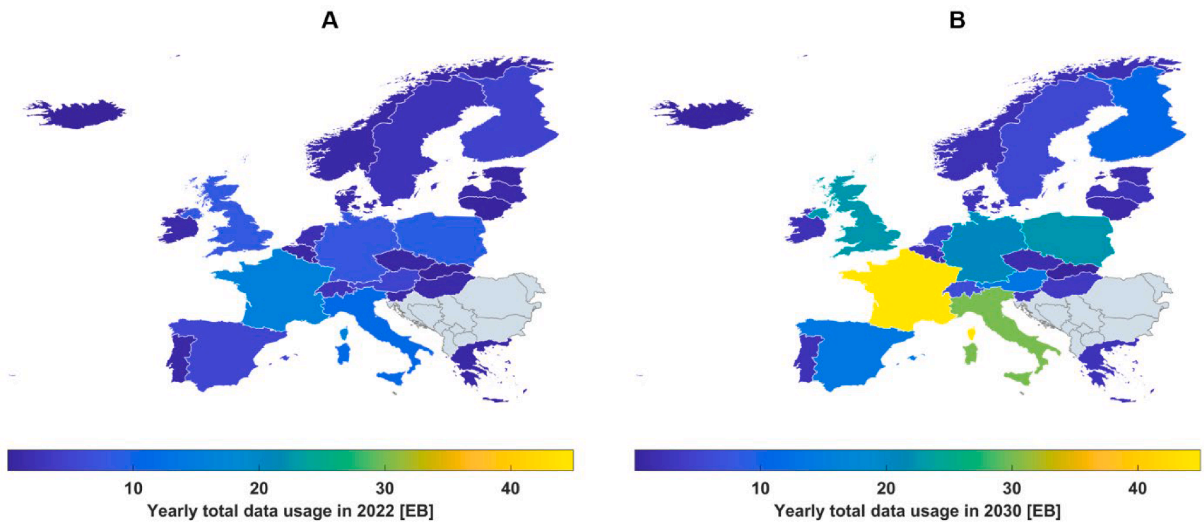

Fig. 5. Projected development of the yearly total data usage in OECD-Europe from 2022 (A) to 2030 (B).

total water consumption for data usage of country “X” in year “Y”.

2.6. Sensitivity of results

The sensitivity of the obtained results was examined from two perspectives:

First, it was investigated how the assumptions on the energy demand for data services might impact the estimates of the total energy (Te_C) and water (*TWC*) consumption rates in OECD-Europe. To perform this analysis, the assumed energy demand for data services was changed from the assumed average value of 0.2 kWh/GB to 0.1 kWh/GB (min value found in literature) and to 0.3 kWh/GB (maximum value found in literature). The results of this analysis are presented in Fig. 9 in the form of min–max interval. Similar analysis was conducted on a per country level. The country-specific min–max intervals for the energy and water demand of data services are provided in Table A1 of Appendix.

Second, it was investigated how the previously calculated country-specific min–max deviations of the energy and water demand may affect the aggregated Te_C and *TWC* OECD-Europe values:

$$eS_{xy} = \frac{\Delta Tec_{XY}}{TeC} \tag{10}$$

$$WS_{xy} = \frac{\Delta TWC_{XY}}{TWC} \tag{11}$$

eS_{xy} and WS_{xy} – sensitivity of the European energy and water demand to the country-specific estimates, in percent. In the equations, ΔTec_{XY} and ΔTWC_{XY} refer to the difference between the midpoint and the previously calculated min (max) values of energy and water demand, respectively. The results of this calculation are presented in Fig. 10.

All sensitivity analyses performed in this study are local because they examine the influence of a single parameter (energy demand for data services) on the final results while holding all other parameters constant.

3. Results

This section presents the core findings of the study, separated into main insight categories.

3.1. Composition of data services’ water demand

Fig. 4 shows the distribution of both direct and indirect components of water consumption for all countries in the study.

As seen in Fig. 4, the distribution of water usage for either cooling or

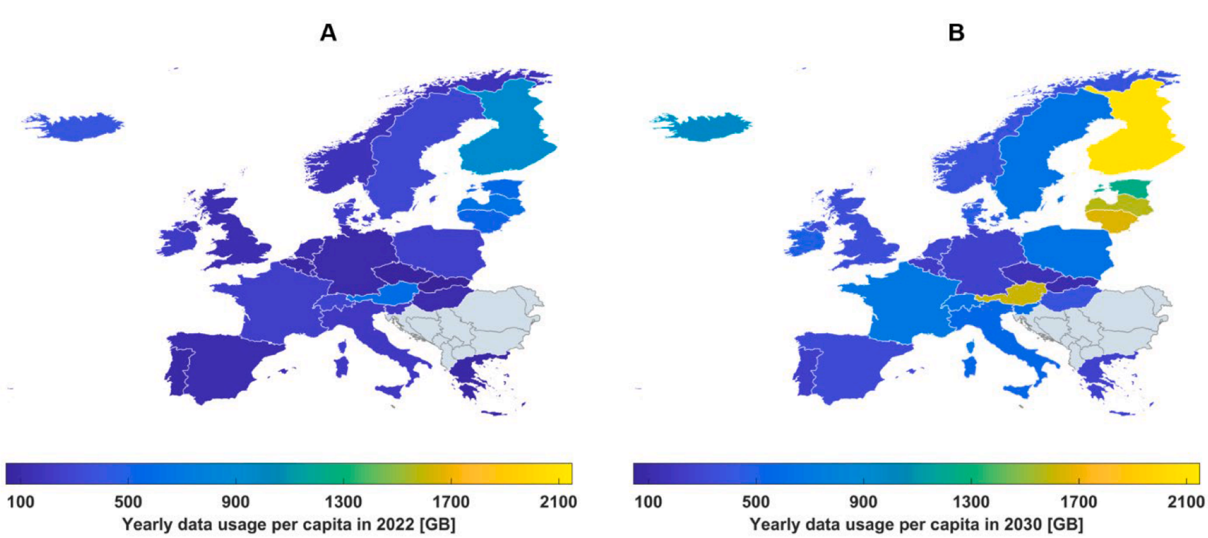

Fig. 6. Projected development of the yearly data usage per capita in OECD-Europe from 2022 (A) to 2030 (B).

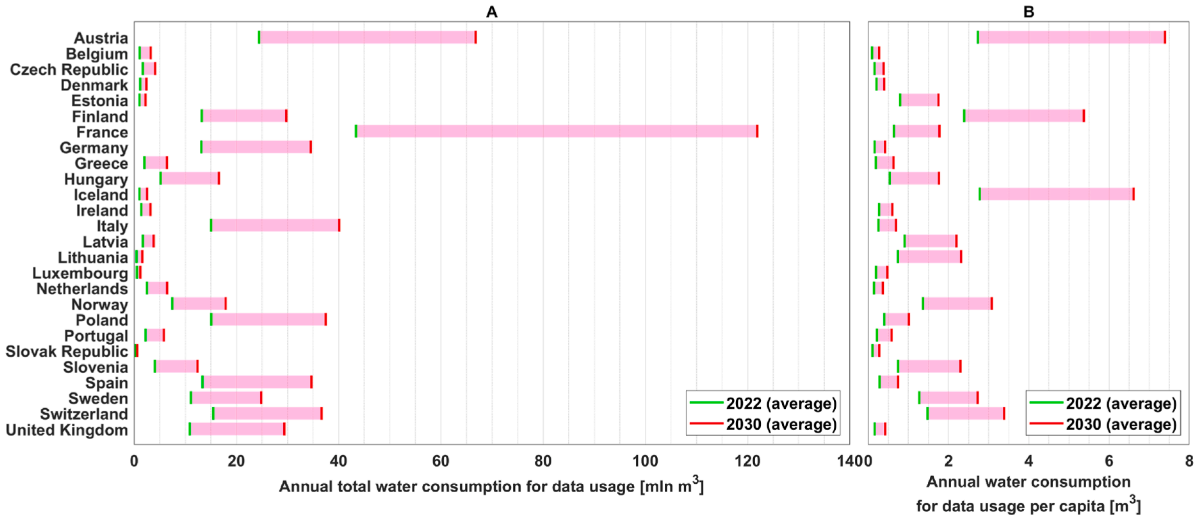

Fig. 7. Projected development of the total (A) and per capita (B) values of water consumption for data usage from 2022 to 2030.

electricity generation varies significantly from one country to another. The variation is directly linked to the composition of the energy system of each country. Consequently, only one country, Denmark, dedicates most of its water use as direct consumption to the cooling of data centers. Out of the 26 countries, 9 countries consume water close to evenly between direct and indirect, and the remaining 16 countries consume either noticeably or significantly more water indirectly than directly.

3.2. Projected development of data usage and population

As projected by The World Bank [27], the populations of the countries within the scope remain relatively constant, with the largest increase in population projected in Lithuania at 9.6% and the largest decrease experienced by Latvia at −8.4% from 2020 to 2030. Overall, the aggregated population of the countries analyzed increases by only 0.1% from 2020 to 2030. Out of the 26 countries analyzed in the study, six have a population exceeding 20 million (mln) inhabitants: Germany (82.3 mln), UK (69.6 mln), France (68.7 mln), Italy (58 mln), Spain (46.7 mln) and Poland (37 mln) in 2030. Since total data usage of each country is a function of the population as well as data usage per capita, these countries naturally represent the largest data consumers within the group.

However, the significant differences in consumer and subscription behavior among the countries causes a significant shift in the standings in comparison with the population. The countries that are projected to have the largest data usage in Exabytes (EB) according to the identified trends are: France (44.3 EB), Italy (30.1 EB), UK (22.7 EB), Poland (22.5 EB), Germany (20.9 EB) and Spain (13.8 EB) as expected by 2030, as shown in Fig. 5. Among these countries, only Poland reached the upper limit of two mobile subscriptions per capita, but with roughly double the data usage per subscription in 2030 compared to Spain and Germany caused it to climb two positions compared to the population rank. The largest drop in standing compared to the population ranking is Germany that, despite having the largest population, is projected to have the lowest data use per subscription among the top six countries, according to the current trends. France tops the rank due to having the second highest population in the group, but the highest data usage per subscription from the top six countries. Among all countries in the scope, Finland is projected to have the highest data usage per subscription by 2030, just as it is today. The highest data usage per capita, shown in Fig. 6, happens in Finland, Austria, the Baltic States and Iceland.

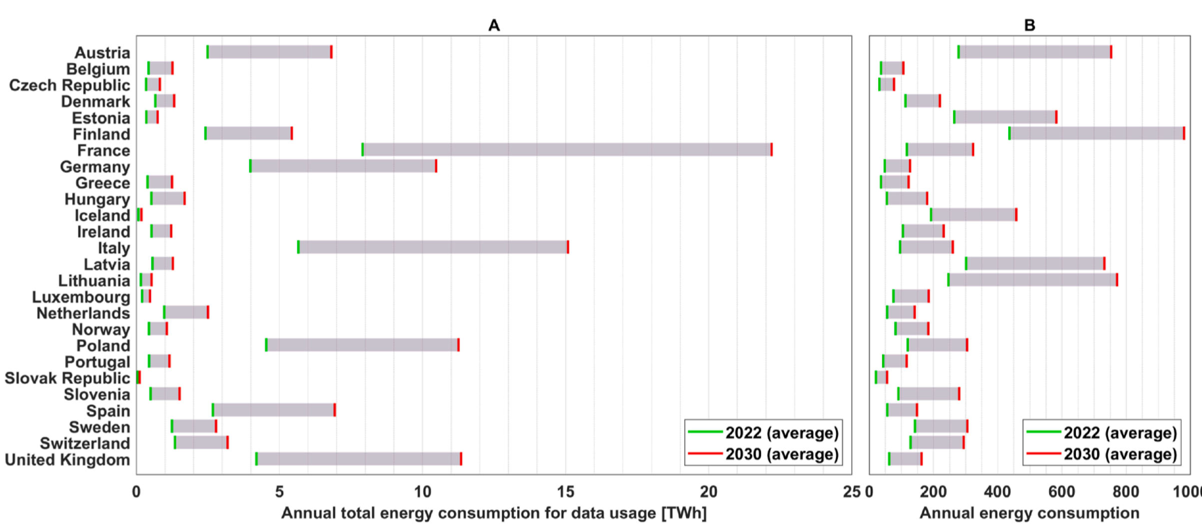

Fig. 8. Projected development of the total (A) and per capita (B) values of electricity consumption for data usage from 2022 to 2030.

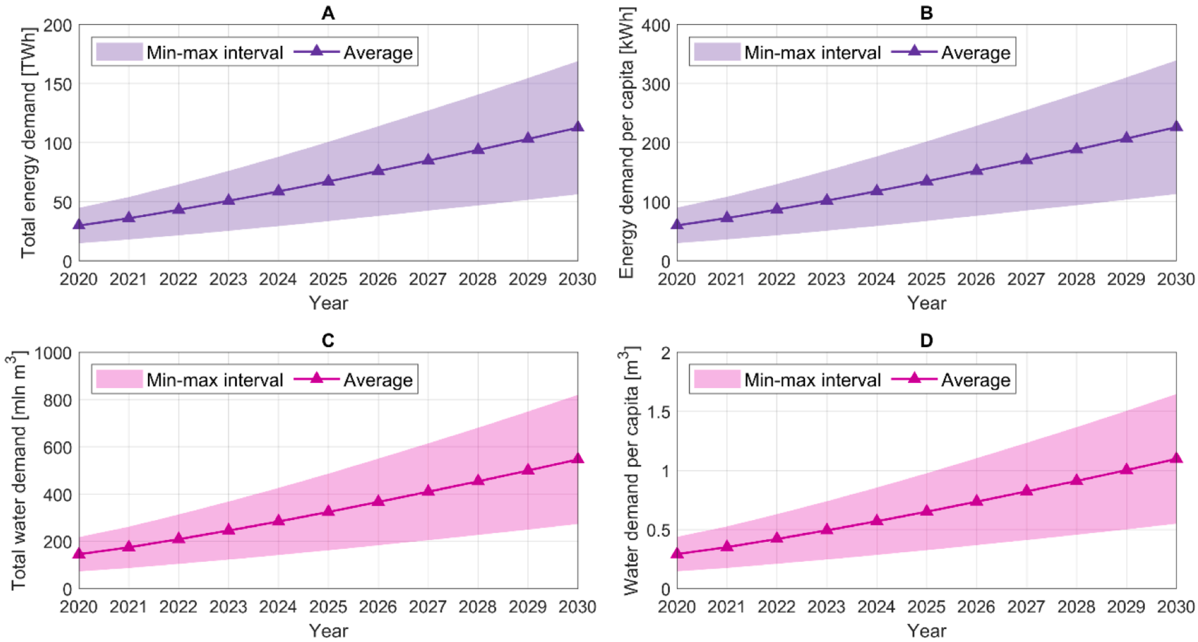

Fig. 9. Projected development of total energy demand (A), energy demand per capita (B), total water demand (C) and water demand per capita (D) for data usage in the aggregated region of OECD-Europe between 2020 and 2030.

3.3. Projected water and electricity consumption

Moreover, aside of the total data usage and subscription behavior, the water intensity of each country's power sector exerts additional influence on the water consumption behavior, added to the previously discussed factors. With a power sector with water footprint close to the average, but large population and data usage, France is projected to require between 60.9 and 182.8 million cubic meters of water yearly for running its data centers by 2030. In second place comes Austria surprisingly, as it has not ranked in the top six countries by any of the previous metrics. With a power system dominated by hydropower, and considerably high data usage per capita (third after Finland and Lithuania), it is projected to require between 33.4 and 100.2 million cubic meters of water in 2030. Italy comes in third place, projected to require between 20 and 60.2 million cubic meters of water in 2030. More than other countries in the top positions for water required for data usage, Italy is currently facing high water stress [38], and this additional load to the water system has the potential to become problematic. Poland, Switzerland and Spain are the next three countries by water demand, each of them having projected to require 18.7–56.2, 18.3–55 and 17.3–52 million cubic meters of water in 2030 respectively. The averages between the minimum and maximum values projected for water demand between 2022 and 2030 for data usage are shown in Fig. 7. The aggregated water demand from all countries studied adds up to between 273.4 and 820.1 million cubic meters of water per year by 2030, 22.3% used by France, 12.2% by Austria, 7.3% by Italy, 6.9% by Poland, 6.7% by Switzerland and 6.3% by Spain. The top six countries thus concentrate 61.8% of the water demand for data purposes of the total from all countries analyzed.

Finally, the electricity consumption for data usage, both in total as well as in per capita values, follows the trends set by the data usage projections. Fig. 8 presents the projected development range of total and per capita values of energy consumption for data usage as averages of the maximum and minimum values for 2022 to 2030. As shown in Fig. 8,

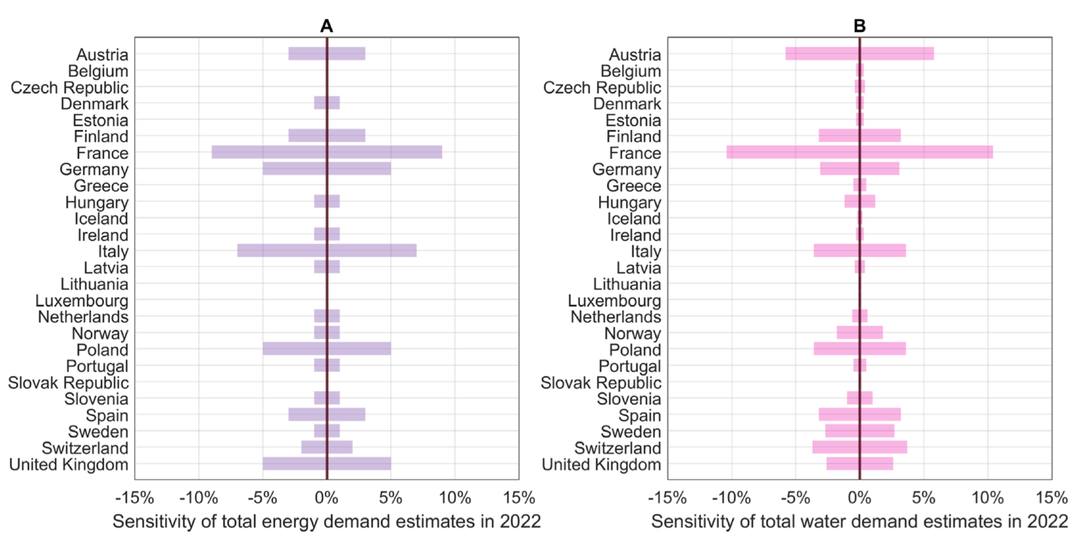

Fig. 10. Sensitivity analysis results of the European energy (A) and water (B) demand assumptions to the country-specific estimates.

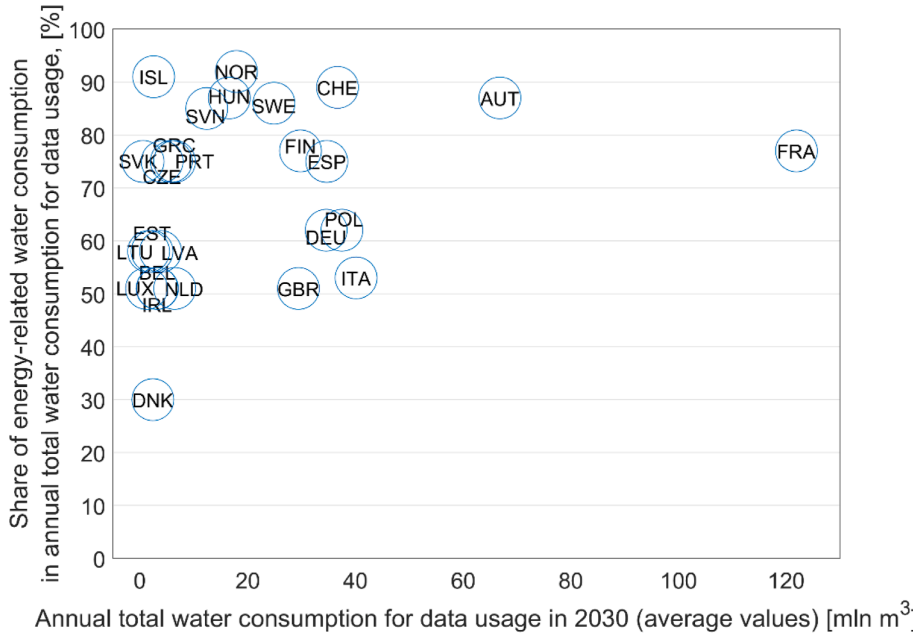

Fig. 11. Water impact of the electricity component as percentage of the total data usage water consumption per country (vertical axis), compared to the total projected water consumption for data usage per country by 2030 (horizontal axis).

the countries that experience higher energy consumption in total are France, Italy, UK, Poland, Germany and Spain with 7.9–22.2, 5.7–15.1, 4.2–11.4, 4.5–11.3, 4–10.5, and 2.7–6.9 TWh respectively.

The results for both energy and water consumption in total and per capita for the reference year 2022 and the projections for 2030 are presented in Table 1A of the Appendix. The developments in water and energy consumption from 2020 to 2030, both in total numbers as well as in per capita numbers, is shown in Fig. 8 for the aggregated region of OECD-Europe. It can be noted that in all cases, the maximum estimation for 2020 is close to the minimum estimation for 2030, highlighting the importance and potential impact of energy and water efficiency developments in the sector. All calculations and the visualization of the obtained results were performed via MATLAB software.

3.4. Sensitivity analysis

The results of the analysis depend on the assumptions used in this study. To understand the possible implication of the energy demand assumptions on the water demand estimates, a sensitivity analysis was performed.

Fig. 9 depicts the Min-Max intervals for each year and for the aggregated region of OECD-Europe. The figure presents the developments in water and energy consumption from 2020 to 2030, both in total numbers as well as per capita. For the average numbers, the demand adds up to roughly 112.7 TWh of electricity and 547 million cubic meters of water, representing around 226 kWh and 1.1 cubic meters of water per capita per year for data usage projected by 2030. It can be noted that in all cases, the maximum estimate for 2020 is close to the minimum estimate for 2030, highlighting the importance and potential impact of energy and water efficiency developments in the sector.

The sensitivity analysis was also performed on a per country level. These results for both energy and water consumption in total and per capita for the reference year 2022 and the projections for 2030 are presented in Table 1A of the Appendix.

The next step was to analyse the sensitivity of the European water and energy demand (shown in Fig. 9) to the country-specific estimates (presented in Table 1A of the Appendix). Fig. 10 demonstrates the results of this analysis.

It is apparent that deviations of the country-specific estimates affect the aggregated OECD-Europe values differently. In particular, the potential deviations of estimates for France have the highest influence on the European water and energy demand, compared to other countries. For example, if the actual energy demand for data services in France will be close to 0.3 kWh/GB (maximum value assumed in this study), the aggregated European energy demand will increase by about 9%, whereas the corresponding water demand will increase by about 10% (see Fig. 10).

4. Discussion

The lack of transparency by data service providers makes it challenging to place a study such as this in a broader context. However, despite the limited scientific literature, there are relevant comparisons to be made. For example, Shehabi et al. [39] estimated that in 2020 the data centers in the United States would consumed around 660 million cubic meters of water per year. In Europe for the same year, the consumption is estimated between 72.6 and 217.8 million cubic meters, which is significantly less than that of United States. However, considering that US alone used roughly 36% of the global electricity in data centers [40], as well as the high concentration of data centers in the country, it makes it more likely for the calculated numbers to be relatively accurate. Therefore, transparency legislation is probably needed to understand with detail the real impact of data usage in different locations. Although unlikely at a global level, the European Union could pilot such legislation, just as they have done in the past with privacy-related legislation, such as EU Directive Regulation 2016/679.

On the other hand, water and energy consumption by the sector still needs to be shown in perspective. For OECD-Europe an average use of 226 kWh per capita per year was projected by 2030, for data usage purposes only. This consumption is relatively small compared to the EU28 average for electricity consumption per capita, which in 2016 was estimated at around 6400 kWh per capita [41].

Nevertheless, because of the “double water impact” of data usage, the impact in water is comparatively more significant than that of the electricity. According to [42], the water consumption of the average European inhabitant is 128 L of water per day, which adds up to 46.7 cubic meters of water per year. Considering that for 2030 the projection average is 1.1 cubic meters per year per person for data usage, this

Table A1
Projected development for water and energy consumption for data usage from 2022 to 2030.

Country	2022				2030			
	Energy [Min - Max]		Water [Min - Max]		Energy [Min - Max]		Water [Min - Max]	
	Total (GWh)	Per Capita (kWh)	Total (mln m^3)	Per Capita (m^3)	Total (GWh)	Per Capita (kWh)	Total (mln m^3)	Per Capita (m^3)
Austria	1245.7–3737.1	139.1–417.4	12.2–36.7	1.4–4.1	3405.6–10216.9	376.5–1129.6	33.4–100.2	3.7–11.1
Belgium	214.3–643	18.4–55.3	0.6–1.7	0.05–0.14	629.9–1889.7	53.2–159.5	1.6–4.9	0.1–0.4
Czech Republic	168.9–506.8	15.8–47.3	0.8–2.5	0.1–0.2	414–1242	38.7–116.1	2.1–6.2	0.2–0.6
Denmark	331.7–995.1	56.5–169.5	0.6–1.8	0.1–0.3	661.4–1984.2	109.8–329.5	1.2–3.6	0.2–0.6
Estonia	175.3–525.9	132.5–397.5	0.5–1.6	0.4–1.2	372.6–1117.7	291.1–873.2	1.1–3.4	0.9–2.6
Finland	1208.4–3625.3	218–654	6.6–19.9	1.2–3.6	2718–8154.1	490–1469.5	14.9–44.7	2.7–8.1
France	3952.2–11856.6	58.4–175.1	21.7–65.1	0.3–1	11099.5–33299	161.5–484.6	60.4–182.8	0.9–2.7
Germany	1992.5–5977.6	24–72	6.6–19.7	0.1–0.2	5236.9–15710.8	63.6–190.9	17.3–51.9	0.2–0.6
Greece	198.1–585.2	18.4–55.2	0.6–1.7	0.1–0.3	624.3–1872.9	61.2–183.7	3.2–9.6	0.3–0.9
Hungary	264.5–793.5	27.3–81.9	2.6–7.8	0.3–0.8	845.3–2535.8	89.8–269.5	8.3–24.9	0.9–2.6
Iceland	36.7–107	96.1–288.4	0.5–1.5	1.4–4.2	88–264.1	228.7–686	1.3–3.8	3.3–9.9
Ireland	266.2–798.5	52.5–157.6	0.7–2.1	0.1–0.4	611.2–1833.6	115.8–347.5	1.6–4.7	0.3–0.9
Italy	2833.2–8499.5	47.8–143.3	7.5–22.6	0.1–0.4	7539–22617.1	130–390.1	20.1–60.2	0.3–1
Latvia	281.4–844.2	150.8–452.4	0.8–2.5	0.5–1.4	636.9–1910.6	366–1098	1.9–5.7	1.1–3.3
Lithuania	79.7–239.2	123.2–369.7	0.2–0.7	0.4–1.1	267.1–801.2	385.4–1156	0.8–2.4	1.2–3.5
Luxembourg	102.7–308.1	37.5–112.4	0.3–0.8	0.1–0.3	237.6–712.9	92.5–277.4	0.6–1.8	0.2–0.7
Netherlands	487.5–1462.4	27.8–83.5	1.3–3.8	0.1–0.2	1253.1–3759.2	70.8–212.3	3.2–9.7	0.2–0.5
Norway	222.8–668.5	40.7–122.2	3.7–11.2	0.7–2	535–1604.9	91.9–275.8	9–26.9	1.5–4.6
Poland	2268.5–6805.6	60–179.9	7.6–22.7	0.2–0.6	5626.2–16878.7	152.1–456.4	18.7–56.2	0.5–1.5
Portugal	224.2–672.6	21.9–65.7	1.1–3.4	0.1–0.3	580.7–1742	58.1–174.4	2.9–8.7	0.3–0.9
Slovak Republic	22.1–66.3	10.5–31.6	0.1–0.3	0.1–0.2	57.8–173.3	27.9–83.6	0.3–0.9	0.1–0.4
Slovenia	247.8–743.3	45.4–136.2	2–6.1	0.4–1.1	755.2–2265.5	140–420	6.2–18.6	1.1–3.4
Spain	1336.1–4008.2	28.3–84.8	6.7–20	0.1–0.4	3467.5–10402.4	74.3–223	17.3–52	0.4–1.1
Sweden	622.9–1868.6	71.2–213.6	5.6–16.7	0.6–1.9	1394.1–4182.4	152.6–457.8	12.4–37.3	1.4–4.1
Switzerland	673.6–2020.7	64.3–193	7.7–23.2	0.7–2.2	1594.9–4784.6	147–441.1	18.3–55	1.7–5.1
United Kingdom	2099.7–6299.1	31–92.9	5.4–16.3	0.1–0.2	5675.9–17027.7	81.5–244.6	14.7–44.1	0.2–0.6
Total	21552–64657	43.3–129.8	104.5–313.6	0.21–0.63	56327–168982	113.1–339.4	273.4–820.1	0.55–1.65

represents about 3 L of water per day on data by 2030.

Moreover, the water impact from the energy component is directly influenced by the composition of the energy system, as described by Lohrmann et al. in [33] and [36]. Therefore, the overall water impact of data usage can be dramatically reduced through transitioning the energy systems towards renewables [31]. Specifically, wind and solar photo voltaic have the lowest water footprint from all power generation technologies [31], while reservoir-based hydropower has the highest water footprint. Thermal power generation such as coal and nuclear have also relatively high water footprints, as described in Lohrmann et al. [33] and Meldrum et al. [43]. Consequently, if the increasingly universal commitment to a carbon–neutral power system comes to fruition, it would cause a significant reduction of water use by the digital service industry, as well as for any other energy-intensive industry. As reference, Fig. 11 shows the percentage of the total water demand for data usage represented by the energy component (data center plus data transmission) on the vertical axis, as well as the total water consumption for data usage (TWC_{XY} from Equation (9)) per country by 2030 on the horizontal axis. A clear outlier in the graph is again France, allocating roughly 77% of the water demand for data usage to electricity production, while having also the largest projected water consumption for data usage by 2030. Norway and Iceland, with relatively small population but with energy systems heavily dominated by hydropower (and geothermal in the case of Iceland), both dedicate over 90% of their water for data usage to the electricity component. In contrast, Denmark, with a power system dominated by wind power, allocates only around 30% of the total water consumption for data usage to electricity generation.

However, not all digital data communication results in a detriment to the environment. For example, the digitalization of controls and sensors can help the optimization of resource management systems, potentially reducing the environmental impact of water and energy systems alike. Some examples of this potential benefit are shown for reservoir management [9], nutrient management for agricultural systems [44], increasing energy efficiency in agricultural systems [45] and municipal scale energy management [46] to name some. Digitalization is also a cornerstone to the deployment and operation of smartgrids, which in turn allows for more distributed power generation favoring renewables over large fossil-based centralized generation [47]. Therefore, the impact of data usage in the larger context regarding energy and water is yet to be thoroughly investigated. Moreover, one should be conscious also of the environmental impact of digitalization also from the increasing demand for rare earth materials needed to produce the electronics associated with digital devices [48].

5. Conclusions

The presence and penetration of digital data has been constantly increasing since its inception, and there is no reason to believe this trend will revert its course anytime soon. However, the growing hunger for data resources comes at a cost, as there is an energy and water cost that is not immediately evident to the users. These costs are not self-evident in part because of the lack of transparency and accurate reporting by data service providers and, on the other hand, digital data usage is not commonly associated with its water and electricity consumption. Instead, digital data is more often mentioned in the context of data volume and data transmission speeds.

Therefore, it is of high importance to provide a clear picture of the energy and water cost of data. To that end, available data provided by the OECD and The World Bank was used, as well as data published in the scientific literature, to produce an estimation and projection of the energy and water needs of the sector from 2022 to 2030. Following the current trends, the data usage in OECD-Europe will grow from the current 86 EB to 225 EB by 2030.

The growth in data usage is therefore projected to cause an increase of energy and water usage by data centers. The estimated yearly energy consumption for data usage is expected to increase from the average level of 29.8 TWh in 2020 up to around 112.7 TWh by 2030, with per capita estimated values increasing from the 2020 average of 54.9 kWh to 226 kWh by 2030. Similarly, yearly water consumption is projected to increase from the 2020 estimate of 145.2 to 546.7 million cubic meters by 2030. In per capita values, yearly water consumption for data usage is projected to increase from the 2020 estimate of 0.29 cubic meters to around 1.1 cubic meters by 2030. If the estimated average of 1.1 cubic meters per capita per year becomes a reality, the daily water consumption for data usage becomes around 3 L per day, which would mean that the average European would be using more water in internet than the amount needed for drinking.

Although these findings are informative in nature, the awareness on the water and energy consumption of digital data services in Europe could function as a reference for future digital infrastructure developments. However, one possible application of this knowledge is for decision-making on where the next data centers should be deployed (logically, locations with the shortest distance to large population centers but in areas of low water stress). In addition, the study could provide a basis for transparency legislation that would oblige data centers operating within the EU to provide open and transparent reports on their data and water usage.

Naturally, alternative approximation methods could provide different results. Particularly for other areas of the world, where the same sources used for this study do not provide data, a collection of sources that vary in the data collection methods or variables reported could still be used to approximate water and electricity consumption in a more expanded geographical scope.

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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Data availability

Data will be made available on request.

Appendix

See Table A1

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