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Spatially distributed freshwater demand for electricity in Africa†

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Although energy requires large amounts of water for its production, (inter)national statistics or reports on water demand for electricity for the African continent are scarce. Here we provide the spatially most detailed analysis presently available on freshwater demand for electricity for the recent year 2020, covering the whole of Africa. We conduct a major data mining effort using only freely accessible data. This results in 2534 individual power plants, including 1447 fossil (coal, oil and natural gas), 1071 renewable (wind, sun, biomass, geothermal and hydropower with the distinction between reservoir and run-of-river or ROR hydropower) and 16 other (waste heat and nuclear) power plants. We categorized the power plants according to applied fuel, operation cycle, infrastructure, cooling system and local climate. The total water withdrawal (WW) and consumption (WC) amount to 33 108 and 23 822 million m^3 per year (Mm^3 per year) respectively, for an annual electricity production of 1 050 674 GWh. Hydropower and natural gas, which have high water withdrawal intensities relative to other energy sources such as wind or sun, account for the largest fractions (70% and 27%, respectively) of total water withdrawal. Our database can be used at any spatial level, as we show results on the national, subnational and river basin level. Countries with high annual WW amounts include Egypt (8937 Mm^3), Ghana (7893 Mm^3), Zambia (5262 Mm^3), Mozambique (2602 Mm^3), Nigeria (2309 Mm^3) and South Africa (1068 Mm^3). River basins with high WW amounts include the Nile (10 377 Mm^3), the Volta (7765 Mm^3), the Zambezi (7596 Mm^3) and the Niger (2562 Mm^3) river basins. In major river basins, these WW amounts do not exceed 10% of renewable water availability, except for the Volta basin, where the value is 43%. By providing all results in a fully open-access database, we provide valuable statistics for any water management or energy stakeholder working in or on Africa.

Water impact

Our research provides the spatially most detailed analysis of freshwater demand for electricity in Africa for the year 2020. We provide our (geo)data freely available. This is crucial because stakeholders often lack the funds to purchase data essential for decision making. As Africa experiences rapid development, this database aims to serve as an exceptional and free resource for sustainable growth.

1 Introduction

Freshwater is a limited resource and its use by different sectors leads to water scarcity in many places around the world.[1] Although the agricultural sector globally uses the most water,[2] water use in other sectors, including the energy sector, is also increasing due to a combination of economic development, population growth, urbanization, and other factors.

Considering Africa has a fast-growing population and the largest population growth between now and 2050,[3] the continent stands out as a key region with projected increases in water demand. Modern energy consumption *per capita* in Africa is currently among the lowest in the world, but the continent is developing fast, with a growing production and consumption of electricity.[4] There are, however large regional differences, with only three countries, South Africa, Egypt and Algeria, producing 60% of Africa's electricity.[4]

Previous research has shown that electricity production requires substantial amounts of water.[5–9] Modeling efforts

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have shown that globally, water use for energy is increasing, indicating the hotspots where this might occur.[10] The latter study, however, also showed that for the African continent, model outcomes have a high degree of uncertainty. This is mainly due to limited data availability. In African countries, electricity is generated by a diverse set of power plants, showing huge variation in installed capacities, and using different fuels and technologies. Peters *et al.*,[11] for example, made an inventory of hydropower plants, solar parks and wind farms for African countries. The study showed that hydropower is the largest renewable electricity source in Africa, contributing 16% to the total production, while the contribution of sun and wind are far less with a contribution of 1.5% and 1.2%, respectively. This means that Africa currently relies on fossil fuels (coal, natural gas and oil) for its electricity supply.

Information on individual power plants is often behind paywalls, sometimes requiring substantial amounts for even limited information.[12] To buy and collect information for more than 2500 African power plants is very resource-intensive for many stakeholders and institutions. In addition, these data often have many access restrictions and cannot be shared once analyzed and harmonized. To be free of any input data license restrictions when sharing scientific results, it is thus essential to use open access input data.

Water needs for electricity generation show huge differences among technologies and fuels.[7,13] Local water availability can, therefore, put serious constraints on the electricity sector. When water availability is low, for example, during dry periods, hydropower output might be smaller than estimated or thermal power plants might need to close.[14,15] To know the water demand of power plants and their exact location is therefore essential for current and future energy planning.

Despite the growing importance of water for electricity, only a few (inter)national statistics or reports on freshwater demand for electricity covering the African continent are available. Aquastat,[16] the international reference for national sectoral water use data, provides only limited data. National reports are scarce and generally do not provide any indication of power plant fuel type or subnational amounts.[17] Currently, for the decade of the 2020s, no spatially detailed analysis differentiating between power plant fuel types and covering the whole African continent exists. Our analysis for the year 2020 fills this scientific gap.

Here, we present a major data mining effort using only open access data to compute the freshwater demand for African power plants. We separated the power plants according to fuel type, operation cycle, infrastructure, cooling system, and local climate, so we could choose the adequate water intensities for each power plant. First, different public sources were used to make an inventory of over 2500 power plants in 54 countries and 6 additional political entities, including their fuel type, installed capacity, electricity generation, operability and exact location.

Water demand was computed as blue water withdrawal (WW) and blue water consumption (WC).[18,19] Blue water or freshwater refers to water in rivers, lakes, wetlands and aquifers. WW refers to the volume of water extracted from its source (rivers, lakes, aquifers) for any economic activity or sector. WC refers to the portion of WW that is not returned to the original water source after being withdrawn or flows to the atmosphere through evaporation. We computed only operational freshwater, such as the cooling water of thermal power plants, the cleaning water of photovoltaic (PV) installations and the evaporation of hydropower water. Our study distinguishes between salt and freshwater, by identifying cooling types and locations per power plant. For hydropower, we estimated specific water consumption and withdrawal per climate zone.

By using only open access input data, we are able to offer our database and analysis open access for any user. Apart from the database, we also provide results on national, subnational and river basin level.

2 Results

We identified 2534 individual power plants, which in 2020 collectively accounted for a total WW of 33 108 Mm^3 per year and a WC of 23 822 Mm^3 per year, for an annual electricity production of 1 050 674 GWh (Fig. 1). Hydropower accounts for the largest fraction, *i.e.* 70% (23 038 Mm^3) of total WW and 97% of total WC, although it only accounts for 13% (141 139 GWh) of total electricity produced. Reservoir hydropower requires much more water than other energy sources to produce the same output of electricity, as shown by its high African average water intensity of 175.7 m^3 MWh^{-1} (Fig. 1 bottom). Run-of-river or ROR hydropower has a much lower water intensity of 2.4 m^3 MWh^{-1}. Reservoir hydropower is the main source of hydropower production in Africa. From 561 hydropower plants, the 183 with a reservoir produce 130 957 GWh whereas the 378 ROR plants produce 10 183 GWh.

The fossil energy sources oil, coal and natural gas produce combined 82% (860 221 GWh) of total electricity (Fig. 1). They account for 30% (9994 Mm^3) of total WW and 3% (761 Mm^3) of total WC. Especially gas, with a relatively high African average WW intensity of 17.3 m^3 MWh^{-1}, accounts for a large fraction (27% or 9003 Mm^3) of total WW.

The renewables wind, sun, biomass and geothermal account combined for 0.2% (70 Mm^3) of total WW and 0.1% (21 Mm^3) of total WC, for 3% (31 971 GWh) of total electricity produced. Biomass is the most water intensive of these renewables (WW 10.5 m^3 MWh^{-1} and WC 2.0 m^3 MWh^{-1}), whereas wind, sun and geothermal have very low water factors (both WW and WC lower than 1.5 m^3 MWh^{-1}). Other energy sources (waste heat and nuclear) account for very low water demands for 1.7% of total electricity produced. Latter amount is largely attributed to the sole African nuclear power plant located at Koeberg, close to Cape Town, in South Africa. Its water factor is low as saline water, and no freshwater, is used for cooling.

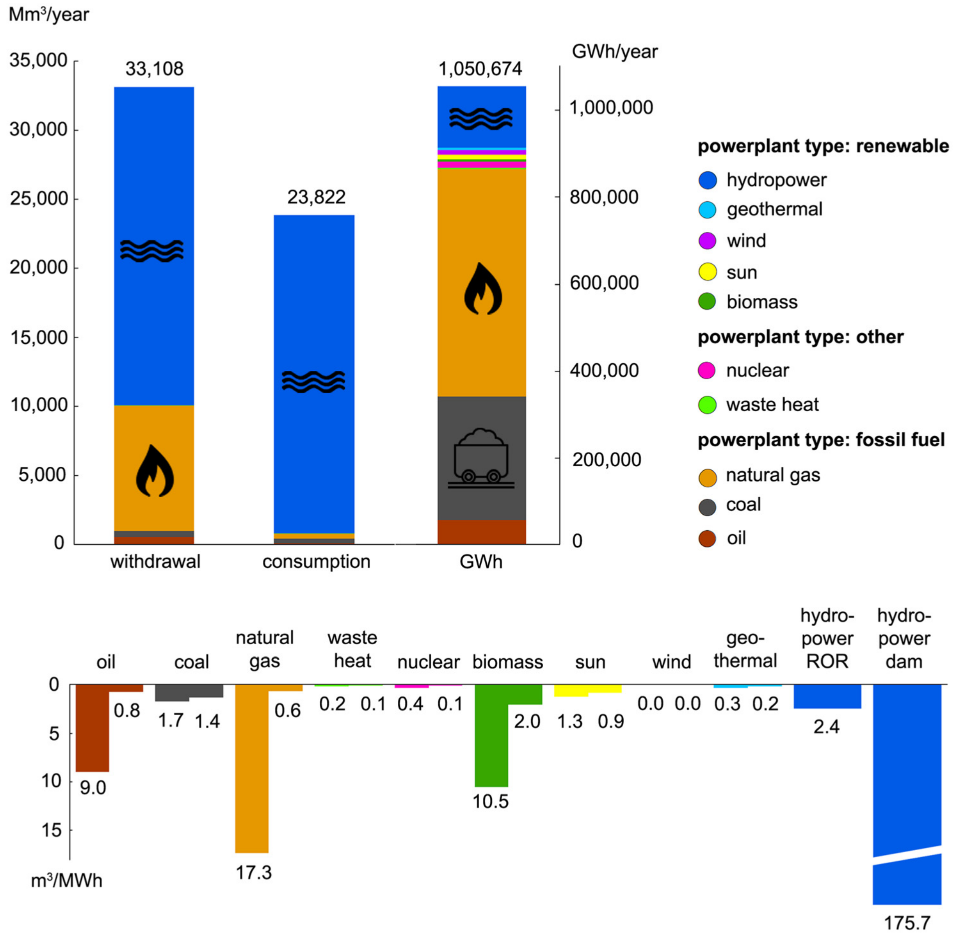

Fig. 1 (Top) Water withdrawal (WW) and consumption (WC) per powerplant fuel for the whole of Africa (in million m^3 per year or Mm^3 per year) as well as the related electricity produced in GWh. (Bottom) Average water intensity (WW and WC) per powerplant fuel for Africa (in m^3 MWh^{-1}). Note that these are average values for all 2534 power plants, whereas individual plants show a wide range (range of values shown in Table 3).

The 2534 individual power plants are distributed over the African continent in a spatially heterogeneous way. Fig. 2a shows the location of power plants according to fuel type and WW quantity. Of 1054 oil-fired power plants (Fig. 2b), 1% accounts cumulatively for more than 95% of the total WW of 506 Mm^3, with the three largest water users at 332 Mm^3 (New Asyut in Egypt), 65 Mm^3 (Kpone Cenpower in Ghana) and 50 Mm^3 (Kenitra in Morocco). Of 49 coal-fired power plants (Fig. 2c), the ten with the highest WW amounts are all located in South Africa, including Kendal (59 Mm^3), Lethabo (53 Mm^3) and Tutuka (52 Mm^3). Of 343 gas-fired power plants (Fig. 2d), the ten with the highest WW amounts are all located in Egypt and account for over 80% of total WW of 9002 Mm^3. The three largest Egyptian plants in terms of WW are South Helwan (1279 Mm^3), Cairo West (892 Mm^3) and Giza North (843 Mm^3).

Of 183 reservoir hydropower plants, 30 account for a WW larger than 100 Mm^3 and cumulatively sum up to exceed 95% of the total WW of 23 013 Mm^3 (Fig. 2a and e). Of these, the four largest exceed 1000 Mm^3: Akosombo in Ghana (7503 Mm^3), Kariba North in Zambia (4904 Mm^3), Cahora Bassa in Mozambique (2319 Mm^3) and Kainji in Nigeria (1135 Mm^3). For all other fuel types, there are 912 power plants, which account for a WW of 167 Mm^3, with 82% of them having WW values lower than 1 Mm^3 (Fig. 2f).

These individual power plant amounts can be aggregated to any political boundary, such as the national level or subnational level (Fig. 3 and Table 1). Countries with the highest national WW amounts are in decreasing order: Egypt (8937 Mm^3), Ghana (7893 Mm^3), Zambia (5262 Mm^3), Mozambique (2602 Mm^3), Nigeria (2309 Mm^3), South Africa (1068 Mm^3), Ethiopia (919 Mm^3), Sudan (849 Mm^3), Cameroon (589 Mm^3) and Tanzania (476 Mm^3).

On the subnational level (GADM level 1 political boundaries,[20] the 10 regions with the highest WW amounts are, in decreasing order: Eastern in Ghana (7503 Mm^3), Southern in Zambia (4913 Mm^3), Al Jizah in Egypt (3587 Mm^3), Tete in Mozambique (2319 Mm^3), Niger in Nigeria (1659 Mm^3), Bani Suwayf in Egypt (1348 Mm^3), Al Buhayrah in Egypt (1188 Mm^3), Asyut in Egypt (727 Mm^3), Al Qahirah in Egypt (629 Mm^3) and Oromia in Ethiopia (604 Mm^3) A full list of (sub)national (GADM level 1) WW and WC amounts is provided in Table 1 and in the Supporting information (SI_Results).

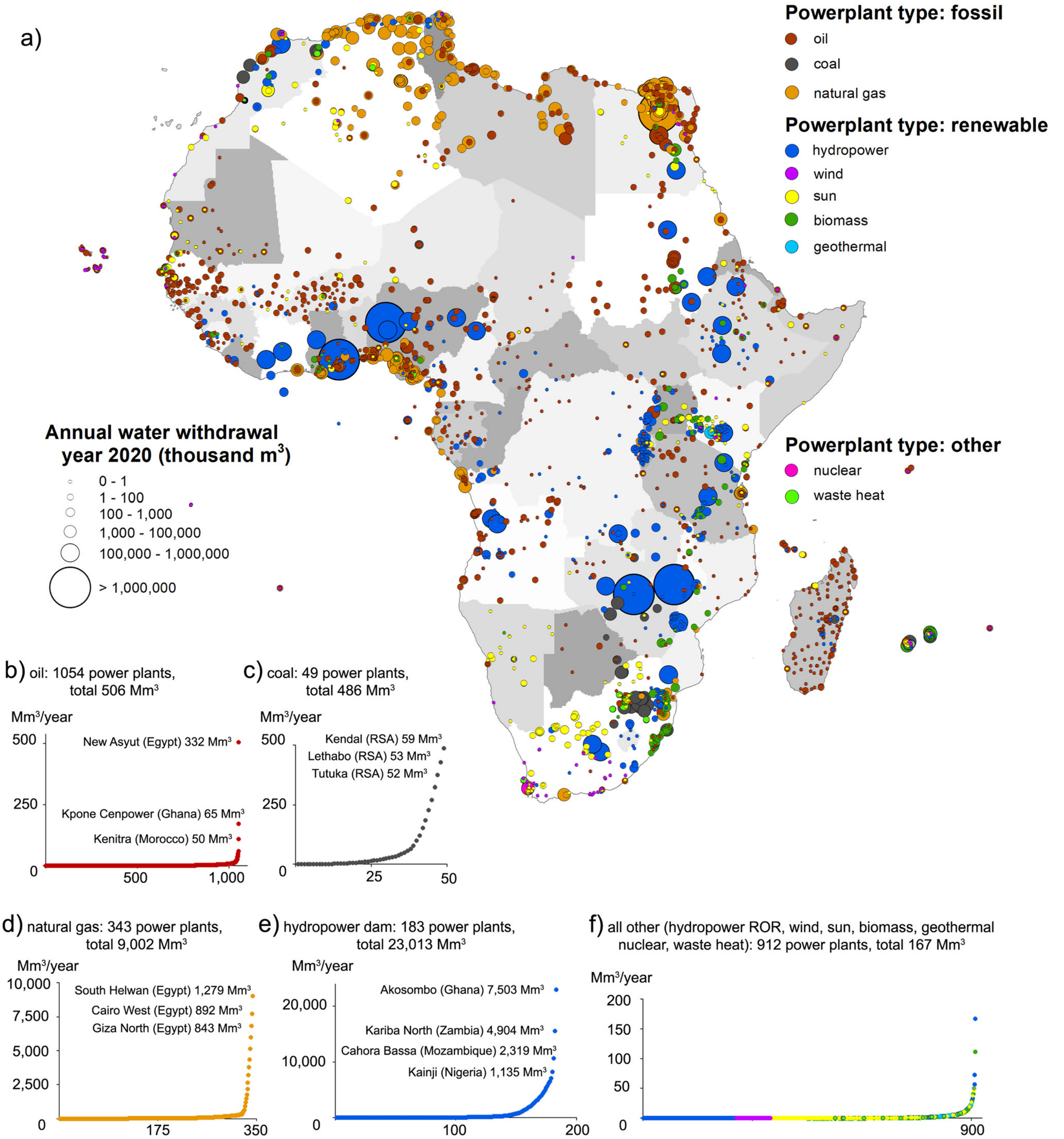

Fig. 2 Annual water withdrawal for the 2534 individual power plants covering Africa. a) Map of Africa with location power plants according to fuel type and water withdrawal quantity (in 10^3 m^3). Greyshade of countries to distinguish between different countries. b–f) Ranking of water withdrawal quantities (in Mm^3) of individual power plants (*Y*-axis) from small to large on a cumulative *X*-axis per fuel type with identification of plants with largest quantities, for b) oil; c) coal; d) natural gas; e) reservoir hydropower and f) all other fuel types (hydropower ROR, wind, sun, biomass, geothermal, nuclear and waste heat).

The individual power plant amounts can also be aggregated to the river basin or subbasin level (Fig. 4). Major river basins with the highest WW amounts (Fig. 4A) are, in decreasing order, the Nile (10 377 Mm^3), the Volta (7765 Mm^3), the Zambezi (7596 Mm^3), the Niger (2562 Mm^3), the Orange (693 Mm^3), the Congo (445 Mm^3) and the Limpopo (374 Mm^3) river basins. Renewable water availability is heterogeneously spread over Africa and its river basins (Fig. 4B). Of the 49 major river basins we assessed (Fig. 4C), in 41 of them WW for electricity is lower

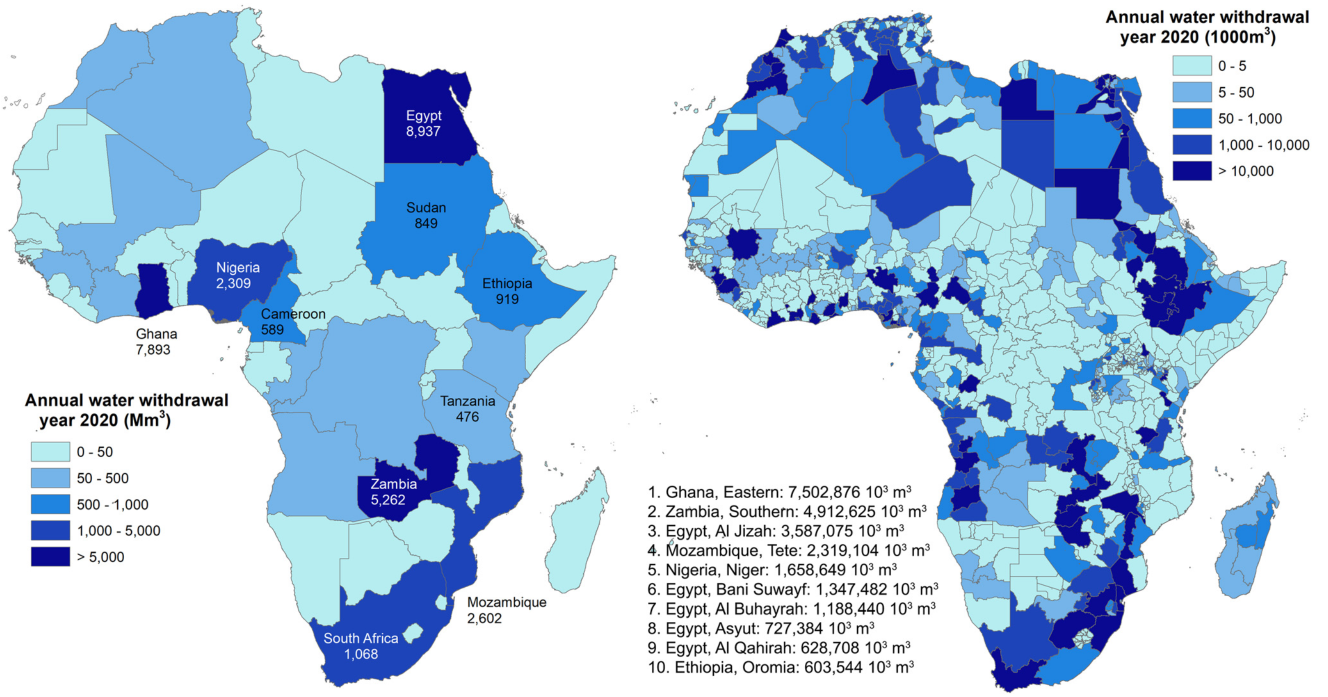

Fig. 3 Annual water withdrawal per country in Mm^3 (left) and on the subnational level in 10^3 m^3 (right). The 10 countries as well as the 10 subnational regions with the highest amounts are highlighted. The subnational values are for GADM level 1 political boundaries.[20] Detailed results for all subnational regions in SI_Results.

than 5% of renewable water availability, including in large river basins such as the Nile (4.8%) and the Niger (2.8%). However, in some this value is between 5 and 10%, such as in the Tana (5.4%), Limpopo (5.4%), Zambezi (8.0%) and Orange (8.7%) river basins. In the Volta basin, the value is with 42.7% very high.

3 Discussion

Our analysis provides the spatially most detailed quantification of the water demand for electricity for the current decade (year 2020) covering the whole of Africa.

We compared our dataset to two other power plant datasets, the World Resource Institute (WRI)'s Global Power Plant Database[22] as well as the Renewable Power Plant Database for Africa (RePP Africa).[11] Both latter datasets do not provide information on WW or WC. Our database includes 2534 power plants (total capacity 245 604 MW), compared to 631 power plants (total capacity 160 533 MW) for the African countries in the Global Power Plant Database (Table 2). For all African countries as well as power plant types, our database has more entries than the Global Power Plant Database. The latter contains over 35 000 power plants globally, with high concentrations in North America, Europe or Brazil, but only a fraction of power plants is located in Africa. RePP Africa includes renewables (hydro, solar and wind) but no thermal power plants. It includes power plants starting with their year of construction until the year 2022. For the year 2022, more power plants (with a higher combined capacity) are included compared to the year 2020 (Table 2). For hydropower, for the year 2020, RePP Africa includes 331 power plants (178 reservoir + 118 ROR + 35 undefined) with a combined capacity of 37 070 MW. Our database includes with 561 power plants (183 reservoir + 378 ROR) many more especially ROR power plants, for a similar total capacity of 36 892 MW. The individual capacity of a power plant is often slightly different due to other data sources used. For sun, our database includes more solar parks (299) compared to RePP Africa (282) (Table 2). For wind, our database includes slightly less wind farms (83) compared to RePP Africa (102). For both sun and wind water intensities are low (Fig. 1 and Table 3), so the difference in amount of power plants will not have a large effect on total WW and WC amounts.

Our analysis fills a large data gap. Aquastat,[16] the global reference on international water use statistics, theoretically includes the statistics "WW for cooling of thermoelectric plants", "instream water usage by hydropower plants" and "evaporation from artificial lakes and reservoirs", for latter two statistics no national data can be found for recent years including the year 2020. For the statistic "WW for cooling of thermoelectric plants", some countries provide statistics, including many European countries. For Africa, only Zimbabwe provides a statistic, *i.e.*, 48 Mm^3 for the year 2020, which is a statistic interpolated from the year 2015. Our study quantifies a WW of 15 Mm^3 for cooling of thermoelectric plants, based on 15 power plants.

Regarding national statistics, few countries provide data on water for energy/electricity. South Africa reports a national

Table 1 National water withdrawal (WW) in Mm^3

	Fossil fuels			Renewables					Other		
Country	Oil	Coal	Natural gas	Hydro-power	Wind	Sun	Biomass	Geo	Nuclear	Waste heat	Total
Algeria	0.4	0.0	83.2	10.7	0.0	0.1	0.0	0.0	0.0	0.1	94.6
Angola	3.6	0.0	9.9	355.5	0.0	0.0	0.0	0.0	0.0	0.0	369.0
Ascension island (UK)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Benin	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
Botswana	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4
Burkina Faso	0.3	0.0	0.0	5.4	0.0	0.0	0.0	0.0	0.0	0.0	5.8
Burundi	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Cameroon	0.6	0.0	0.3	588.3	0.0	0.0	0.0	0.0	0.0	0.0	589.2
Cape Verde	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Central African Republic	0.0	0.0	0.0	3.6	0.0	0.0	0.0	0.0	0.0	0.0	3.6
Chad	0.9	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0
Comoros	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Congo (Republic of het Congo)	0.0	0.0	1.9	77.2	0.0	0.0	0.0	0.0	0.0	0.0	79.0
Congo Dem Rep	0.0	0.0	0.0	357.5	0.0	0.0	0.0	0.0	0.0	0.0	357.5
Cote D'Ivoire	0.0	0.0	1.6	348.3	0.0	0.0	0.0	0.0	0.0	0.0	349.9
Djibouti	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1
Egypt	345.2	0.0	8361.2	190.1	0.0	0.6	39.6	0.0	0.0	0.0	8936.6
Equatorial Guinea	0.0	0.0	0.8	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.8
Eritrea	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Ethiopia	0.0	0.0	0.0	918.8	0.0	0.0	0.1	0.0	0.0	0.0	918.9
Gabon	0.0	0.0	1.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	1.3
Gambia	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Ghana	64.8	0.1	69.3	7758.8	0.0	0.0	0.0	0.0	0.0	0.0	7892.9
Guinea	0.2	0.0	0.0	83.9	0.0	0.0	0.0	0.0	0.0	0.0	84.1
Guinea-Bissau	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kenya	0.5	0.0	0.0	272.3	0.0	0.0	0.1	1.8	0.0	0.0	274.7
Lesotho	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Liberia	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.2
Libya	7.3	0.0	36.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	43.7
Madagascar	0.2	0.5	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.8
Malawi	0.1	0.0	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0	1.3
Mali	0.3	0.0	0.0	60.5	0.0	0.0	0.0	0.0	0.0	0.0	60.8
Mauritania	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4
Mauritius	0.3	4.8	0.3	0.7	0.0	0.0	4.3	0.0	0.0	0.0	10.4
Mayotte (FR)	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Morocco	52.0	9.3	20.4	239.1	0.0	10.1	0.0	0.0	0.0	0.0	330.9
Mozambique	0.0	0.0	0.7	2600.7	0.0	0.0	0.1	0.0	0.0	0.0	2601.5
Namibia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Niger	0.3	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3
Nigeria	2.3	0.0	347.8	1959.3	0.0	0.0	0.1	0.0	0.0	0.0	2309.4
Reunion (FR)	0.7	4.3	0.0	1.5	0.0	0.0	1.5	0.0	0.0	0.0	8.1
Rwanda	0.1	0.0	0.0	2.7	0.0	0.0	0.0	0.0	0.0	0.0	2.8
Sao Tome & Principe	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.3
Senegal	1.1	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	2.6
Seychelles	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
Sierra Leone	0.0	0.0	0.0	17.4	0.0	0.0	0.0	0.0	0.0	0.0	17.4
Somalia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
South Africa	0.1	446.9	29.2	582.8	0.0	2.1	1.1	0.0	5.2	0.4	1067.8
South Sudan	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1
ST Helena (UK)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sudan	16.5	0.0	6.8	825.3	0.0	0.0	0.5	0.0	0.0	0.0	849.0
Swaziland	0.0	0.0	0.0	0.8	0.0	0.0	1.8	0.0	0.0	0.0	2.6
Tanzania	0.1	0.0	5.3	466.1	0.0	0.0	4.1	0.0	0.0	0.0	475.7
Togo	0.0	0.0	0.0	30.7	0.0	0.0	0.0	0.0	0.0	0.0	30.7
Tristan da Cunha (UK)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Tunisia	0.2	0.0	26.4	5.5	0.0	0.0	0.0	0.0	0.0	0.0	32.1
Uganda	4.8	0.0	0.0	10.9	0.0	0.0	1.3	0.0	0.0	0.0	17.0
Western Sahara (Morocco)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Zambia	0.0	2.4	0.0	5259.6	0.0	0.0	0.0	0.0	0.0	0.0	5262.0
Zimbabwe	0.0	15.0	0.0	2.0	0.0	0.0	0.4	0.0	0.0	0.0	17.3
Total Africa	**505.5**	**486.2**	**9002.5**	**23 037.9**	**0.0**	**13.0**	**55.0**	**1.8**	**5.2**	**0.7**	**33 107.9**

WW amount of 335 Mm^3 for electricity for the year 2016.[17] We quantify 448 Mm^3, based upon 23 coal-fired power plants (sum 447 Mm^3), 25 oil-fired power plants (sum 0.1 Mm^3) and 30 biomass-fired power plants (sum 1 Mm^3). Botswana

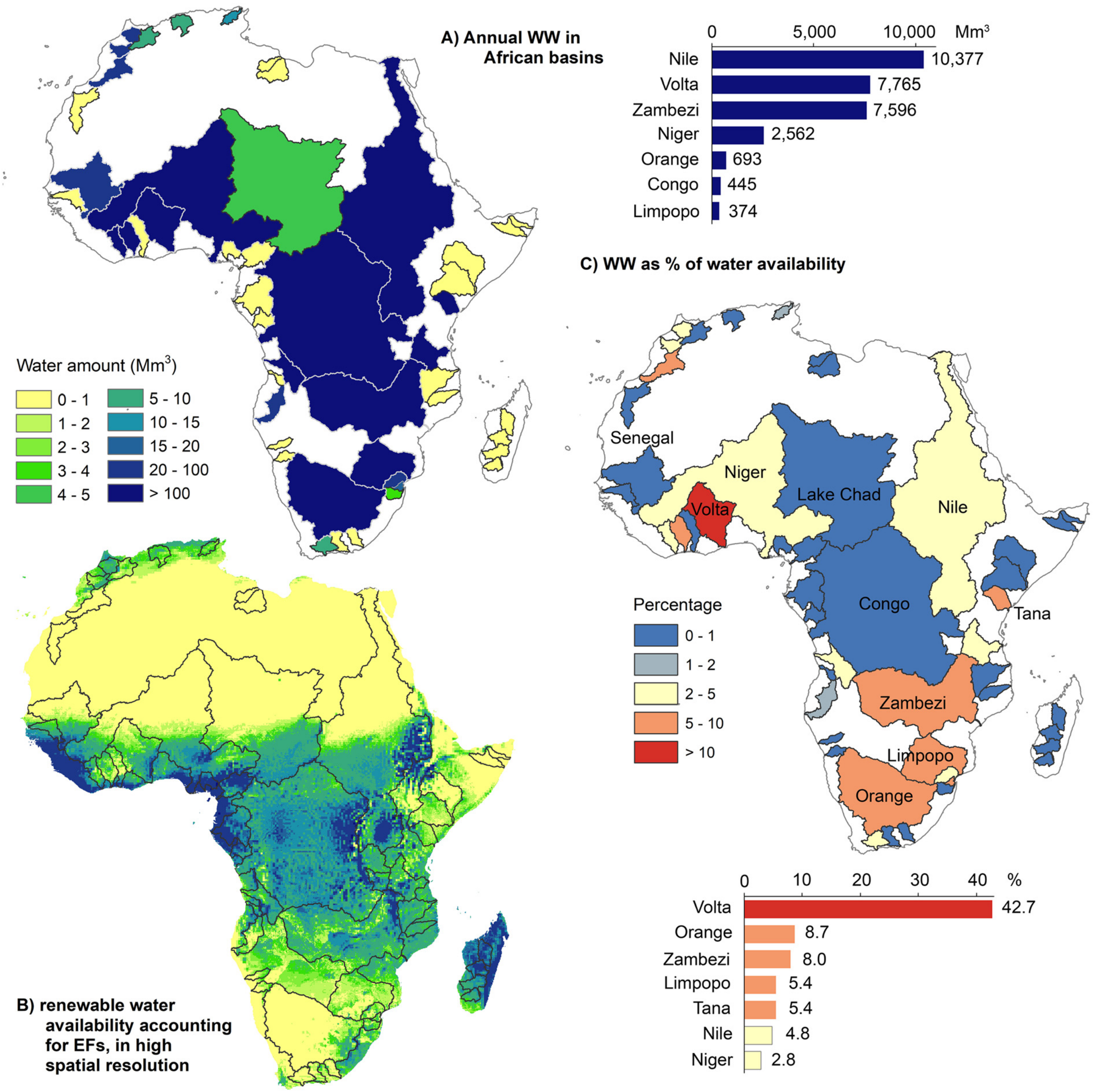

Fig. 4 Annual water withdrawal in major African river basins. A) Annual WW in Mm^3 highlighting the seven basins with the highest amounts; B) annual renewable water availability (natural water availability minus EFs) in high spatial resolution (0.1 degrees) (source Vanham *et al.*[21]); C) WW as percentage to renewable water availability per basin, highlighting selected basins with the highest amounts. Detailed results for all basins in SI_Results.

reports a national statistic of 0.4 Mm^3 for electricity WW for the year 2018/2019,[26] whereas we quantify 0.44 Mm^3, based upon 3 coal-fired power plants and 6 oil-fired power plants. For most African countries, we did not find any national reporting on water for electricity, let alone on the subnational level.

AQUASTAT's Geo-referenced Database on Dams is a comprehensive source of data on detailed information about the location, height, reservoir capacity, surface area, and primary purpose of dams, including the ones located in African countries. It also provides estimations regarding the evaporation of the bodies of water impounded before those dams. However, as it relies on input from the Global Reservoirs and Dams Database (GRanD),[27] it mainly covers large dams and reservoirs while excluding smaller infrastructure, *i.e.*, weirs and diversions for ROR hydropower plants. In this study, we included most of the reservoirs and weirs used for hydropower plants, even including minor water diversions. Thus, it presents a more complete and detailed source of information. Moreover, previous studies[28] have shown that when assessing the water evaporation from bodies of water used for hydropower, the detailed approach used in this paper provides a more accurate estimation of the OWSs and the volumes of water that evaporate from them

Table 2 Comparison of data entries (number of power plants and capacity in MW) between our database, WRI's Global Power Plant Database[22] and the Renewable Power Plant database for Africa (RePP Africa)[11]

	This study, year 2020		WRI's Global Power Plant Database[22]		Renewable Power Plant database for Africa (RePP Africa),[11] Year 2022		Renewable Power Plant database for Africa (RePP Africa),[11] Year 2020	
	Number	Capacity (MW)	Number	Capacity (MW)	Number	Capacity (MW)	Number	Capacity (MW)
Oil	1054	22 265	102	8425				
Coal	49	49 807	31	45 097				
Natural gas	343	119 263	134	64 293				
Hydropower (reservoir + ROR)	561 (183 reservoir + 378 ROR)	36 892	163	30 399	336 (178 reservoir + 121 ROR + 37 undefined)	37 849	331 (178 reservoir + 118 ROR + 35 undefined)	37 070
Wind	83	5646	42	4499	117	9024	102	7631
Sun	299	6150	129	4893	348	8313	282	7163
Biomass	121	1958	15	320				
Geo	8	813	7	761				
Nuclear	1	1860	1	1800				
Waste heat	15	951	7	46				
Other								
Total	2534	245 604	631	160 533				

than the ones obtained using the GRanD database. Therefore, while AQUASTAT's data covers a larger geographical area, our approach provides a more detailed option for those seeking to make informed decisions regarding water resource management, especially at the local level.

Many past studies[5–9] have assessed freshwater use for electricity production in different regions by using the median values of water intensities presented in available databases. However, the data sources used in these studies often rely on a limited literature review regarding electricity production technologies. Such data sources present a range of water intensities, *i.e.*, Macknick *et al.*[29] or Gleick.[30] This approach has led to the double or even triple counting of the original source, as the same water intensity is passed on from one source to another.[31] Additionally, these databases are often separated by fuel without considering the specifics regarding electricity production technology or the power plant's location. Most of the available information on water intensities for electricity production comes from case studies of power plants in the global North, which makes median values unreliable for specific electricity-producing technologies and climates that are primarily present in the global South, such as Africa. Besides, not considering climate's impact on water intensities for power plant technologies may underestimate WW and WC. Several cooling technologies have different water requirements depending on the climate of the place where they are located. For instance, a cooling tower located in a hot and dry climate will require more makeup water than the same system placed in a hot and wet climate, as the air can absorb more evaporated water in the first case. Future studies in this matter should assess uncertainties and locate hotspots where water intensities are grouped by climate zones, not only by technologies. Therefore, a more precise estimation of water usage for electricity production is necessary, as done in this study.

Our analysis shows that WW and WC for electricity is a significant water user on a continental level, albeit not the largest one. Irrigated crop production is the largest water user.[32] Nevertheless, on a regional and local level, the water demand for electricity can be high, potentially contributing to water stress. Our analysis showed for major river basins that energy WW amounts do not exceed 10% of renewable water availability (except for the Volta basin). On the subbasin level, these values can be higher.

Our detailed geographical assessment, therefore, provides the opportunity to conduct spatially detailed water stress assessments,[19] when detailed spatial water demand data for other sectors are also available. Although spatial water stress assessments are available for Africa,[1,33] such studies make a lot of assumptions for the spatial distribution in water demand of certain sectors, including municipal water demand, industrial water demand or the water demand of mining. More research is required to provide sound assessments of the spatial distribution of these other sectors, to the level of detail we provide for the electricity sector. Only then detailed and sustainable water allocation, water management as well as energy management and planning decisions can be made by stakeholders in African (sub)river basins.

Our assessment also shows the differences in water intensities for different powerplant fuels (Fig. 1 for African average amounts and Table 3 for the range per fuel). With projected increases in electricity demand, decision makers need to take account of these differences when aiming at decarbonising the energy system to mitigate climate change. The choice of which renewable energy sources to develop will have a large impact on limited water resources in many already stressed river basins. Certain renewables have low water intensities (sun, wind, geothermal and ROR hydropower), whereas the water intensity of (certain) biomass is higher and that of reservoir hydropower is very high. Future development

Table 3 Water factors/intensities, data sources Meldrum *et al.*,[13] Williams *et al.*,[23] Dziegielewski and Kiefer[24] and many others as listed in SI_Database. Climate according to Peel *et al.*[25]

Technology	First cat	Second cat	Third cat	Fuel	Climate	WW $m^3\ MWh^{-1}$	WC $m^3\ MWh^{-1}$
Biomass	Rankine	Steam turbine	No cooling	Various crops	NA	0.162	0.114
			Once through (fresh)	Various crops	Aw, BWh	189.271	1.136
			Wet tower	Various energy crops	Af, Am, Aw, BSh, BWh	4.542	4.164
					Cfa, Csb, Cwa, Cwb	2.472	1.931
	Combined	Gas turbine + heat recovery	Wet rower	Various crops	Aw	2.877	1.022
	ICE	Gas-engines	Dry cooling	Biogas	NA	0.324	0.227
Coal	Rankine	Steam turbine	No cooling	Circulating fluidized bed	NA	0.162	0.114
			Dry cooling	Pulv – subcritical	NA	0.162	0.114
				Pulv – supercritical	NA	0.162	0.114
			Once through (saline)	Circulating fluidized bed	NA	0.162	0.114
				Pulv – subcritical	NA	0.162	0.114
				Pulv – ultrasupercritical	NA	0.162	0.114
			Wet Tower	Circulating	Af	3.785	2.650
				fluidized bed	Cwa	2.385	2.025
				Pulverized – subcritical	Af, BSh, BSk, BWh	4.542	4.164
					Cfa, Cwa, Cwb	2.472	1.931
	Combined	Steam turbine	Wet tower	IGCC	Aw	1.999	1.582
					Cwb	1.469	1.211
Geothermal	Geothermal	Steam turbine	Wet tower	Flash	Csb	0.068	0.042
			Dry cooling	Binary – dry cooled	NA	1.568	1.098
Natural Gas	Brayton	Gas turbine	No cooling	Natural gas, oil derivatives	NA	1.609	1.287
	Combined	Combined cycle (CC)	Dry cooling	Natural gas	NA	0.038	0.026
			Once through (saline)	Natural gas	NA	0.038	0.026
			Once through (fresh)	Natural gas	Aw, BWh	75.708	0.416
			Wet tower	Natural gas	Am, Aw, BSh, BWh	2.877	1.022
					Cwb	0.908	0.791
	ICE	Gas-engines	Dry cooling	Natural gas	NA	0.324	0.227
	Rankine	Steam turbine	Once through (saline)	Natural gas	NA	0.038	0.025
			Once through (fresh)	Natural gas	Am, BWh	132.489	0.719
			Wet tower	Natural gas	Am, BWh, Csa	4.580	3.653
Oil	Brayton	Gas turbine	No cooling	Oil derivatives	NA	1.609	1.287
	Combined	Combined cycle (CC)	Once through (fresh)	HFO, NG	Aw	75.708	0.416
			Wet tower	LPG, diesel	BWh	2.877	1.022
	ICE	Diesel-engines	Dry cooling	Oil derivatives	NA	0.324	0.227
				Syngas	NA	0.324	0.227
	Rankine	Steam turbine	Once through (saline)	Oil derivatives	NA	0.162	0.108
			Once through (fresh)	Oil derivatives	Csa	132.489	0.757
					BWh	189.271	1.136
			Wet tower	Oil derivatives	Aw, BSh, BWh	4.542	4.164
					Csa, Cwb	2.472	1.931
Uranium	Nuclear	Steam turbine	Once through (saline)	Uranium	Na	0.379	0.114
waste heat	Rankine	Steam turbine	Dry cooling	Heat recovery	NA	0.038	0.026
			Once through (saline)	Heat recovery	NA	0.038	0.026
			Wet tower	Heat recovery	BSh	2.877	1.022
					Cwa, Cwb	0.908	0.791

Table 3 *(continued)*

Technology	First cat	Second cat	Third cat	Fuel	Climate	WW m^3 MWh^{-1}	WC m^3 MWh^{-1}
	ICE	Diesel engine	Dry cooling	Syngas	NA	0.324	0.227
Solar	PV	Flat	Rooftop	NA	Af, Am, Aw, BSh, BWh	0.014	0.010
					Cfb, Csa, Csb, Cwa, Cwb	0.004	0.003
			Land	NA	Af, Aw, BSh, BSk, BWh, BWk	0.098	0.069
					Cfb, Csb, Cwa, Cwb	0.023	0.016
		Concentrated	Land	NA	BWh – desert hot	0.295	0.207
					BWk – arid desert – hot	0.295	0.207
	CSP	Parabolic	Dry cooling	NA	BWh, BSh	0.757	0.530
		trough	Wet tower	NA	BWh	10.275	7.192
		Fresnel	Wet tower	NA	CWb	5.408	3.785
		Central tower	Wet tower	NA	BWh	4.651	3.255
Wind	Wind turbine	Onshore	No cooling	NA	NA	0.000	0.000

should not be conducted in silo-thinking but should address a wider nexus approach.

4 Method and data

The assessment of blue freshwater withdrawal and consumption for electricity in Africa for the year 2020 was done for 54 countries and 6 additional political entities, including 2534 individual power plants, in three steps in a bottom-up approach. Step 1 identified the individual power plants operational in 2020 and their characteristics per country, step 2 assessed specific freshwater withdrawal and consumption per unit of generated electricity and step 3 combined the results from step 1 and 2 to arrive at water withdrawal and consumption per power plant and country. The 54 countries are all UN-recognized African countries. The 6 additional political entities are the islands of Reunion and Mayotte (French overseas departments), the islands of Tristan da Cunha, St. Helena and Ascension island (UK overseas territories) as well as the region of Western Sahara.

4.1 Step 1, identification African power plants and their characteristics

For the identification of African powerplants and their characteristics, step one made an inventory for all 54 countries and 6 additional regions including the powerplants per fuel type, installed capacity, electricity generation, fresh or salt water use, and location. First, we checked whether a powerplant was operational in 2020. This was done by accessing publicly available data sources, where GEM wiki[34] and Wikipedia[35] were the preferred sources, because they provide recent information on power plants, especially on the large ones. Other data sources used were power technology that gives information on installed capacity and year of commission, Open Street maps, reports from international organisations, *e.g.*, the JRC,[6] the Worldbank, or national ministries, scientific papers, companies and also newspapers that give information on the opening or closure of specific plants. We also checked and adapted location coordinates using Google Maps.

Second, we categorized the power plants according to applied fuel, operation cycle, infrastructure, cooling system, cooling fluid and local climate. The applied fuels include biomass (sugar cane residues, bagasse, wood *etc.*), coal, oil (*i.e.*, diesel, gasoline or heavy fuel oil), natural gas (including biogas), and uranium for nuclear power plants, water, sun, wind, waste heat and geothermal heat. Next, we identified the operation cycles, *i.e.*, Brayton, Rankine, internal combustion cycle or combined cycle for thermal power plants; dammed reservoirs, run-of-river (ROR) and in-conduit for hydropower, photovoltaics (PV) and concentrated solar power (CSP) (sun). Infrastructure includes gas turbines, steam turbines and heat recovery (thermal power plants), one or multipurpose plants for hydropower, PV on land or on rooftops, Fresnel, solar tower and parabolic through (CSP). There are many cooling types for thermal power plants. We included once trough, wet tower, dry cooling and no cooling. Both salt and freshwater can be applied for cooling, when no water is available, power plants use air cooling. Finally, we identified the climate zone based on the Köppen–Geiger classification.[25,36]

Electricity generation per power plant was preferably adopted from literature. However, this information was lacking for most power plants so that we had to estimate the generation based on installed capacities. The information on applied fuel, together with the downscaled production factor per fuel per country, gives the electricity generation, $E_{p,n,s}$ (MWh y^{-1}), per power plant p in country n with energy source s (MWh y^{-1}) as:

$$E_{p,n,s} = I_{p,n,s} \times \frac{E_{n,s}}{I_{n,s}} \quad (1)$$

where $I_{p,n,s}$ is the installed capacity of power plant p (MW) in country n with fuel s, $E_{n,s}$ is the total annual electricity generation in country n for fuel s and $I_{n,s}$ is the total installed capacity in country n for fuel s. We derived data on installed capacities from our power plant inventory.

For all thermal power plants, we identified the cooling type and the type of water used, *i.e.* salt or freshwater. For all hydropower plants, we identified their infrastructure, *i.e.*, dams, weirs, open canals, *etc.*, and the open water surfaces (OWS) that these infrastructures create. The Supporting information (SI_Guide_Infrastructure_SatellitePictures) gives the guide for identifying power plants and their characteristics using satellite photographs. For oil fuelled power plants with a relatively small installed capacity, *i.e.* below one MW, we assumed that it concerned diesel generators without cooling. The assessment was done for 2534 power plant operational in 2020 using Google Maps.

The Excel file in the Supporting information (SI_Database) gives the database that includes all power plants, installed capacities, electricity generated in 2020, location coordinates and information on water type for cooling per fuel type per African country. We validated total electricity production per country per energy source with data from the IEA for 2020. For small countries for which the IEA did not give data, we validated using data from IRENA[37] for 2021.

4.2 Step 2, assessment of specific water withdrawal and consumption per unit of generated electricity

Step 2 assessed the specific freshwater withdrawal and consumption per unit of generated electricity per fuel type, operation cycle, infrastructure, and local climate. We derived data from Meldrum *et al.*[13] and Williams *et al.*[23] that give information on life cycle use of freshwater for electricity including ranges. We made an estimate of the withdrawal and consumption within the range depending on the climate. For electricity from wind, we applied the smallest value. Table 3 and the SI gives an overview of the specific freshwater withdrawal and consumption per unit of generated electricity per fuel type, operation cycle, infrastructure, and local climate.

For a few types of thermal power plants in certain climate zones, there were no sources to provide withdrawal but only consumption. In these cases where there were no data about withdrawal, we applied a consumptive use factor provided by Dziegielewski and Kiefer,[24] to calculate the corresponding withdrawal factor. For hydropower plants, water consumption $\text{Water}_{h,n}$ of plant h in country n occurs due to evaporation of water from OWSs. The calculation was made based on the gross method[38] as:

$$\text{Water}_{h,n} = \eta \sum_{r=1}^{R} \left(10 \times \text{Ev}_{h,n,r} \times S_{h,n,r}\right) \quad (2)$$

where η is the allocation factor for multipurpose OWS, $\text{Ev}_{h,n,r}$ is the annual evaporation (mm) of the open water surface r, $S_{h,n,r}$ is the area of the OWS r (ha) and 10 is the conversion factor to convert mm to m^3. Depending on the infrastructure, a hydropower plant can have more than one OWS. The calculation of the consumption considers the sum of the evaporation from the OWS of each power plant (from $r = 1$ to R). The Excel file in the SI provides the OWSs of the hydropower plants assessed.

Multipurpose OWS serve to provide different services besides electricity, *e.g.*, domestic water supply, irrigation, aquaculture and flood control. We checked all the available public information regarding the OWSs per hydropower plant and included the different services they provide. We calculated the allocation factor, η, as the ratio between the economic values of hydroelectricity and the economic value of the sum of other services in the OWS for the cases where there was available information regarding the other services besides electricity. For cases in which we could not find any information that could provide the economic value of the other services, we considered that all evaporation is allocated to the hydropower plant. The Excel file in the Supporting information (SI), indicates the cases in which the allocation factor could not be calculated.

The $\text{Ev}_{h,n,r}$ was calculated as the sum of the monthly evaporation from the OWSs, excluding oceans. Data were collected from the ERA5-Land reanalysis dataset[39] for each of the locations of the OWSs. The $S_{h,n,r}$ were measured using satellite images from Google Earth® and by applying its surface measuring tool. In cases in which the OWSs were extremely large, we relied on the available information of the surfaces from the sources checked in step 1. For ROR hydropower plants with relatively small installed capacity, *i.e.*, below one MW, we considered that their OWSs were negligible. Finally for hydropower plants, we considered that withdrawal is the same as consumption.

4.3 Step 3, calculation of water withdrawal and consumption per power plant and country

For the calculation of freshwater withdrawal and consumption for electricity in Africa, we only included the operational stage and excluded freshwater for fuel supply and construction, *i.e.*, the water in the supply chain.[7] Freshwater consumption per power plant p per country n per energy source s, $\text{Water}_{p,n,s}$ ($m^3\ y^{-1}$) was calculated as:

$$\text{Water}_{p,n,s} = E_{p,n,s} \times W_{s,o,c} \quad (3)$$

in which $E_{p,n,s}$ is the electricity generation of power plant p (MWh y^{-1}) in country n with fuel s and $W_{s,o,c}$ is the specific freshwater consumption for a power plant with energy source s, operational characteristic o (operation cycle and infrastructure) in climate c (m^3 MWh^{-1}). Freshwater withdrawal per powerplant p was calculated in the same way using the specific freshwater withdrawal data of energy source s in climate c from step 2.

Next, we calculated freshwater consumption per country n (Water_n, $m^3\ y^{-1}$) as:

$$\text{Water}_n = \sum_{p=1}^{t} \text{Water}_{p,n,s} \quad (4)$$

Freshwater withdrawal per country n was calculated in the same way.

4.4 Calculation of water demand as percentage of renewable water availability for major African basins

We quantified the relation of the water demand for electricity to renewable water availability in the major river basins of Africa. We defined renewable water availability as natural renewable water minus environmental flows (EFs):

$$\text{renewable water availability} = \text{natural renewable water} - \text{EF} \quad (5)$$

Natural renewable water in high spatial resolution (0.1 degrees or 11.1 km at the equator) was taken from Vanham *et al.*,[21] who used the hydrological model LISFLOOD.[40] The model works at a daily time step for the period 1980–2018 and generates natural water availability as the sum of renewable surface and groundwater. We used the geodataset on river (sub)basins of Hydrosheds[41] to aggregate grid natural renewable water amounts to the basin level.

Environmental flows (EFs) are the quantity and timing of water flows required to maintain the components, functions, processes and resilience of aquatic ecosystems and the goods and services they provide to people. They are required to maintain ecosystem integrity in streams, rivers, wetlands, riparian zones and estuaries. EFs also provide many additional ecosystem services, with direct links to specific Sustainable Development Goals.[19,42]

To quantify EFs, we used the presumptive standard for EFs by Richter *et al.*,[43] which defines 80% of the natural flow as EF. The remaining 20% is considered as water available for human use, in this paper defined as renewable water availability. The methodology by Richter is widely used in water management studies.[1,33,44–48] This presumptive standard is supported by empirical studies showing that flow alterations within 20% support native fish species and flow alteration beyond this level strongly affects biodiversity and ecosystem structure and function.[49]

We did not conduct a full water stress assessment, for which all water demand stakeholders (such as agriculture, municipal water use, mining and industrial water use) are required. The reason is that not all of these stakeholders have the spatially detailed data to the level of detail of our energy assessment.

Supplementary information

SI_Database: power plant database with Supplementary information.

- Worksheet "main": database of 2534 individual power plants.
- Worksheet "Hydro_OWS": details on hydro OWS – open water surfaces.
- Worksheet "Hydro_EV": Hydro: monthly evaporation values.
- Worksheet "water_intensities": more details on water intensities. Extended information regarding to Table 3.
- Worksheet "withdrawal WIs": data/literature references for water intensities WW.
- Worksheet "consumptive WIs": data/literature references for water intensities WC.

SI_Results: Excel file with (sub)national and river basins WW and WC amounts:

- Worksheet "(sub)national": (sub)national data on WW and WC (in m^3) according to power plant fuel type. Subnational data according to GADM level 1 regions.
- Worksheet "riverbasins": data on WW and WC (in m^3) according to power plant fuel type for major African river basins. River basin data according to hydrosheds.

SI_Guide_Infrastructure_SatellitePictures: guide for identifying power plants using satellite photographs.

Conflicts of interest

The authors declare no competing interests.

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