European Commission

JRC TECHNICAL REPORT

Current and projected freshwater needs of the African energy system

González Sánchez, R.

Hidalgo González, I.

Fahl, F.

Seliger, R.

2020

Joint Research Centre

EUR 30278 EN

Contact information
Name: Rocío González Sánchez
European Commission, Joint Research Centre (JRC)
Via E. Fermi, 2749, 21027 Ispra VA, Italy
Email: Rocio.GONZALEZ-SANCHEZ@ec.europa.eu
Tel.: +39 033278-5549

EU Science Hub
https://ec.europa.eu/jrc

JRC120834

EUR 30278 EN

PDF	ISBN 978-92-76-19977-9	ISSN 1831-9424	doi:10.2760/808928

Luxembourg: Publications Office of the European Union, 2020

How to cite this report: González Sánchez, R., Hidalgo González, I., Fahl, F., Seliger, R., *Current and projected freshwater needs of the African energy system*, EUR 30278 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-19977-9, doi:10.2760/808928, JRC120834.

Contents

Foreword

Increasing water stress will intensify competition between water uses. Lack or excess of water may undermine the functioning of the energy and food production sectors with societal and economic effects. Energy and water are inextricably linked: we need “water for energy” for cooling, storage, biofuels, hydropower, fracking etc., and we need “energy for water” to pump, treat and desalinate. Without energy and water, we cannot satisfy basic human needs, produce food for the rapidly growing population and achieve economic growth. Producing more crops per drop to meet present and future food demands means developing new water governance approaches.

The Water Energy Food and Ecosystem Nexus (WEFE Nexus) flagship project addresses in an integrated way the interdependencies and interactions between water, energy and agriculture, as well as household demand. These interactions have been so far largely underappreciated. The WEFE-Nexus can be depicted as a way to overcome stakeholders ’view of resources as individual assets by developing an understanding of the broader system, thus realising that acting from the perspective of individual sectors cannot help tackle future societal challenges

The overall objective of the Water-Energy-Food-Ecosystems Nexus flagship project (WEFE-Nexus) is to help in a systemic way the design and implementation of European policies with water dependency. By combining expertise and data from across the JRC, it will inform cross-sectoral policy making on how to improve the resilience of water-using sectors such as energy, agriculture and ecosystems

WEFE-NEXUS Objectives

- Analyse the most significant interdependencies by testing strategies, policy options and technological solutions under different socio-economic scenarios for Europe and beyond.
- Evaluate the impacts of changes in water availability due to climate change, land use, urbanisation, demography in Europe and other geographical areas of strategic interest for the EU, such as Africa.
- Deliver country and regional scale reports, outlooks on anomalies in water availability, a toolbox for scenario-based decision making and science-policy briefs connecting the project’s recommendations to the policy process.

How is the analysis done?

JRC experts use a broad range of models and sources to ensure a robust analysis. This includes hydrological and climate models to understand current and future availability of water resources, and energy models and scenario employed to understand current energy demands and forecast future ones, as well as the related water footprint of the energy sector.

The results from these models are expected to provide i) an understanding of the impacts of water resources on the operation of the energy system, and vice versa, ii) spatial analysis and projection of water and energy requirements of agricultural and urban areas in different regions, iii) insights for a better management of water and energy resources.

What is this report about?

The aim of this technical report is to provide a reliable estimate of the current freshwater use in the African energy sector (both primary energy supply and transformation) and long-term projections until 2050. The projections are based on the combination of water withdrawal and consumption factors for different energy technologies with detailed energy scenarios for Africa.

Acknowledgements

Estimates of water use for cooling and clarifications on energy scenarios: Pappis, I., Howells, M., Sridharan, V., Usher, W., Shivakumar, A., Gardumi, F. and Ramos, E. (KTH)

Estimation of hydropower's water use: De Felice, L., and Farinosi, F. (JRC)

Comments: Peteves, S., Thiel, C., Taylor, N., Medarac, H., Kougias, I. and Scarlat, N. (JRC)

Proofreading: Realini, B. (JRC)

Authors

González Sánchez, R., Hidalgo González, I., Fahl, F, Seliger, R.,

Abstract

Africa's expected rapid economic development and population growth will increase in all likelihood the stress on water and energy resources in the coming decades. A number of studies have addressed the water needs of the energy sector, both at global scale or for certain developed countries. However, very few of them have focused on Africa, often overshadowed by other industrialised regions with a much higher water use for energy. Contrary to other studies, this report also addresses hydropower and fuelwood, not only due to the important role they play in many African countries but also because they consume large amounts of water and are therefore extremely vulnerable to water scarcity. The methodology used to assess hydropower in this study differs from other analyses, which would normally obtain the reservoirs' areas needed to estimate the evaporation losses from global databases. In this report, the assessment of hydropower relies on the more accurate information provided by the Global Surface Water Dataset (Pekel et al., 2016), a JRC product based on satellite data, which provides monthly water surfaces at 30 m spatial resolution. In this study, the current and future water needs (consumption and withdrawals) of the African energy sector have been estimated on a country-by-country basis. Primary energy production (fuel extraction), energy transformation (oil refining and electricity generation) and power plant construction have been evaluated.

The results of this analysis reveal that in the year 2016, 42 bcm[1] of water were lost through evaporation in hydropower reservoirs, 4.5 bcm were used for fuelwood production and 1.2 bcm were consumed by the rest of the energy types combined. Non-hydro renewable energies such as wind and solar have a negligible effect on water use, making them an interesting alternative to conventional energy sources for the sustainable development in Africa, especially given their large untapped potential in the continent.

Future projections of freshwater use at country level are also analysed, based on three energy scenarios for Africa, aligned with the JRC's Global Energy and Climate Outlook (GECO) 2018 (Keramidas et al., 2020; Pappis et al., 2019): i) a reference scenario (hereafter denoted R) that extrapolates the current situation into the future, ii) a 2.0 °C scenario in which new policies and emission targets are implemented to keep global mean temperature increase to 2.0 °C over pre-industrial levels with a 67% probability, and iii) a 1.5 °C scenario that assumes a stronger climate objective pursuing a reduction in carbon dioxide emissions to levels lower than in the reference and the 2.0 °C scenarios with a 50% probability of reaching 1.5 °C warming by 2100. These projections indicate that by 2030, depending on the scenario, the water loss allocated to hydropower due to evaporative losses will be 93.8 bcm (R), 94.8 bcm (2.0 °C) and 93.1 bcm (1.5 °C); the water consumption for fuelwood production: 7.6 bcm (R), 7.7 bcm (2.0 °C) and 7.8 bcm (1.5 °C); and the water consumption for the other energy types: 1 bcm (R) and 0.8 bcm (1.5 °C and 2.0 °C). By 2050, hydropower water losses will rise up to: 139 bcm (R), 155 bcm (2.0 °C) and 160.7 bcm (1.5 °C); water consumption for fuelwood production: 7.2 bcm (R), 7.4 bcm (2.0 °C) and 7.9 bcm (1.5 °C) bcm; and water consumption for the other energy types: 1.3 bcm (R), 0.7 bcm (2.0 °C) and 0.5 bcm (1.5 °C).

The low carbon policies will not only have a positive effect on emissions but also on the water consumption in some energy sub-sectors, reducing the use of water for primary energy production and transformation, and increasing the penetration of some renewable energies such as solar, wind and geothermal. However, other more water-intensive renewables (e.g.: hydropower and biomass) are also expected to increase their share in the future energy mix, causing significant impacts on water use. The penetration of oil and gas to substitute fuelwood use in households will reduce the water use in the continent. At the same time, despite the large untapped potential of hydropower in Africa, the water impacts of new hydropower developments need to be effectively considered, especially in regions characterised by severe water scarcity. New ways to limit evaporation from hydropower reservoirs need to be deployed in order to mitigate their impact on water stress.

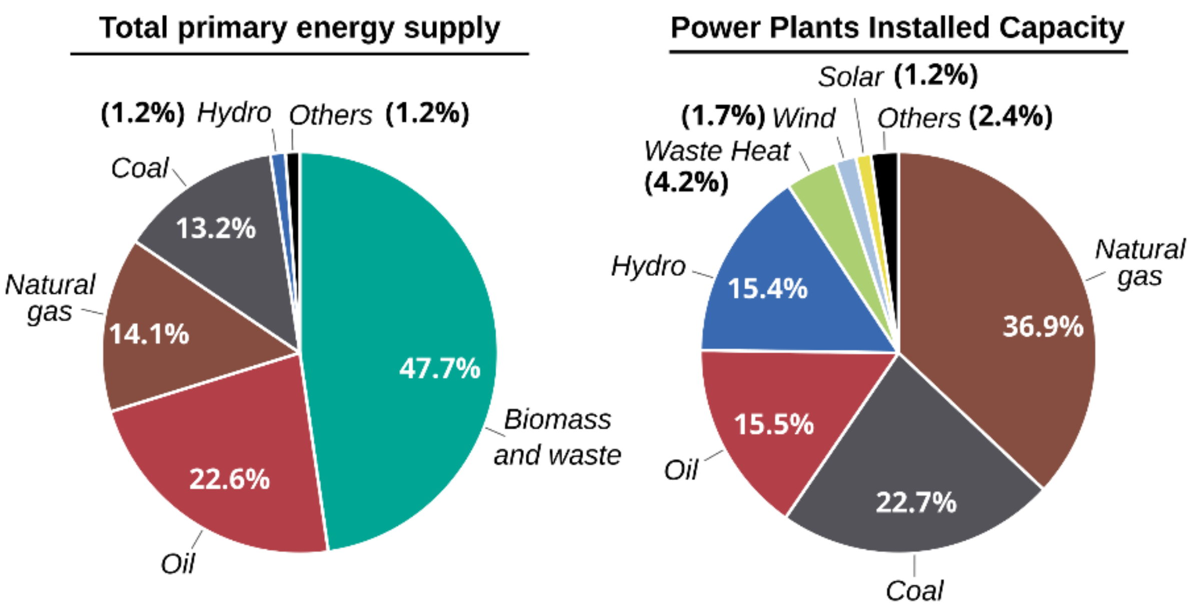
[1] Billion cubic metres

1. Introduction and review

Significant amounts of water are used for energy production worldwide, especially in industrialised countries. Europe and the United States for instance, dedicated up to 40% of their total water abstractions (mainly freshwater) to the production of energy during 2014 (IEA, 2016; EEA, 2018). The European Commission's Joint Research Centre estimates that the freshwater withdrawn by the energy sector in the EU and the United Kingdom during 2015 was in the range 63-69 bcm, depending on the energy scenario considered, while the freshwater consumption amounted to 7-8 bcm (Hidalgo González, 2020). Africa's present context differs significantly from the one in industrialised regions with 86% of the water withdrawals used for agriculture, 10% for municipal purposes and 4% for industry, including energy (FAO, 2005).

Figure 1 depicts the total primary energy supply and the installed capacity of power plants by fuel type in Africa in the year 2016. Most of the primary energy is obtained from biofuels and waste which are mainly used in households for cooking and heating (IEA, 2018). This dependency on biomass increases dramatically when looking at Sub-Saharan Africa, reaching up to 76% of the total primary energy use (IEA, 2018). Installed capacity for electricity production is instead dominated by fossil fuels, followed by hydropower. However, each region presents a very different energy mix in terms of installed capacity. North and Western Africa are dominated by natural gas, Southern Africa by coal and Central and Eastern Africa by hydropower (IEA, 2018).

Figure 1 - Total primary energy supply and installed capacity in Africa by fuel type in the year 2016



Source: Adapted from (Gonzalez Sanchez et al., 2020; IEA, 2018)

Current energy demand in the continent is only 6% of the total worldwide and more than two thirds of the population lack access to modern energy (e.g. grid power and gas). However, Africa presents the fastest population growth in the world with an increase of 270 million people in sub-Saharan Africa alone from 2000 to 2012. As a consequence, energy demand surged by 45% (IEA, 2014), which in turns has also increased the demand of water for energy production (Rodriguez et al., 2013). Water scarcity on the other hand is affecting 300 million people in sub-Saharan Africa (UN Water, 2014). Not only the vast majority of the continent is arid or semi-arid but the water resources are unevenly distributed among the different regions. These differences will become larger due to the increasingly frequent extreme events caused by climate change (Rodriguez et al., 2013). Sectoral competition for water resources combined with a growth in population and energy demand may lead to a significant increase in water stress in a number of regions, especially under global warming conditions. Considering the current water, energy and demographic context in Africa, it is important to determine the present and future water needs of the growing African energy sector for a better planning of the water and energy resources in the continent.

The water demand of the energy sector has been addressed in previous studies both at global scale and country level, mainly to obtain the water use for the production of electricity through life cycle analysis (Liao, Hall, and Eyre, 2016; Srinivasan et al., 2018; Lee et al., 2018; Mekonnen, Gerbens-Leenes, and Hoekstra, 2015; Spang et al., 2014). Normally these studies are based on water factors from the literature corresponding to the different processes involved in the electricity generation (Meldrum et al., 2013; Macknick et al., 2012). Some African countries have been included in previous studies performed at global level (Mekonnen, Gerbens-Leenes, and Hoekstra, 2015; Spang et al., 2014) however, they are generally overshadowed by other industrialised countries due to their much larger amounts of water use for energy. This study provides an in-depth analysis of the water use of the African energy sector, including different stages of the energy production and energy types at country level. Additionally, a detailed analysis of the water lost by evaporation from hydropower plants has been performed. This component is seldom addressed in other studies of water use for energy production due to its complexity; however, the water losses in artificial reservoirs can often be very large (Mekonnen and Hoekstra, 2012; Macknick et al., 2012). Hydropower plays a key role in Africa covering 15% of the total installed capacity and many countries depend highly on it (including some that depend almost exclusively on it) (IEA, 2018). Therefore, estimating the hydropower component is considered necessary in this analysis to obtain a more complete view of the "water for energy" context in Africa.

The first part of this study focuses on the current water demand of the energy sector, including primary energy production (biomass production, coal mining and oil and gas extraction), crude oil refining, power plant construction and power plant operation. The second part analyses the water use for the future energy projections in three energy scenarios for Africa aligned with the JRC's Global Energy and Climate Outlook (GECO) 2018 (Keramidas et al., 2020; Pappis et al., 2019): i) a reference projection that extrapolates the current situation into the future, ii) a 2.0 °C scenario in which new policies and emission targets are implemented to keep global mean temperature increase to 2.0 °C over pre-industrial levels with a 67% probability, and iii) a 1.5 °C scenario that assumes a stronger climate objective pursuing a reduction in carbon dioxide emissions to levels lower than in the reference and the 2.0 °C scenarios with a 50% probability of reaching 1.5 °C warming by 2100.

2. Estimated current freshwater use

Freshwater use in the African energy sector have been estimated by using the methodology presented in (Gonzalez Sanchez et al., 2020) with the water factors included in Annex 1. The current water use is based on 2016 energy data, in order to keep consistency among the different data sources used throughout the study and for which more recent data was not always available. Water consumption allocated to hydropower and fuelwood production are not included in the total water use but are addressed in a separate section as "Other water uses" (section 2.2) due to their magnitude and particularities.

2.1. Total water use

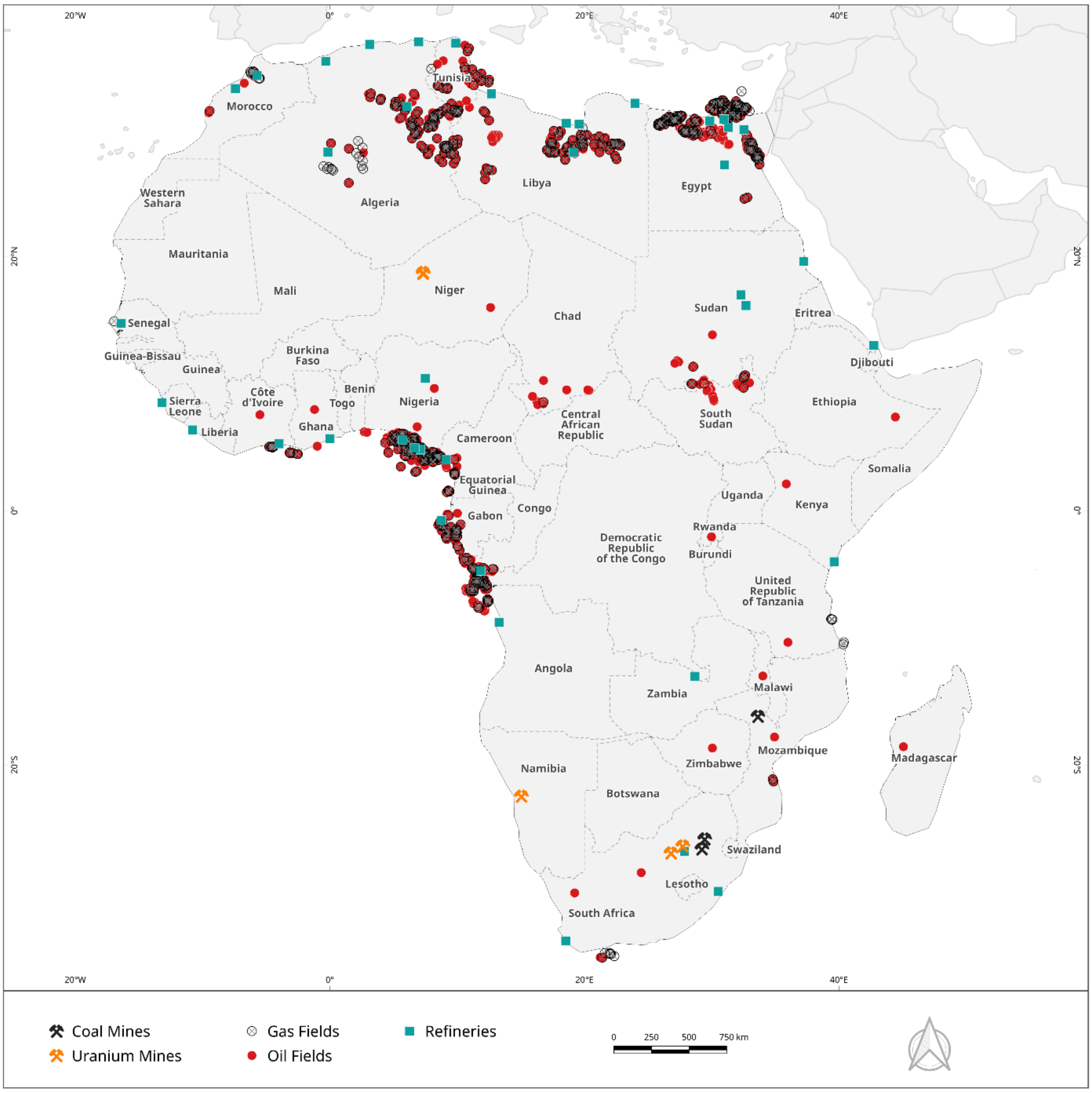
2.1.1. Water use for primary energy production and oil refining

The analysis presented in this section is based on coal, oil and natural gas production data from IEA and AFREC statistics (AFREC, 2017; IEA, 2018) and data on uranium production from the World Nuclear Association (WNA, 2019). Only onshore oil extraction has been considered, since offshore oil fields use seawater for the extraction. Information on onshore/offshore oil production per country has been obtained from (Rystad Energy., 2018). Figure 2 presents a map with all the coal and uranium mines as well as oil and gas fields and refineries in Africa.

Oil extraction and oil refining are the processes that require the highest amount of water between the different fuel types, accounting for 86% of the total water allocated to primary fuel extraction. On the other hand, natural gas is the second primary energy source after oil, but it accounts for only 1% of the water consumption because its extraction process is much less water-intensive. Figure 3 presents the 20 countries with the highest water consumption for primary fuel production as well as the actual fuel production for comparison purposes. Most of them are countries with an oil and gas-based economy, except South Africa which depends on coal. Some of the countries with important production of oil such as Angola, Congo, Equatorial Guinea, Ghana and Cameroon are however not present among the top 20, since their oil production is mostly offshore and uses seawater for extraction. The total freshwater consumption for primary fuel production in Africa has been estimated at 728 mcm[2]. Water withdrawal and consumption factors are considered the same, as reported in the available literature for many of the processes involved in fuel production. Therefore, we assume that total water withdrawal is equal to total water consumption.

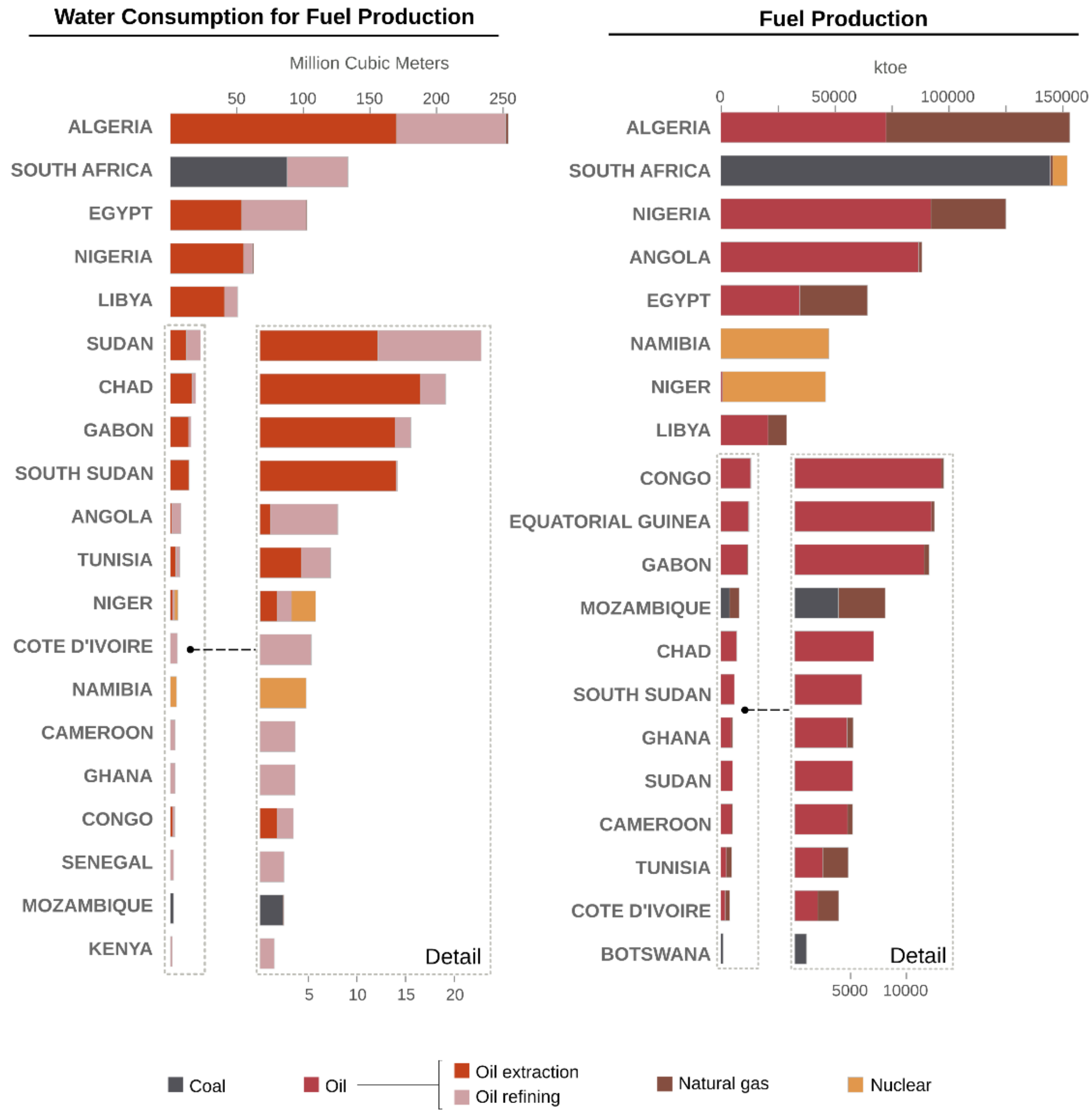
[2] Million cubic metres.

Figure 2 - Map of coal mines, oil and gas fields and oil refineries in Africa



Sources (Oil & Gas Journal, 2019; The World Bank, 2014)

Figure 3 - Fuel production and water consumption per fuel type in Africa in 2016 for the top 20 countries with the highest water consumption.

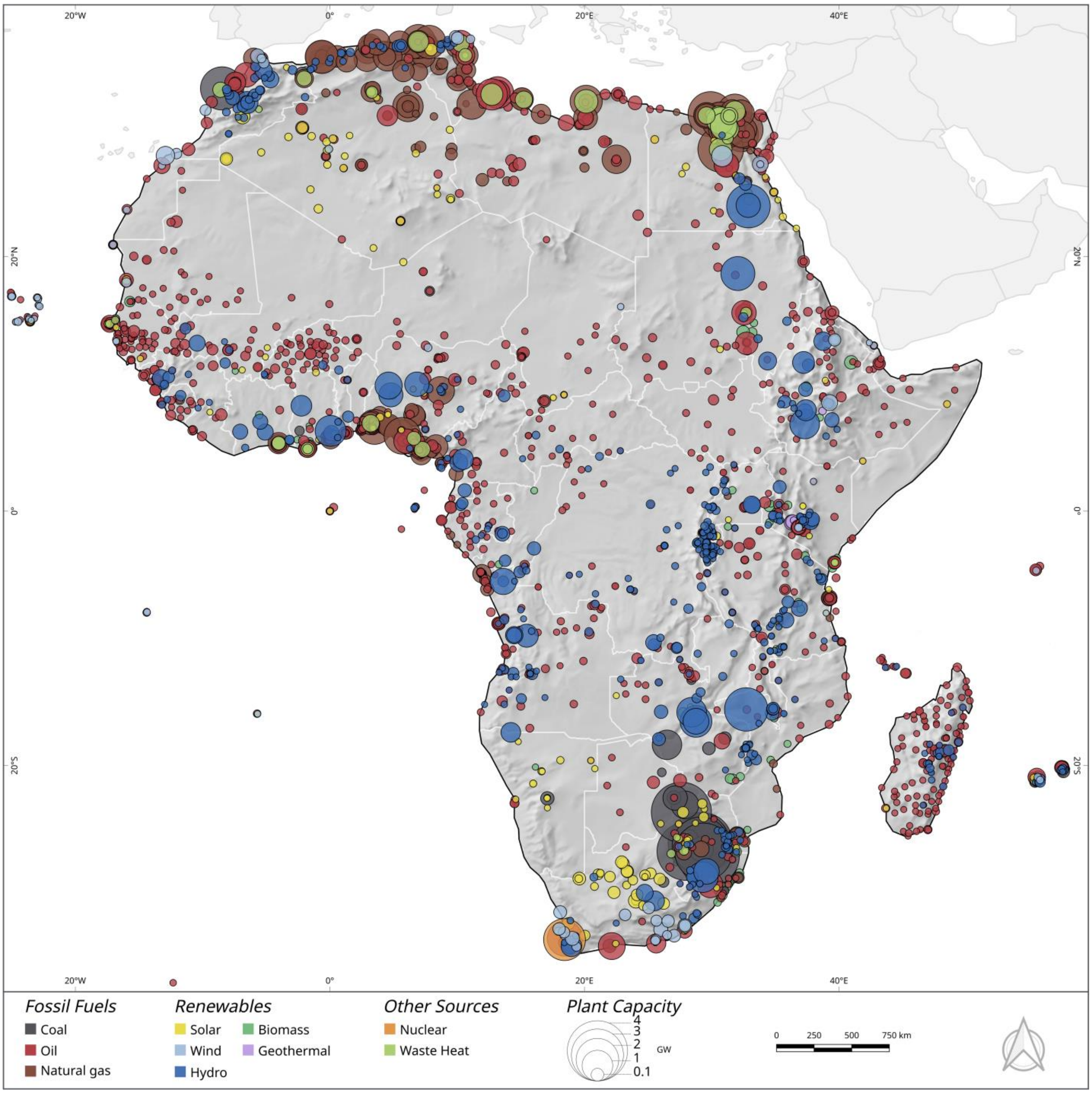


Source: Adapted from (Gonzalez Sanchez et al., 2020)

2.1.2. Water for power plant operation and construction

Power plant data has been obtained from PLATTS (S&P Global Platts, 2016), which contains information on the type of plant, fuel, installed capacity and cooling system among others. PLATTS data has been complemented with the plants' geographical location from other sources (Energydata.info, 2012; Harvard, 2010; WRI, 2018), in order to establish which power plants could be using seawater instead of freshwater for cooling. In this study, all power plants located up to 5 km from the coastline are assumed to use seawater for cooling purposes, while the rest, located inland, are assumed to use freshwater for the same purpose. The total installed capacity of operational plants in Africa in 2016 accounts for 196 GW and its distribution among the different type of energy sources is shown in Figure 1. The total water consumption and withdrawals associated to the operation of these power plants have been estimated at 502 mcm and 5418 mcm respectively.

Figure 4 - Distribution or African power plants classified by size and fuel type in 2016.

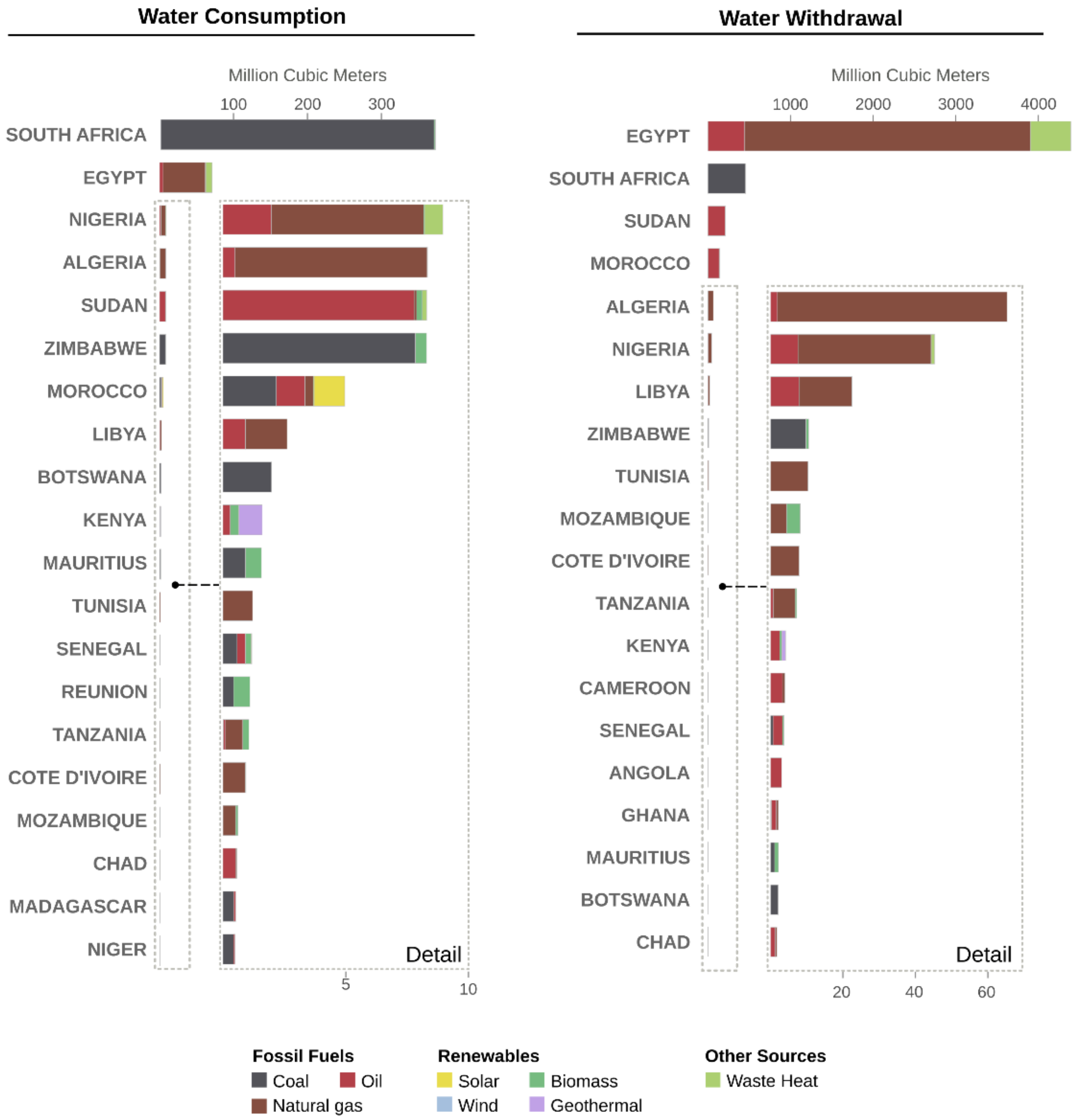


Source: Reprinted from (Gonzalez Sanchez et al., 2020)

Most of the freshwater is used for the operation of thermal power plants, which accounts for 96% of the consumption and 91% of the withdrawals. Natural gas power plants, despite having the highest installed capacity in Africa, consume only 15% of the total since they use more open cycle cooling systems that consume less water. For this reason, water withdrawals are higher, amounting to 67% of the total withdrawals. Figure 5 presents the operational water consumption and withdrawals by fuel type for the African countries with the highest water use. North African countries and Nigeria are the main contributors to water use from natural gas power plants. The opposite occurs with coal power plants, which consume most of the freshwater (77% of the total) but explain a small fraction of the withdrawals (9%). This is due to the use of more closed cycle cooling systems in South Africa, the country that dominates the coal-fired power production. Oil power plants hold the third position in terms of power production in Africa and are the highest in number among the thermal plants, however, their impact on water use is smaller compared to other fuel types. Most of the oil power plants are small internal combustion engines, except from some oil-fired steam turbines located in Egypt, Morocco and Sudan that ultimately drive the water withdrawals of oil power plants in the continent. Despite having important installed capacities of oil plants, countries like Libya, South Africa, Nigeria and Tunisia have smaller water use than others, due to the use of seawater for cooling or less water-intensive technologies such as gas turbines.

The contribution of non-hydro renewable energies to the water use for power plant operations is negligible compared to fossil fuels. The main reason is the low capacity currently installed in Africa (only 4% of the total). However, it is important to highlight that the water factors are also much smaller compared to the ones of fossil fuels (e.g.: wind and solar plants only use water for cleaning purposes). Consequently, a much higher impact on water use is not expected in the case of a wider installation of renewables in the continent, except for concentrated solar power (CSP) technologies and biomass steam turbine plants as the water factors associated to them are comparable to fossil fuels due to the need of water for cooling.

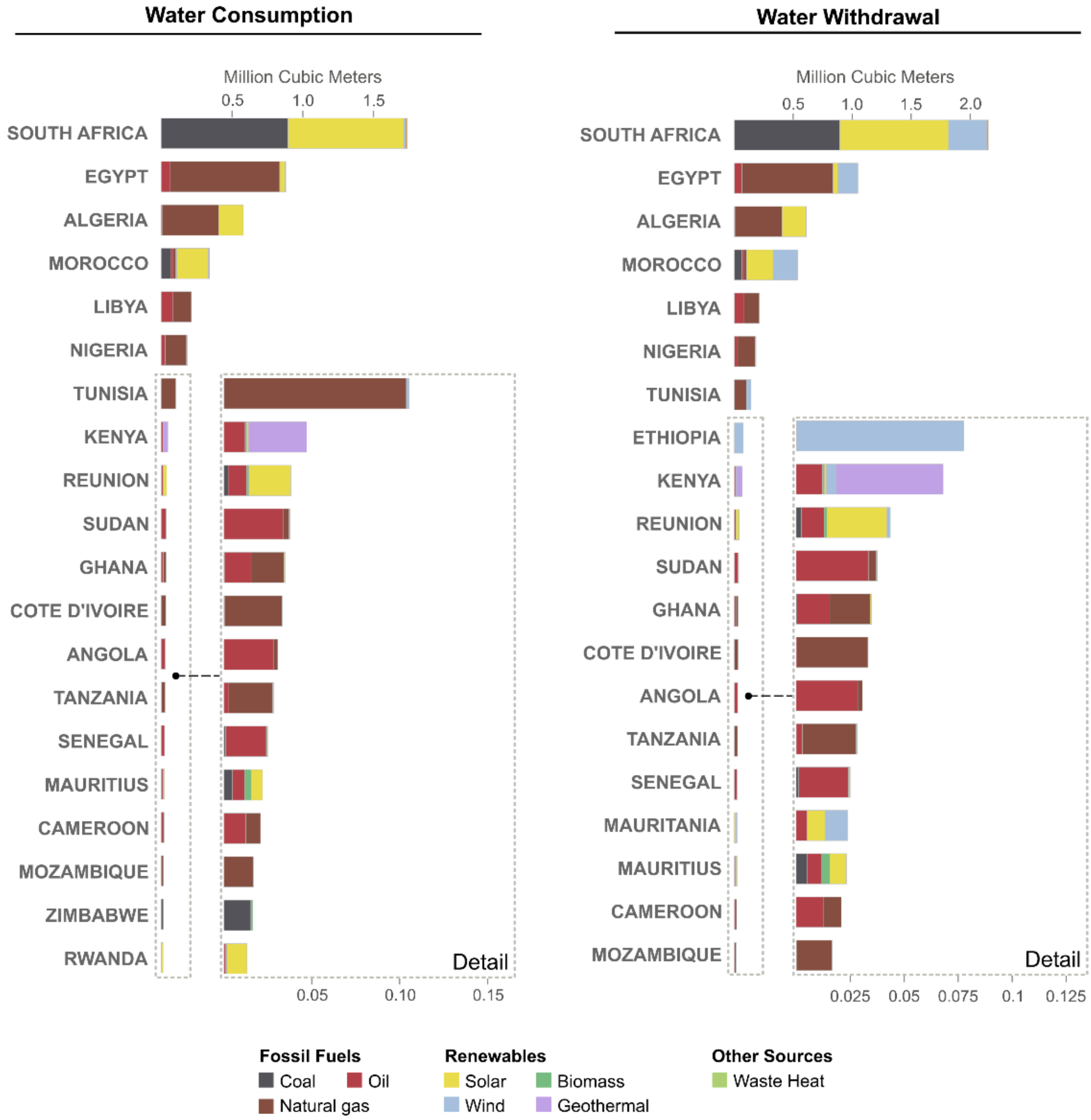
Figure 5 - Water consumption and withdrawal for power plant operations by fuel type and country in 2016 for the top 20 countries with the highest water use.



Source: Adapted from (Gonzalez Sanchez et al., 2020)

Water use for power plant construction has also been calculated, although it is almost negligible for most thermal technologies in comparison to the water use for operations. The total water consumption and withdrawals for power plant construction have been estimated at 4.5 mcm and 5.5 mcm respectively. Renewable energies (especially solar technologies) play an important role in this case, covering 43% of the withdrawals and 31% of the consumption. It is important to note that some components of the power plants (e.g.: turbines, photovoltaic (PV) components, etc.) are imported and therefore virtual water would be accounted for them. It is difficult to quantify this amount, hence, virtual water use for power plant construction is accounted as part of the water use.

Figure 6 - Water consumption and withdrawals for power plant construction by fuel type and country in 2016 for the top 20 countries with the highest water use.

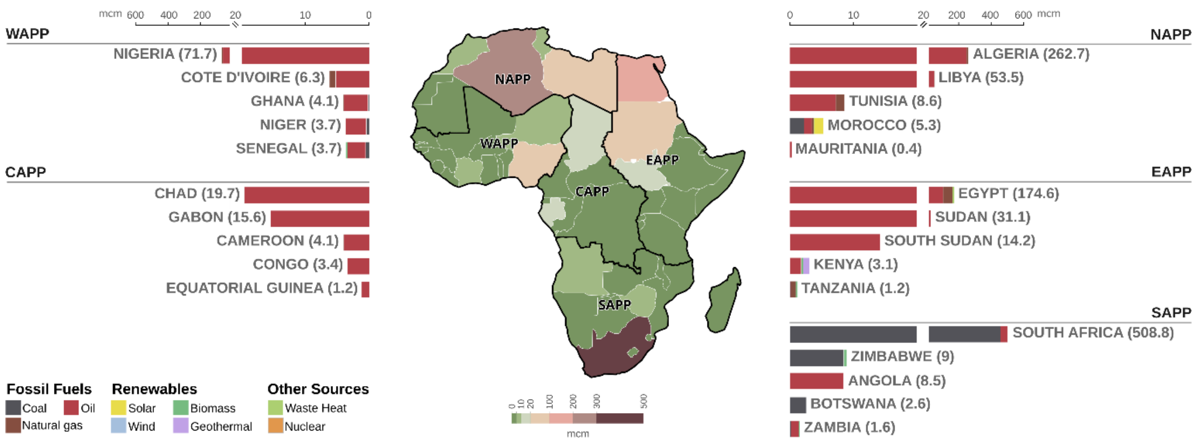


Source: Adapted from (Gonzalez Sanchez et al., 2020)

2.1.3. Total water use (excluding hydropower and fuelwood production).

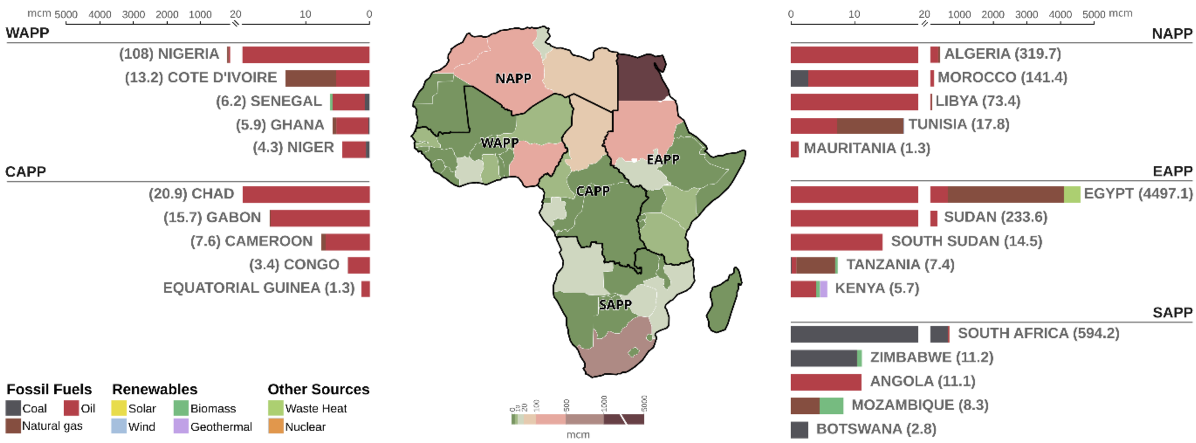
The total water use for energy production has been obtained as the sum of water use for primary fuel extraction and refining, power plant construction and power plant operations. More than half of the total water consumption is attributed to oil, because of the high water consumption during extraction and refining. On the other hand, oil plays a smaller role in total water withdrawals. Most of the withdrawals, 59%, are due to the cooling of natural gas power plants. The total water consumption and withdrawals have been estimated in 1235 mcm and 6152 mcm respectively and the distribution among fuel types, power pools and countries are shown in Figure 7 and Figure 8. At power pool level, oil is the main contributor to water consumption in all power pools except SAPP, which is dominated by coal, due to the influence of South Africa. Natural gas occupies a secondary position with only a more significant impact in EAPP caused by the influence of natural gas power plants in Egypt. Figure 9 provides an overview of energy and total water use (consumption and withdrawals) in each of the power pools.

Figure 7 - Total water consumption per country by fuel type for the five power pools in 2016.



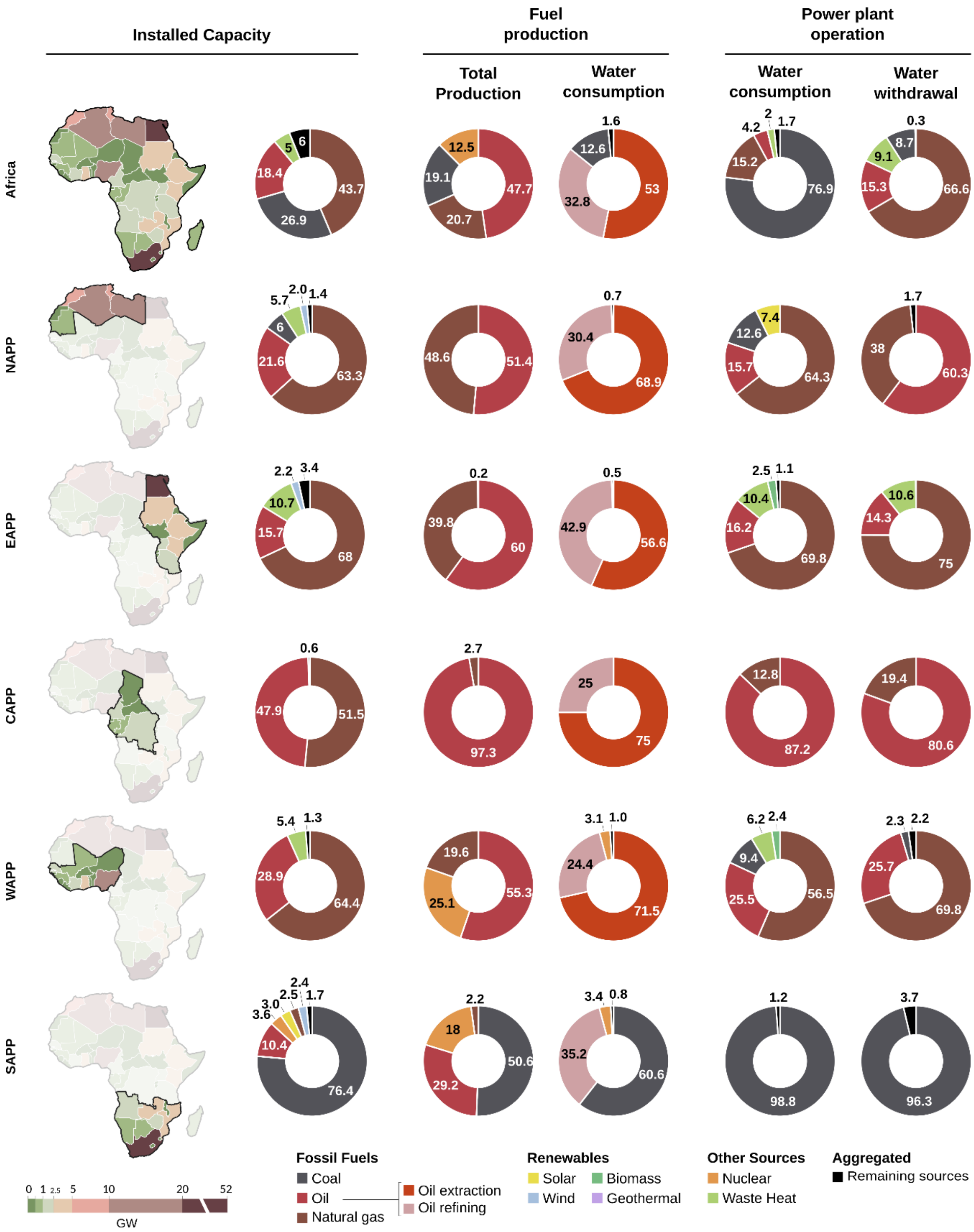
Source: Adapted from (Gonzalez Sanchez et al., 2020)

Figure 8 - Total water withdrawal per country by fuel type for the five power pools in 2016.



Source: Adapted from (Gonzalez Sanchez et al., 2020)

Figure 9 - Water and energy summary by power pool and fuel type in 2016.



Source: Adapted from (Gonzalez Sanchez et al., 2020)

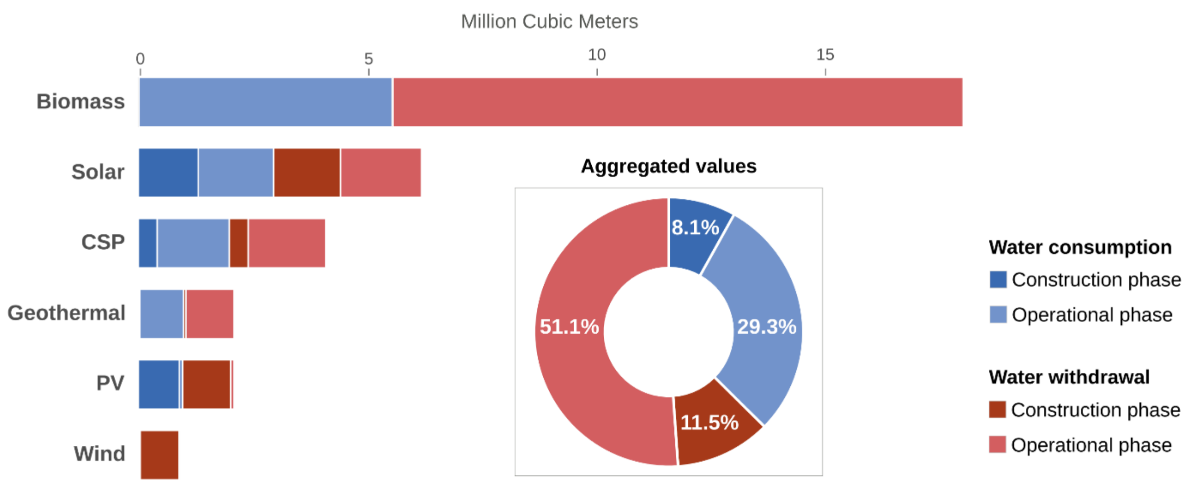
Column "Installed capacity": map with the total installed capacity for all energy types and shares in the region; column "Fuel production": share of each fuel type in the total fuel production and its associated share of water consumption per region; column "Power plant operation": share of each energy type in the total water consumption and withdrawals for power plant operation in the region.

2.1.4. Detailed view of water use by non-hydro renewable energy sources

The presence of renewable energies is still small in Africa, with a total installed capacity of 38 GW compared to 157 GW for fossil fuels in 2016. Hydropower is the most important energy source among renewables, covering 79% of them, representing however only 15% of the total installed capacity in Africa for all fuel types. Aside from hydropower, the installed capacity of other renewable energy sources is marginal in Africa. In this subsection, we take a closer look at the water use of non-hydro renewable energies, normally overshadowed by fossil fuels, keeping a separate subsection for hydropower as previously mentioned (section 2.2.2). With regards to biomass, only operational water use of biomass power plants is considered here, leaving a separate subsection to water for fuelwood production (section 2.2). The total water consumption and withdrawals associated to non-hydro renewable energies (construction and operations) has been estimated at 10 mcm and 18.3 mcm respectively. Biomass power plants are the highest consumers of water, due to cooling needs (60% of the total consumption and 70% of the total withdrawals), followed by solar technologies. CSP uses larger amounts of water for operations than PV because water is used for cooling, in contrast to PV technologies, which only require water for cleaning purposes.

With regard to water use for construction (noting that as previously mentioned it also includes virtual water), Figure 10 shows that this is the largest component for PV technologies while for CSP, water for cooling is the dominating use. However, it is important to mention that despite being the smallest component in CSP, the construction water factors for this technology double those of PV. Nonetheless, the total water use for PV construction is higher than for CSP, owing to a much higher installed capacity of PV compared to CSP (2058.6 MW vs 364.6 MW). Wind energy on the other hand is the smallest contributor to water use among all renewable energies, despite holding the second position in terms of installed capacity, after hydropower, in Africa. Most of its water use is linked to the construction phase, with small amounts of water used during operations for cleaning purposes.

Figure 10 - Water consumption and withdrawals of renewable energy sources in 2016 for plant construction and operation. Solar energy includes CSP and PV.



Source: Adapted from (Gonzalez Sanchez et al., 2020)

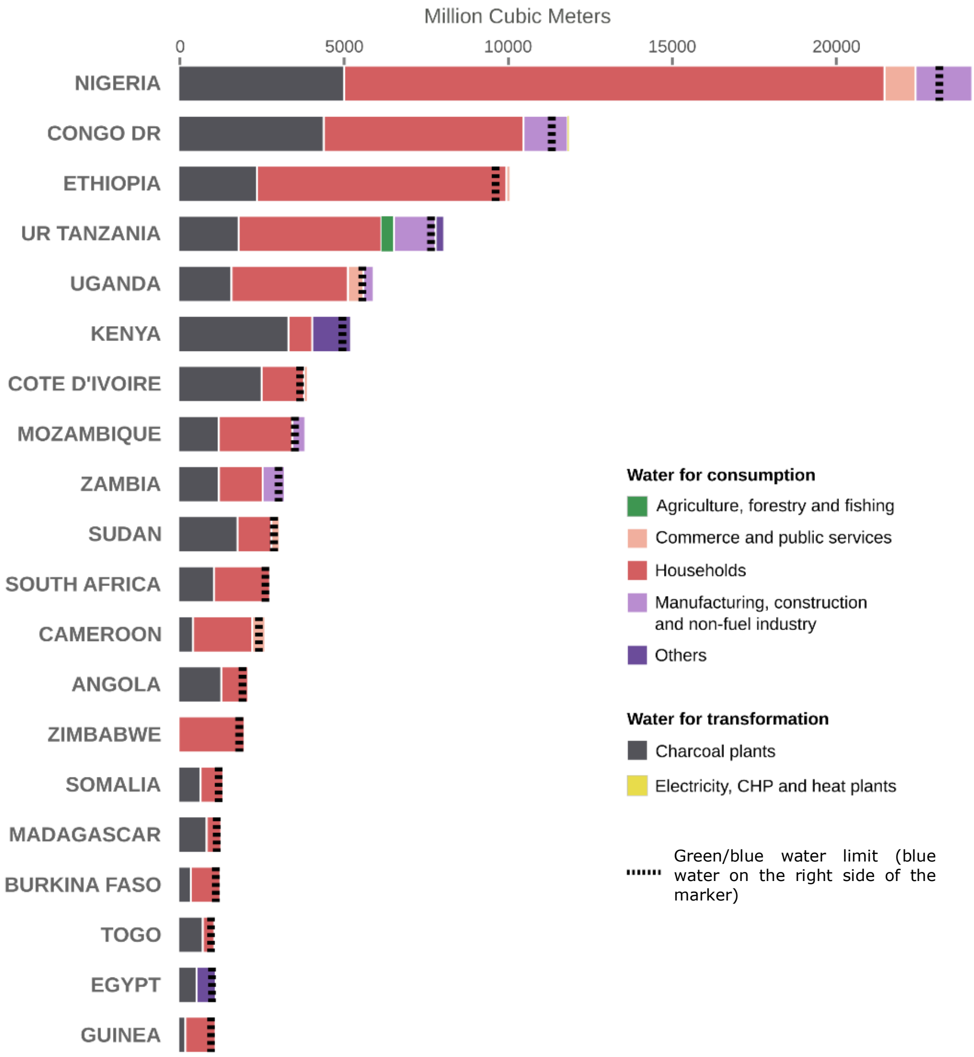
2.2. Other water uses

2.2.1. Water consumption for fuelwood production

UN data show that fuelwood consumption for energy is an important element to consider in Africa, as almost half of the total primary energy production comes from biomass (UN, 2016).

Green water (precipitation) and blue water (groundwater through capillary rise) (Schyns, Booij, and Hoekstra, 2017) for fuelwood production have been estimated at 103820 mcm and 4579 mcm respectively, figures significantly higher than in other energy sub-sectors. According to (IEA, 2017), 66% of the African population relies on biomass (mainly fuelwood) for cooking, with 22 countries in which this dependency reaches values up to 80%. As a consequence, and as depicted in Figure 11, most of the water consumption for fuelwood production is associated to use in households. It is important to notice in this case the magnitude of blue water consumption allocated to fuelwood in comparison to the water use for the production of other types of fuels (4579 mcm vs 728 mcm).

Figure 11 - Water consumption for fuelwood production by country and final use in 2016.



Source: Adapted from (Gonzalez Sanchez et al., 2020)

2.2.2. Water loss allocated to hydropower

Hydropower capacity represented 15% of the total installed power generation capacity in Africa in the year 2016. However, the dependency on hydropower varies from region to region. While in Northern and Southern Africa it accounts for less than 10% of the total installed capacity, in Western Africa represents 30% (excluding Nigeria), in Eastern Africa 54% and in Central Africa 58%. Furthermore, a number of countries have a high dependency on it, with eight countries exceeding 70% of their total installed capacity (2018). At the same time, hydropower is severely affected by droughts and the African countries which depend highly on it have been affected by recurrent electricity cuts (Africa-ME, 2016; Reuters, 2016).

Water is lost in reservoirs through evaporation and seepage. Evaporation from the surface of the reservoirs is the biggest contributor to water consumption from hydropower and can be several times larger than the water consumption from other types of fuels (Gleick, 1994; Macknick et al., 2012). On the other hand, while seepage has been estimated to cause an annual average loss of 5% of the volume of the reservoir, it is not considered a real loss, since the water remains in the water basin (Gleick, 1994). Consequently, in this study only evaporation losses have been analysed. The methodology used in this study to estimate the water loss from hydropower differs significantly from the methodology commonly applied to other fuel types, in which water factors are applied. The range of the water factors provided in the literature can be very wide, and therefore it can lead to an important underestimation or overestimation of the water losses (Mekonnen and Hoekstra, 2012; Macknick et al., 2012). A number of studies have addressed the water loss from hydropower reservoirs, focussing on both a large number of reservoirs at global scale as well as case studies (Zhao and Liu, 2015; Bakken et al., 2016; Coelho et al., 2017). In the first case, reservoir data is normally obtained from databases such as ICOLD and Grand (ICOLD, 2013; Lehner et al., 2011), while case studies often can access more detailed data for specific reservoirs. While seemingly large amounts of data are available in the global databases, they lack details regarding the accuracy of the measurements, the moment in which the data have been gathered or any information on the temporal evolution of the reservoir extension. One of the purposes of this study is to analyse a large number of reservoirs in Africa with a good spatial and temporal resolution using the JRC Global Surface Water dataset (Pekel et al., 2016), which provides the monthly water history of the water extents at 30m resolution. Reference evapotranspiration data have been obtained from the JRC LISVAP (a pre-processor for the LISFLOOD water balance and flood simulation model) (Burek, Van Der Knijff, and Ntegeka, 2013; Alfieri et al., 2019). The evaporation losses have been calculated using the FAO methodology for open water surfaces (FAO, 2015) expressed as (details on the methodology can be found in (Gonzalez Sanchez et al., 2020):

$$Ev = ET_o * A * 10^{-3}$$

where *ETo* (mm) is the reference evapotranspiration obtained from LISVAP and *A* (m^2) is the area of the reservoir obtained from the Global Surface Water.

Lastly, it is important to identify the different uses of the reservoirs since most of them are multipurpose. This is one of the main challenges the analysis of water use from hydropower faces and most of the studies allocate water loss fully to hydropower. In these cases, the water consumption associated with hydroelectricity is overestimated. There are different methodologies to identify the reservoir uses, however, according to (Bakken, Killingtveit, and Alfredsen, 2017), the most effective way to do a proper distinction is to use a combination of methods. It is out of the scope of this study to do an in depth analysis of the uses of each of the African reservoirs and therefore a ranking methodology has been selected (Scherer and Pfister, 2016; Mekonnen, Gerbens-Leenes, and Hoekstra, 2015) based on the uses information on GRanD, ICOLD and FAO databases (FAO, 2016; ICOLD, 2013; Lehner et al., 2011). When hydropower is the main use, 100% of the water loss has been allocated to electricity production, in case of secondary use: 50%; tertiary use: 33%, etc.

In this study, 159 out of the 529 operational hydropower plants in Africa in 2016 have been selected for the analysis. The criteria used for the selection is based on installed capacity (only plants above 5 MW have been considered since the exact location is not always available for smaller plants) and type of reservoir (some run-of-river plants have been discarded if no accumulation of water was identified). The 159 plants included in this study represent 95 % of the total hydropower installed capacity in Africa in 2016 (30.2 GW).

The total water loss through evaporation in the 159 hydropower plants analysed has been estimated at 42239 mcm. Table 1 summarises different energy and water loss parameters from hydropower at country level, including aggregated information of other types of energies for comparison. As expected, the countries with the highest water loss (Ghana, Egypt, Zambia, Mozambique and Zimbabwe) host the four largest dams in the continent (Figure 12). These reservoirs cover all together an area of 22733 km^2 and are responsible of two thirds of the total water loss allocated to hydropower in Africa. The water loss associated to hydropower (WL) is always larger than the water consumption from other fuel types (WC), except for South Africa and Equatorial Guinea. Moreover, in the countries with the highest WL, this value is several orders of magnitude larger than the WC (e.g.: 3560 times in the case of Zambia). Of all these countries, the only exception is South Africa, which has the highest WC in Africa (due to a very developed coal-based industry) and a smaller WL. Among the countries with a lower WL level, where its value starts to be comparable to WC, Algeria stands out. Its WC is the second largest in Africa and its WL is 23 times smaller than WC. This is a consequence of the very water intensive oil extraction and refining processes happening in the country and the modest presence of hydropower in its energy mix.

Table 1 - Summary of water losses associated to hydropower and different energy parameters for hydropower and non-hydro energy types per country for the year 2016 (ordered by WL)

	Hydropower							**Total Non-Hydro energies**		
Country	**IC (GW)**	**EP (GWh)**	**WL (mcm)**	**N**	**% TIC**	**RA (km^2)**	**WL/EP (mcm/GWh)**	**IC (GW)**	**EP (GWh)**	**WC (mcm)**
Ghana	1,61	5638	9524.63	3	100%	6004.73	1.69	2,152	8387	4,10
Egypt	2,69	12790	5757.43	2	95%	5248.37	0.45	35,867	172111	174,58
Zambia	2,20	10143	5626.23	6	94%	3387.15	0.55	0,287	465	1,58
Mozambique	2,18	15580	4421.75	4	100%	2391.20	0.28	0,684	3178	3,10
Zimbabwe	0,68	2296	3105.37	1	96%	1862.29	1.35	1,429	4161	8,95
Nigeria	1,97	7601	2881.69	4	99%	1815.36	0.38	13,841	31113	71,72
Sudan	1,59	8043	2718.96	5	100%	1966.50	0.34	2,464	6708	31,12
Cote D'ivoire	0,62	1564	1738.42	6	100%	1240.85	1.11	1,345	7608	6,30
Cameroon	0,75	4504	1065.80	3	100%	610.02	0.24	0,545	3753	4,13
Tanzania	0,57	2401	1024.10	7	98%	613.08	0.43	1,371	4706	1,21
Ethiopia	2,42	10834	923.27	9	84%	796.06	0.09	0,684	830	0,09
Congo D.R.	1,32	4799	640.46	8	90%	401.51	0.13	0,053	14	0,80
Mali	0,32	1891	618.44	3	98%	826.80	0.33	0,395	861	0,20
Morocco	1,76	1649	439.38	22	99%	408.94	0.27	6,492	29989	5,33
Burk. Faso	0,03	146	419.88	2	93%	353.84	2.88	0,366	835	0,16
South Africa	2,93	3561	302.14	13	99%	449.26	0.08	49,083	249164	508,81
Angola	1,18	4381	301.80	8	99%	201.02	0.07	1,202	4546	8,46
Togo	0,07	201	204.82	1	97%	138.84	1.02	0,241	23	0,00
Kenya	0,75	3234	182.03	7	92%	180.27	0.06	1,812	6692	3,13
Guinea	0,34	1014	151.75	4	94%	109.13	0.15	0,376	512	0,27
Congo	0,19	1126	78.11	2	100%	53.51	0.07	0,406	794	3,45
Gabon	0,29	1380	34.94	3	86%	27.69	0.03	0,314	711	15,57

	Hydropower							Total Non-Hydro energies		
Country	**IC (GW)**	**EP (GWh)**	**WL (mcm)**	**N**	**% TIC**	**RA (km²)**	**WL/EP (mcm/GWh)**	**IC (GW)**	**EP (GWh)**	**WC (mcm)**
Madagascar	0,10	549	16.94	4	75%	26.46	0.03	0,499	908	0,52
Sierra Leone	0,06	219	13.89	2	97%	10.03	0.06	0,207	85	0,01
Algeria	0,24	76	11.82	7	87%	36.55	0.16	19,620	73073	262,72
Tunisia	0,06	38	10.17	3	90%	39.10	0.27	5,043	20767	8,63
Namibia	0,35	1567	8.43	1	100%	5.16	0.01	0,198	91	4,79
Mauritius	0,04	68	3.65	2	68%	3.28	0.05	0,834	3333	1,59
Rwanda	0,03	86	3.47	1	35%	3.26	0.04	0,096	341	0,07
Malawi	0,34	1904	2.79	3	99%	1.92	0.00	0,083	256	0,21
Eswatini	0.06	124	2.37	4	97%	6.49	0.02	0.109	205	0.49
Uganda	0.67	3169	1.88	5	95%	1.32	0.00	0.337	415	0.41
Burundi	0.02	96	1.72	1	51%	1.53	0.02	0.006	24	0.00
Eq. Guinea	0.12	121	0.98	1	94%	0.85	0.01	0.185	542	1.21
Lesotho	0.07	502	0.20	1	94%	0.18	0.00	0.002	0	0.00
C. Afr. Rep.	0.02	134	0.02	1	99%	0.01	0.00	0.007	1	0.00

IC: Installed Capacity

EP: Energy Production

WL: Water Loss Through Evaporation In Hydropower Reservoirs

N: Number Of Reservoirs Included In The Study

% TIC: % Of Total Hydropower Installed Capacity Covered By The Study.

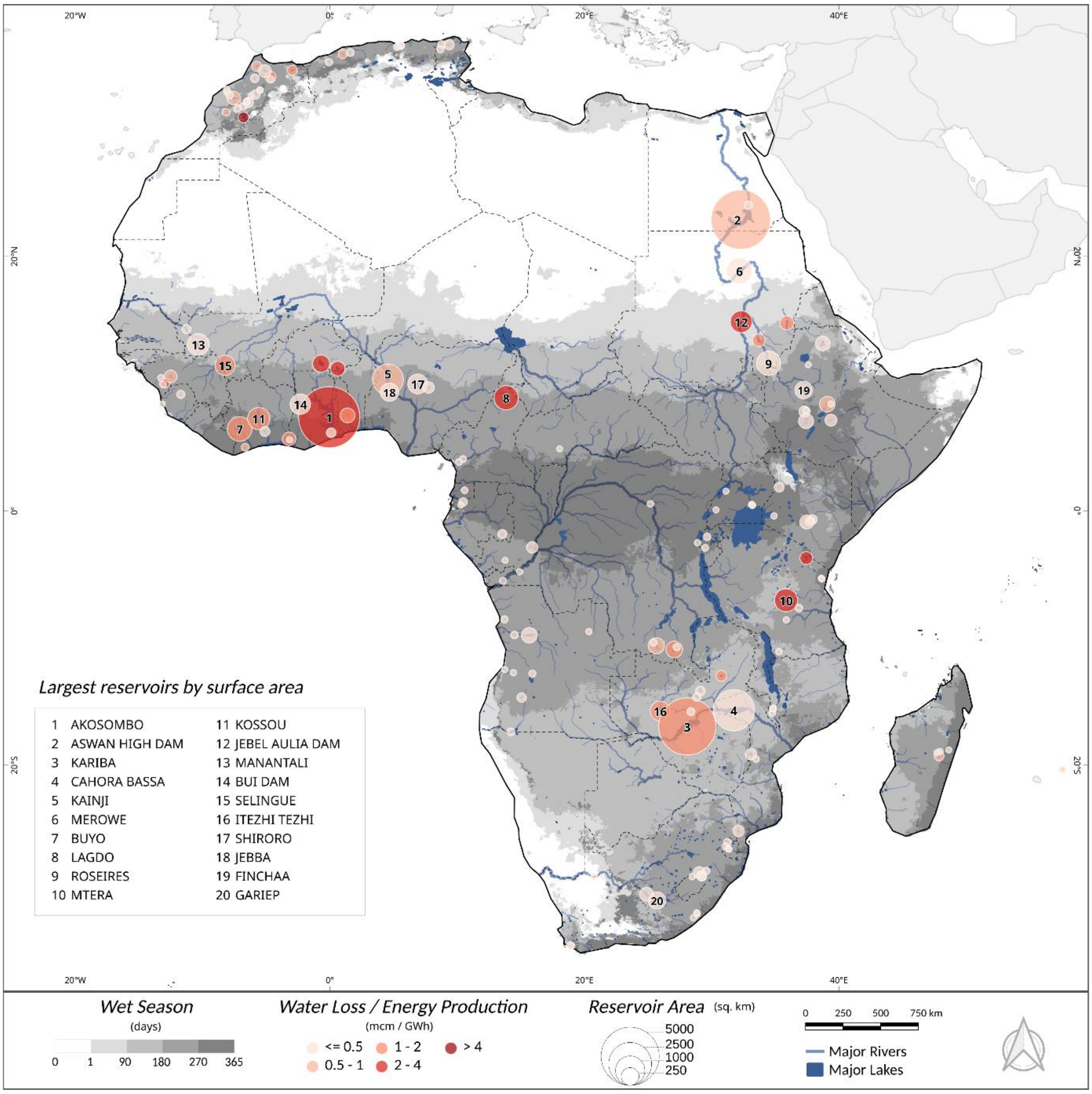
RA: Reservoir Area

WC: Water Consumption From Non-Hydro Energies.

Mcm: Million Cubic Meters

Source: Adapted from (Gonzalez Sanchez et al., 2020)

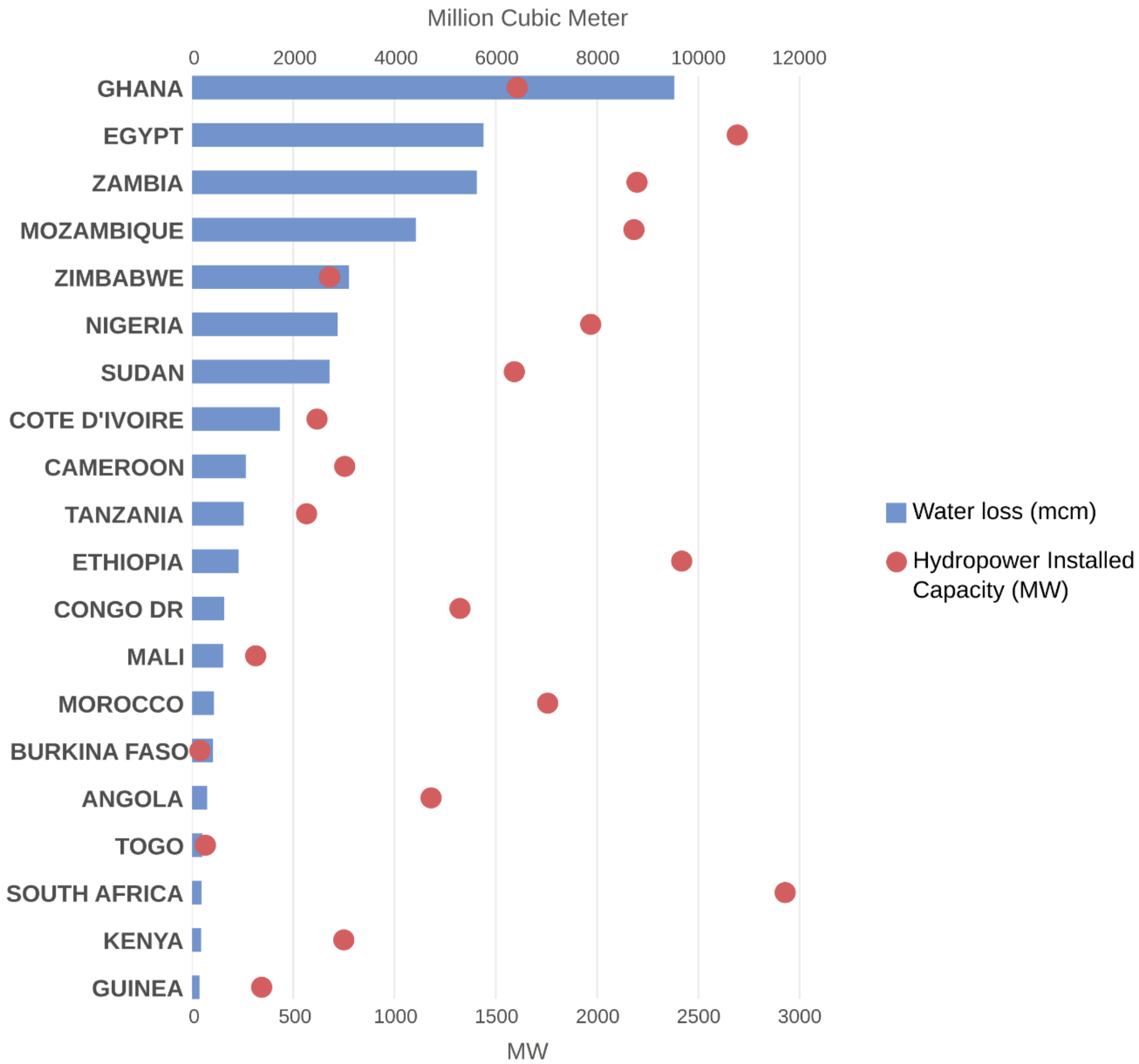
Figure 12 - Distribution of the largest hydropower plants classified by size and water loss through evaporation in 2016. Wet season duration and main rivers in Africa are also indicated.



Source: Reprinted from (Gonzalez Sanchez et al., 2020)

Figure 13 depicts the relationship between water loss and installed capacity. Egypt, Zambia, Mozambique, Ghana and Zimbabwe show the highest water loss compared to their installed capacity caused by the presence of large reservoirs. On the contrary, South Africa, Ethiopia, Morocco, Congo D.R. or Angola have relatively small water losses compared to their installed capacity. This can be explained by the presence of smaller reservoirs (which cause less evaporation) compared to other countries with similar installed capacities but larger reservoir areas.

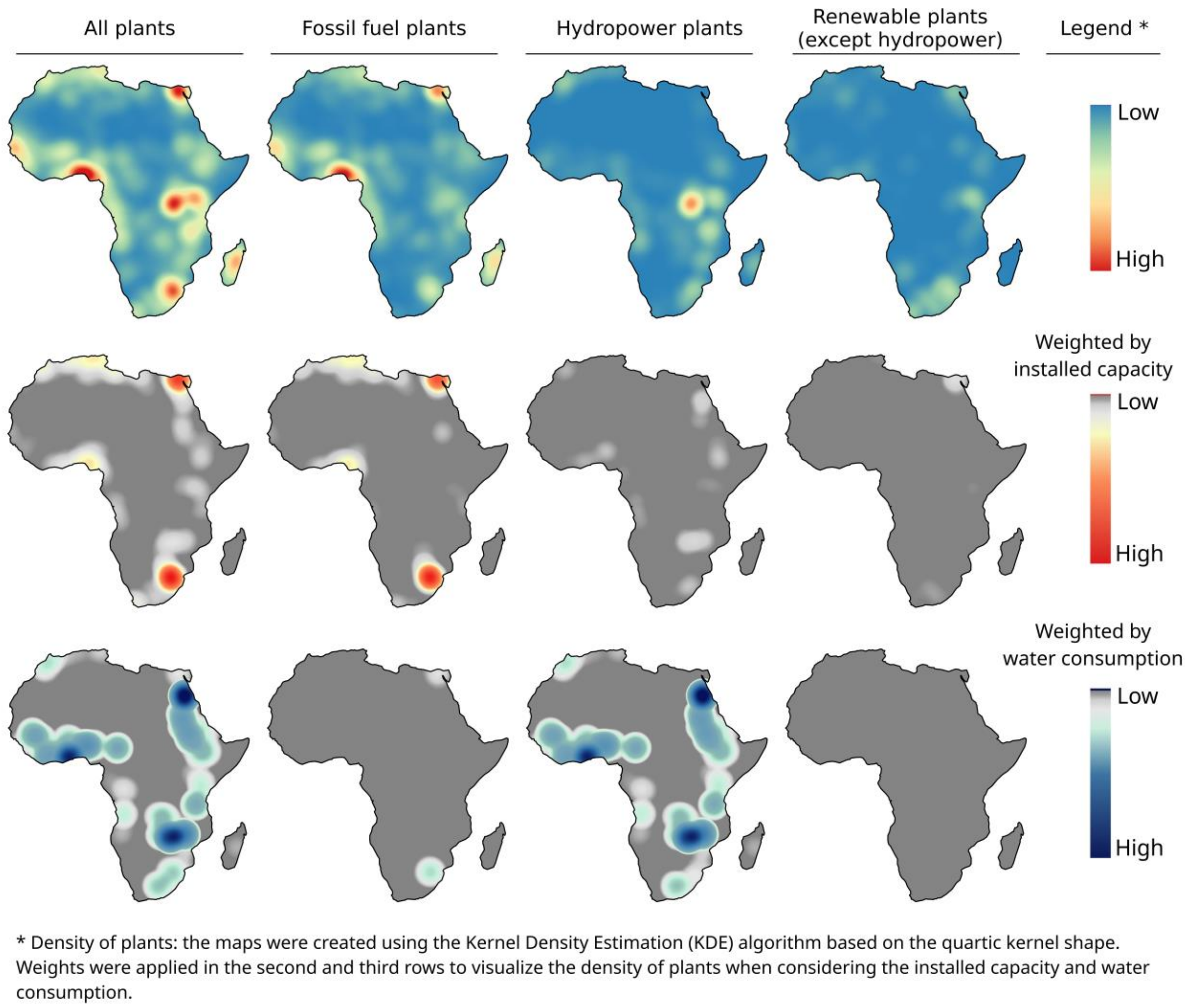
Figure 13 - Water loss through evaporation vs hydropower installed capacity for the top 20 countries with the highest water loss in the year 2016.



Source: Adapted from (Gonzalez Sanchez et al., 2020)

Despite presenting a higher density of power plants and installed capacity, compared to hydropower, non-hydro energies have a marginal impact in terms of water consumption. Furthermore, as their water use is almost negligible compared to hydropower, non-hydro energies can be an interesting option in water stressed countries. Figure 14 presents a visual summary of the density of power plants in Africa (first row) as well as the density combined with installed capacity (second row) and water consumption (third row). Two high-density areas can be observed in east and west Africa; however, these plants are characterised by low installed capacity. On the other side, when looking at density combined with water consumption, these plants play a more important role in high water consumption, due to the presence of hydropower plants in the area.

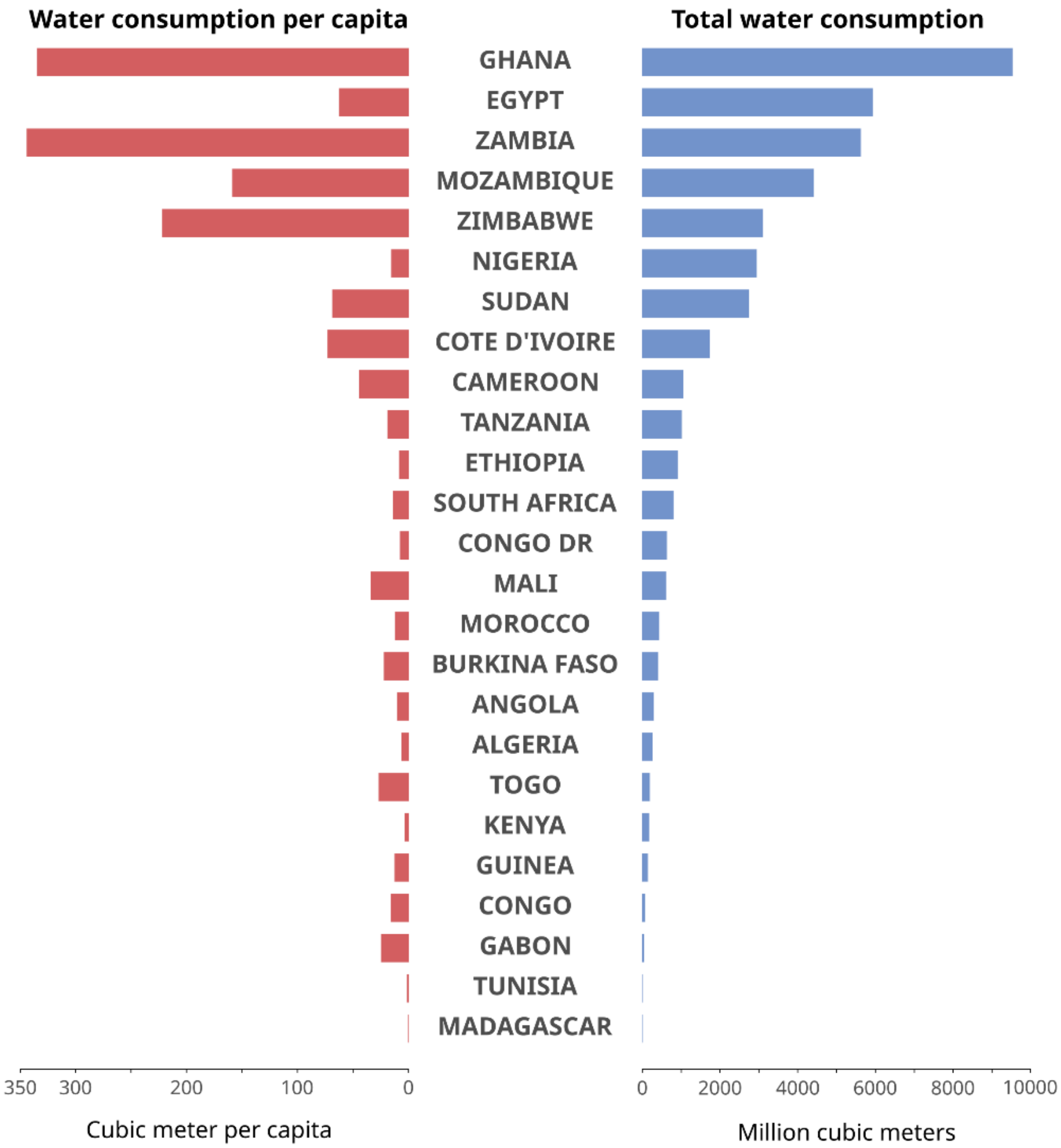
Figure 14 - Density maps of the power plants in Africa in 2016. Row 1: power plant location; Row 2: power plant location weighted by installed capacity; Row 3: power plant location weighted by water consumption.



Source: Reprinted from (Gonzalez Sanchez et al., 2020)

Lastly, in Figure 15, the total water consumption (for all fuel types) is represented against its values per capita. Countries with similar total water consumption (e.g.: Zambia and Egypt; Zimbabwe and Nigeria) present, however, very different values per capita. It is worth noting that in some of these countries with high water consumption for energy production per capita (i.e.: Zimbabwe and Zambia) the population with access to electricity is much lower than the corresponding countries with similar total water consumption (i.e.: Nigeria and Egypt).

Figure 15 - Total water consumption for energy (excluding fuelwood) vs total water consumption per capita for the 25 countries with the highest water consumption in the year 2016.



Source: Adapted from (Gonzalez Sanchez et al., 2020)

3. Projected freshwater use

In this section, the projected freshwater use for energy production in Africa is analysed both at continental scale and for each of the power pools. As for the present situation, water use allocated to hydropower and fuelwood are presented separately in sections 3.2 and 3.2.2. The results of water use are based on a previous study on the future energy projections in Africa for the reference, 2.0 °C and 1.5 °C scenarios (Pappis et al., 2019).

3.1. Total water use

With a high share of electricity generation from thermal power plants (IEA, 2018) the amount of water withdrawn and consumed by this infrastructure is important in the African continent, especially when there is a high uncertainty in climate change-induced water availability. In this section, we explore the future long-term trends in water withdrawal and consumption in the continent under three scenarios compatible with GECO (Keramidas et al., 2020; Pappis et al., 2019):

- The first or reference scenario assumes no new energy or climate policies in place. The reference scenario extrapolates the current situation into the future to project a plausible African energy system where energy policies do not evolve.
- In the 2.0 °C scenario, there are policies and emission targets aimed at keeping global mean temperature increase to 2.0 °C over pre-industrial levels with a 67% probability.
- The 1.5 °C scenario assumes a stronger climate objective pursuing a reduction in carbon dioxide emissions to levels lower than in the Reference and 2.0 °C scenarios with a 50% probability of reaching 1.5 °C warming by 2100.

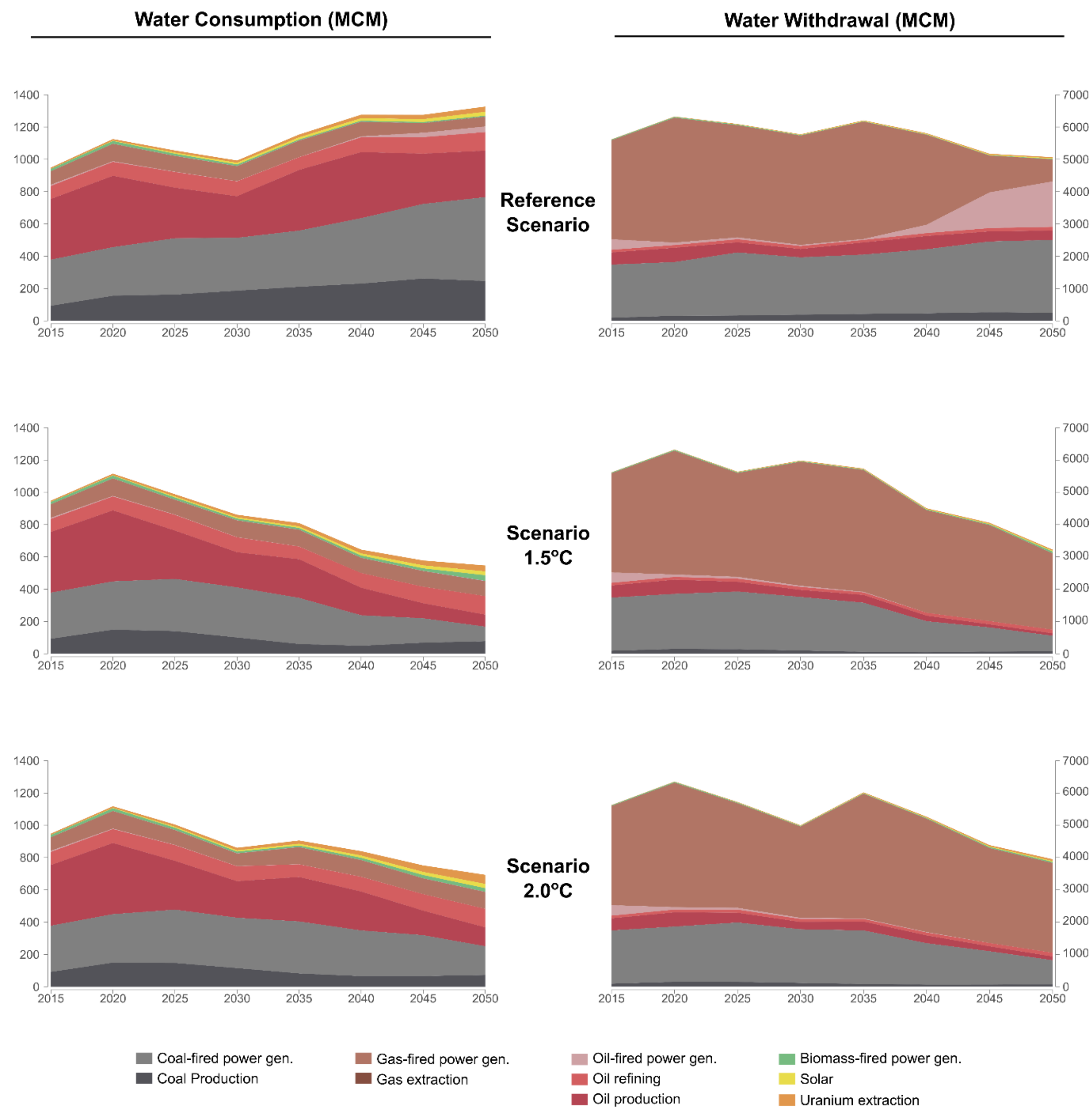
The reference scenario takes into consideration the national renewable policies that were in force until 2017, without considering new policies. The 1.5 °C and 2.0 °C scenarios consider the national renewable policies that were set in the reference scenario as well as emission targets that will reduce the overall emissions in the continent to meet future climate goals.

3.1.1. All Africa

In the reference scenario, we observe an increase of renewable energies (solar, wind and geothermal) from less than 1% of the total primary energy supply to 9% in 2050, however, fossil fuels continue covering most of the energy supply. In terms of electricity production, coal-based electricity and solar PV experience the most important increase by 2050. The projections indicate that the total water consumption of all energy types (except fuelwood and hydropower) will increase from approximately 1235 mcm (2016) to 1326 mcm (2050). The increasing trend appears to be caused by a raise in water use for cooling of coal power plants and coal extraction by 2050 as electricity generation from coal power plants grow. Water withdrawals on the other hand, show a decreasing trend, changing from 6152 mcm (2016) to 5068 mcm (2050) mainly due to an important drop in the water withdrawals from gas power plants. As gas-based electricity remains stable throughout the study period, this decrease in water withdrawals could be caused by a switch in cooling technologies from open-cycle cooling systems (that currently dominate in the African gas power plants) to close-cycle systems. Increasing water withdrawals for cooling of oil power plants start to appear after 2035, partially compensating for the drop caused by gas plants. This raise may be caused to a limited extent by the slight increase in oil-based electricity generation (as we also observe a small increase in water consumption) but also by a change in cooling technologies.

In the 2.0 °C and 1.5 °C scenarios, there is a clear higher penetration of solar, wind and geothermal energies, becoming all together 12% and 15% of the primary energy mix in the continent by 2050. Nuclear energy becomes more prominent after 2040, providing respectively 3% and 6% of the primary energy supply by 2050 in these two scenarios. This new nuclear infrastructure is expected to be located in coastal areas near the load centres, and therefore use seawater for cooling. Coal-based generation decreases and electricity from oil power plants becomes almost inexistent. The trends in both water consumption and withdrawals show a clear decrease, partially caused by the higher use of renewable energies. The lower use of coal and oil is expected to cause a reduction in water use, while gas power plants still largely contribute to the water withdrawals to meet their cooling needs. The total water consumption decreases by 48% and 59% in the 2.0 °C and 1.5 °C scenarios respectively, while water withdrawals on the other hand, show a decrease of 22% and 36% in these two scenarios. The higher penetration of renewable energies in the energy mix is expected to contribute in reducing the future total water use.

Figure 16 - Water consumption and withdrawals in Africa for the three scenarios by energy type (first row: reference scenario; second row: 2.0 °C scenario; third row: 1.5 °C scenario)



Souce: JRC, 2020

In the following sections, a detailed discussion of the future trends in each African power pools helps to better understand the continental trends discussed above. Detailed figures of the water use for each of the power pools (equivalent to Figure 16) by fuel type for each scenario are included in the Annex.

3.1.2. West African Power Pool (WAPP)

WAPP accounts for a significant share of the water used for energy in the continent, especially in countries like Nigeria with their future high gas and oil usage. By 2050 in the reference scenario, 21% of the total water consumption in Africa is expected to occur in WAPP and its share will increase to 30% and 38% in the 2.0 C and 1.5 C scenarios respectively. Most of the water consumption in WAPP is used for oil extraction and refining in the three scenarios, following however a decreasing trend in the 2.0 °C and 1.5 °C scenarios, caused by the higher penetration of renewable energies as we move forward into the future. The water consumption for oil extraction keeps decreasing steadily, especially in the 2.0 °C and 1.5 °C scenarios, while water use for oil refining keeps raising in the three scenarios. Coal-based electricity is low in all the scenarios, although it experiences a slight increase in the reference scenario with the consequent raise in the water use, especially after 2040. In the 2.0 °C and 1.5 °C scenarios the small coal use reaches maximum levels towards the middle of the modelling period before starting to decrease until is almost inexistent in the 1.5 °C scenario. The associated water use is therefore minimal. Expected new nuclear power plants replacing coal plants in countries like Ghana, Nigeria and Ivory Coast will contribute to the decrease in the water consumption after 2040.

Water withdrawals on the other hand experience an increase in the future after 2025 in the three scenarios, mainly caused by the water use for cooling of natural gas power plants, probably as a consequence of the higher use of open-cycle cooling systems. Inland, biomass-based generation in Burkina Faso will start appearing after 2045 in the 1.5 °C scenario, slightly increasing both water consumption and withdrawals in WAPP.

3.1.3. North African Power Pool (NAPP)

Electricity generation in NAPP is dominated by natural gas in the three scenarios. The impact of gas is not as strong in water consumption as it is in water withdrawals, where other energy types are overshadowed by it, especially after 2020. The continuous use of open-cycle cooling systems in gas power plants in the NAPP countries appears to be cause of the high-water withdrawals. Coal production in Tunisia and Morocco increases moderately in the future for the reference scenario, while it remains small and almost constant in the 2.0 °C and 1.5 °C scenarios. The effect of coal-based electricity on water consumption is, however, quite significant due to the installation of close-cycle cooling systems characterised by high water consumption and small withdrawals. Oil production continues to be an important consumer of water in the three scenarios, with only a moderate decrease after 2045 in the 1.5 °C scenario. Renewable energies on the other hand penetrate strongly and not only in the two low-carbon scenarios but also in the reference scenario where by 2050 are expected to cover half of the electricity production. Solar and wind energy specially will constantly keep growing and replacing coal generation as we move forward into the future. However, future increase in solar CSP technologies in Egypt and Morocco will be the cause of important water consumptions, especially in the 1.5 °C scenario where by 2050 these technologies will be responsible for around half of the total water consumption. Overall, water consumption in NAPP remains constant until 2030, peaks around 2035, and decreases afterwards in the 2.0 °C and 1.5 °C scenarios. Water withdrawals on the other hand generally show a decreasing trend except from a slight raise in the reference scenario from 2030 to 2045. NAPP, as a whole, represents a small share of the total water use in Africa, reaching a maximum of 11% of the water consumptions in the 2.0 °C scenario caused by the mix of fossil fuels and the initiation of solar CSP technologies.

3.1.4. Eastern African Power Pool (EAPP)

Among all the power pools, the EAPP is the strongest contributor to the continental water withdrawals due to the cooling of gas power plants. In the 1.5 °C scenario, the water withdrawals in EAPP constitute 58% of the total withdrawals in the continent. Only in the reference scenario oil power plants start taking over natural gas in terms of water withdrawals from 2040, reaching 100% of the share by 2050. Oil-based generation disappear practically in the 2.0 °C and 1.5 °C scenarios, where renewable energies clearly take over by 2050, producing most of the electricity in the region. Oil production and refining have a strong presence in water consumption in EAPP, although natural gas power plants still dominate throughout the years, being always present in the three scenarios. Electricity generation from conventional natural gas power plants remains almost constant being replaced gradually by plants equipped with CCS towards the end of the modelling period. Coal-based electricity on the other hand is only present in the reference scenario taking over natural gas by 2050 and only then contributing significantly to the water consumption. It is also interesting to notice the presence of biomass-based power plants that remain rather constant in the three scenarios. Overall, the total water consumption remains relatively constant during the modelling period, especially in the reference and 2.0 °C scenarios. For water withdrawals, we can appreciate a decreasing trend, probably caused by the replacement of gas power plants equipped with open-cycle systems with the much less water intensive renewable energies.

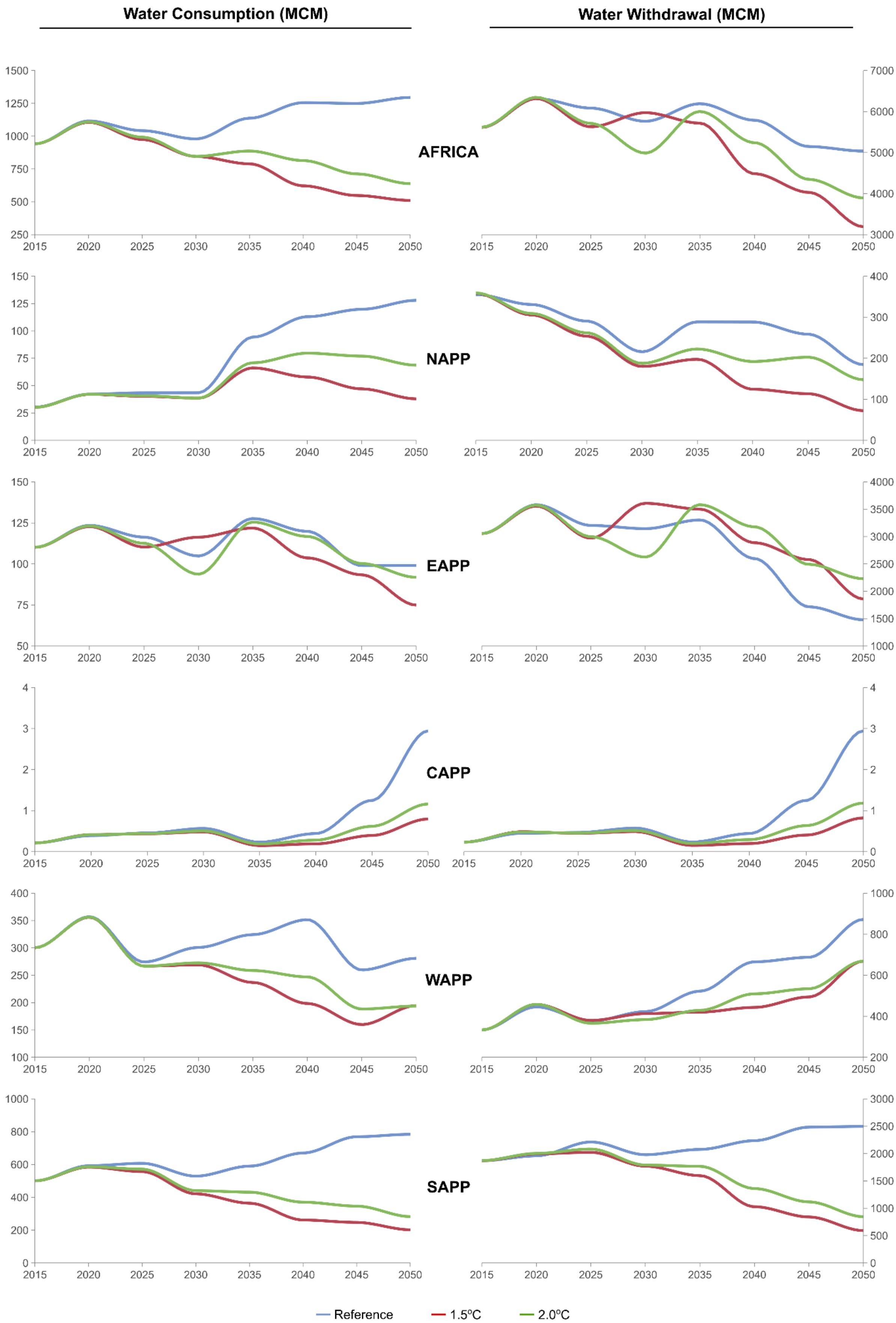
3.1.5. Central African Power Pool (CAPP)

In the reference scenario, the CAPP has already a high penetration of renewable energies in the power sector, mainly from hydropower (water use not addressed in this section) but also some from solar and wind energies. This hydropower dominance will keep intensifying in the 2.0 °C and 1.5 °C scenarios. Fossil fuels contribute less than 20% of the power pool's electricity generation, therefore, the water withdrawal and consumption figures are the lowest amongst all the power pool's consumption (0.06% on average) and withdrawal (0.01% on average). Crude oil extraction is the main contributor to water consumption and withdrawals in all scenarios. In the first years of the 2.0 °C and 1.5 °C scenarios, we also observe the presence of water use for oil power plants, but this is still significantly smaller compared to the water use for oil extraction. Natural gas and coal are used to produce a small share of electricity in the reference and 2.0 °C scenarios, however, we do not observe any impact on water use due to the higher dominance of oil extraction. The overall trends of water consumption and withdrawal follow very similar patterns, with both increasing especially towards the end of the modelling period, due to the increase in oil production.

3.1.6. Southern African Power Pool (SAPP)

In the 1.5 °C and 2.0 °C scenarios, the power system starts shifting away from heavy coal dependence after 2030, turning to renewables (solar PV, wind and hydro). Nuclear energy remains with a small contribution in the energy mix. In terms of water consumption, the three scenarios are still dominated by coal mining and the cooling of coal power plants, leaving only a small share to oil production. Water consumption due to uranium production in SAPP is the highest among the power pools and it increases slowly throughout the years, however its contribution to water use is still small. In the reference scenario, we observe a slight increment in both consumption and withdrawals, while in the 2.0 °C and 1.5 °C scenarios water use starts decreasing after 2025, where renewable energies begin to replace coal. SAPP is the main contributor to continental water consumption due to coal, reaching a maximum of 61% of the total consumption and 50% of the total withdrawals in the last years of the modelling period for the reference scenario.

Figure 17 - Water consumption and withdrawals per power pool for the reference, 2.0 °C and 1.5 °C scenarios.



Source: JRC, 2020

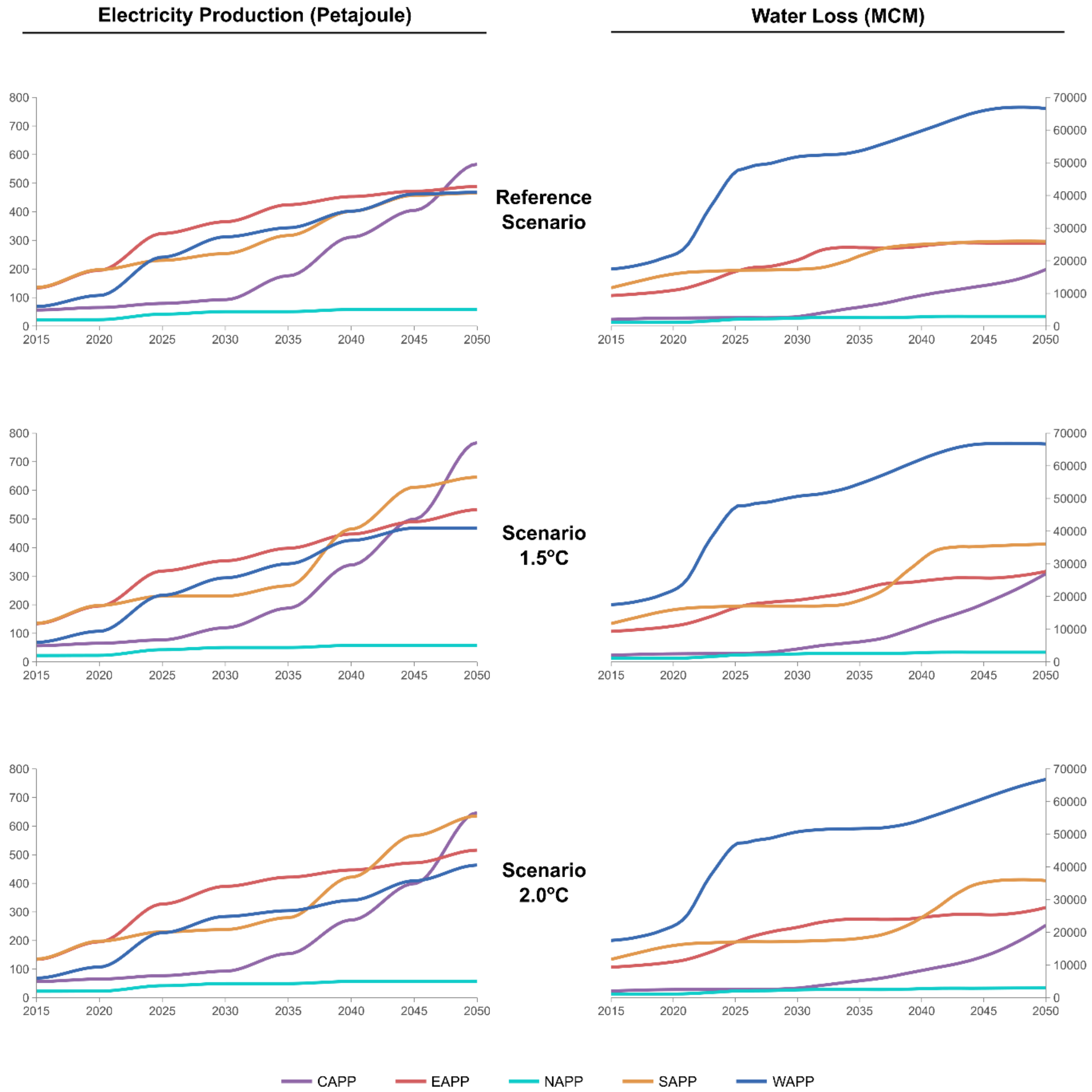
3.2. Other water uses

3.2.1. Hydropower

The future projections of water loss through evaporation in hydropower reservoirs have been estimated based on the electricity projections for the three different scenarios. Due to lack of data regarding the amount of hydroelectricity produced from each type of power plant (reservoir or run-of-river types) in each country, the same distribution as in the present situation has been applied assuming that it remains constant in the future. Only reservoir-type power plants are considered since they cause most of the evaporation. Country-specific water factors have been obtained from the present situation and applied to the future hydroelectricity production.

Figure 18 depicts the future projections of water loss allocated to hydropower in the three scenarios under study. As hydropower generation keeps growing in the future, the total water loss expected by 2050 is 139 bcm, 155 bcm and 160 bcm for the reference, 2.0 °C and 1.5 °C scenarios. In the reference scenario, the hydroelectricity projections in the WAPP, EAPP and SAPP evolve very similarly. However, we observe a significant increase of water loss in WAPP due to a much higher water factor in the region caused by countries like Ghana (with the presence of Akosombo, the biggest hydropower reservoir in Arica), Nigeria, Burkina Faso or the Ivory Coast, where very high values of evaporation per MWh are produced by their hydropower reservoirs. CAPP on the other hand presents the steepest increase in hydroelectricity production after 2040, however due to a low water factor, water use is moderate in comparison to the rest of the power pools, except from NAPP. In NAPP, both the electricity production and water loss are low due to a less hydropower installed capacity and also to the presence of small reservoirs in Morocco, which cause a smaller evaporation per MWh produced. The 1.5 °C and 2.0 °C scenarios do not present significant differences in terms of general trends compared to the reference scenario.

Figure 18 - Future projections of hydroelectricity production and water loss associated to hydropower per power pool in the reference, 2.0 °C and 1.5 °C scenarios.

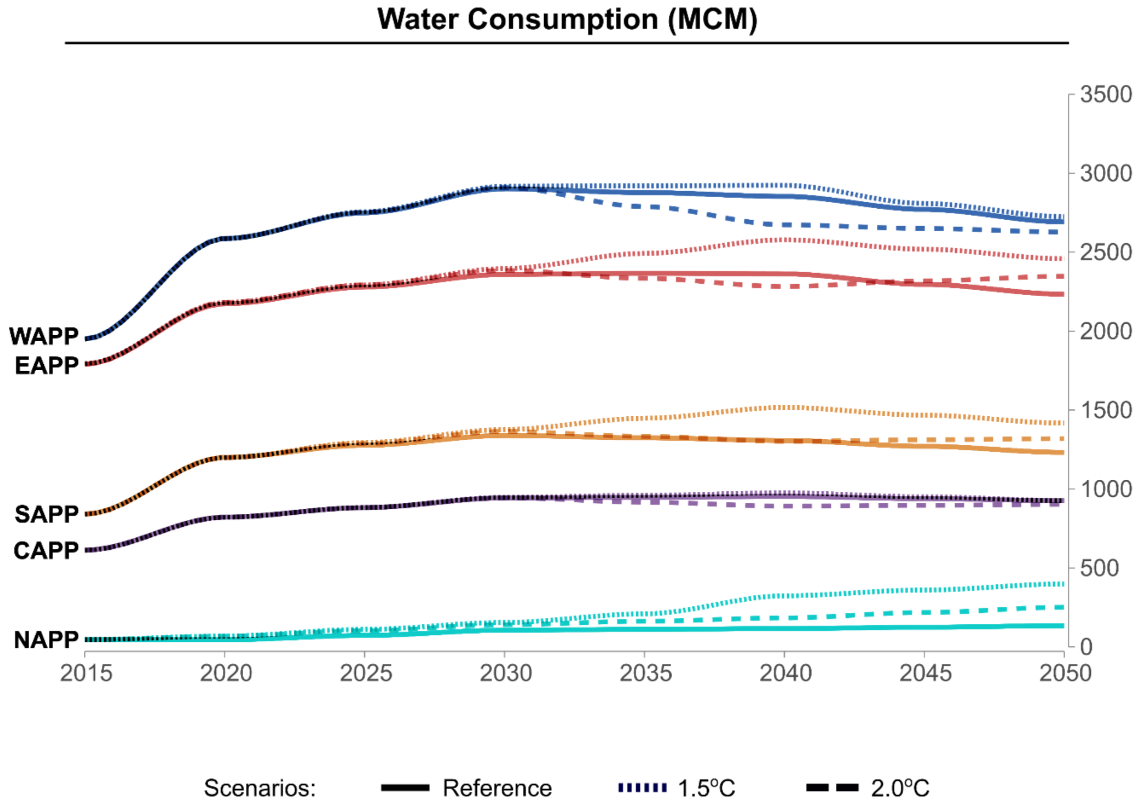


Source: JRC, 2020

3.2.2. Biomass (fuelwood) production

The use of biomass in the continent keeps increasing approximately until 2030 in the reference and the 2.0 °C scenarios, and until 2040 in the 1.5 °C scenario, to start a slight decrease afterwards. Due to the lack of data, this biomass is assumed to be fuelwood, and therefore the corresponding projected freshwater use is based on this hypothesis. In 2050, biomass covers 26%, 37% and 48% of the total primary energy supply in the reference, 2.0 °C and 1.5 °C scenarios respectively. The presence of more biomass in the 1.5 °C scenario compared to the others causes the consequent higher water consumption, growing from 4579 mcm in 2016 to 7934 mcm in 2050 for the whole continent. For the reference and the 2.0 °C scenarios, water use is expected to increase up to 7216 mcm and 7455 mcm by 2050 respectively. The highest fuelwood use occurs in WAPP, while in NAPP is minimal, being however, the only power pool showing a continuous increasing trend in biomass use for the three scenarios (Figure 19).

Figure 19 - Future projections of water consumption associated to fuelwood production per power pool for the reference, 2.0 °C and 1.5 °C scenarios



Source: JRC, 2020

4. Comparison with previous studies

The results obtained in this study have been compared with previous analyses available in the literature. These studies differ from each other in terms of scope (energy processes included, type of water analysed, etc.), time frame and geographical coverage. The number of studies in the literature addressing water use for energy production in Africa is also very limited. Below we describe briefly each of the studies considered in order to provide a better view of previous work on the topic:

— (Vassolo and Döll, 2005): Global-scale gridded estimations of freshwater consumption and withdrawal for the year 1995 are obtained. The scope of this study covers only water for the cooling of thermal power plants. The results obtained for Africa are 344 mcm and 3637 mcm for water consumption and withdrawals respectively.

— (Davies, Kyle, and Edmonds, 2013): Global and regional lower-, median-, and upper-bound estimates of freshwater consumption and withdrawals for the cooling of power plants are obtained for the base year of 2005. The median values obtained for the year 2005 (not including hydropower) are 7600 mcm and 1020 mcm for withdrawals and consumption respectively. Future projections until 2095 for ten scenarios are also estimated. Values for Africa in the "median_lotech scenario" (median water intensity factors, no adoption of advanced water saving technologies, and an assumed share of cooling systems) including hydropower, range from 3125 mcm (2005) to 45950 mcm (2095).

— (Mekonnen, Gerbens-Leenes, and Hoekstra, 2015): The water consumption for the three stages of energy production is obtained for the period 2008-2012 per country at global scale. Hydropower is included in the estimations and it is assumed that freshwater is used for all cooling systems. The values of water consumption obtained are 1007 mcm for primary fuel extraction, 53879 mcm for power plant operation and 2.2 mcm for power plant construction.

— (Spang et al., 2014): Freshwater consumption in 2008 is obtained at global scale per country for fuel production and power plant operation. Hydropower is not included in the estimations. Not all the African countries are represented in the published article, however, the water consumption estimations for South Africa, Nigeria, Algeria and Angola together is 1575 mcm.

— (Flörke et al., 2013): Freshwater consumption and withdrawals are obtained from 1950 to 2010. Hydropower is not included and only the cooling of thermal plants is analysed.

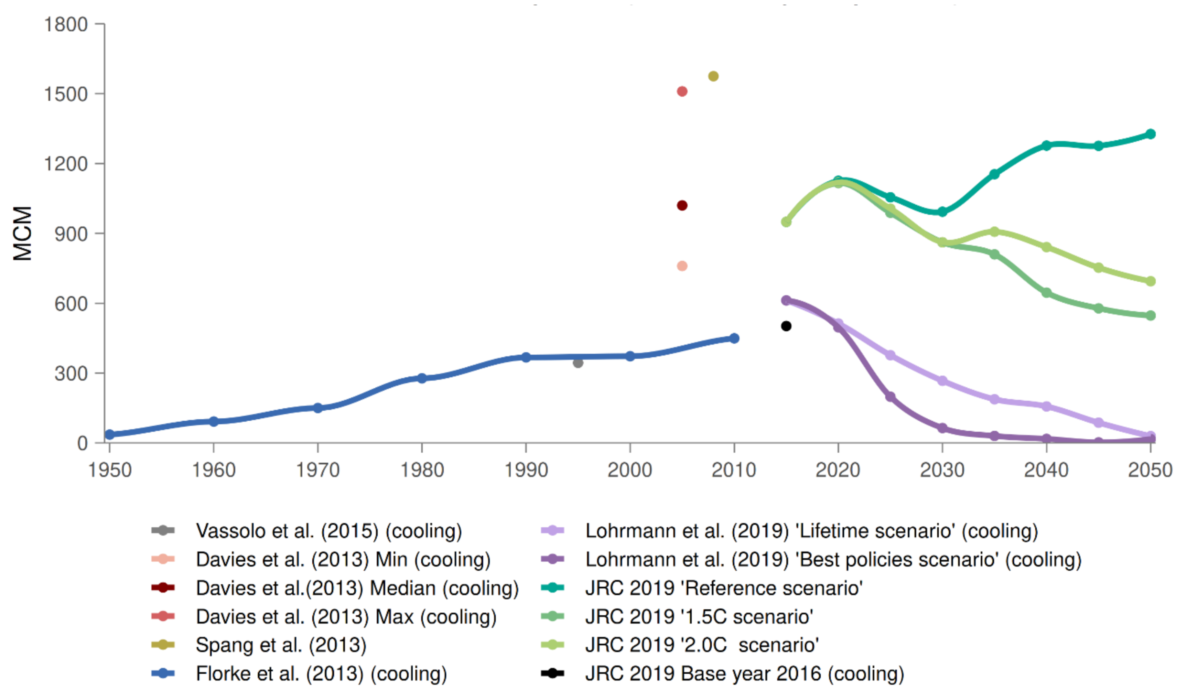
— (Lohrmann et al., 2019): Water consumption and withdrawals in thermal power plants are estimated. No distinction is done between freshwater and seawater. Water use is obtained for a base year (2015) and for two scenarios in the future (lifetime scenario and best policies scenario) towards a net-zero greenhouse gas emissions economy by 2050.

— (Fricko et al., 2016): Freshwater consumption and withdrawals are obtained for Sub-Saharan Africa for the base year (2010) and for the future through a combination of different pathways to reach the 2 °C objective. Hydropower is included in the calculations. Values of water use are provided for the reference and the GEA-mix scenario for the year 2100.

(Mekonnen, Gerbens-Leenes, and Hoekstra, 2015) and (Spang et al., 2014) are the most similar studies to ours in terms of scope, with the first covering the three stages of energy production and the second covering the two most water-intensive processes, fuel production and plant operation. The results in (Mekonnen, Gerbens-Leenes, and Hoekstra, 2015) present globally a good alignment with our estimations and small differences may arise from the fact that freshwater is assumed for cooling in all thermal power plants, overestimating freshwater needs since many plants are located in the coast and use seawater. Comparing our estimations of water consumption with (Spang et al., 2014) for the four African countries provided in the article, our results are consistently smaller. This may be the result of the assumptions made in (Spang et al., 2014) regarding freshwater and seawater use for fuel production and cooling of thermal power plants, for which the methodology used to differentiate both types of water is not completely clear. In the case of South Africa and Algeria, the water consumption values show a good alignment between both studies. Water for power plant operations, and in particular for cooling thermal plants, is normally the focus of many of these studies. In this case, the estimations obtained in (Vassolo and Döll, 2005), (Lohrmann et al., 2019), (Flörke et al., 2013) and our study, show consistency for the base years in each study. On the other hand, water use in (Davies, Kyle, and Edmonds, 2013) presents always higher values compared to the other studies, especially for water consumption. The future projections in (Lohrmann et al., 2019) show a steep decrease, more pronounced than in our scenarios, since these projections are defined towards a net-zero greenhouse gas emissions economy by 2050.

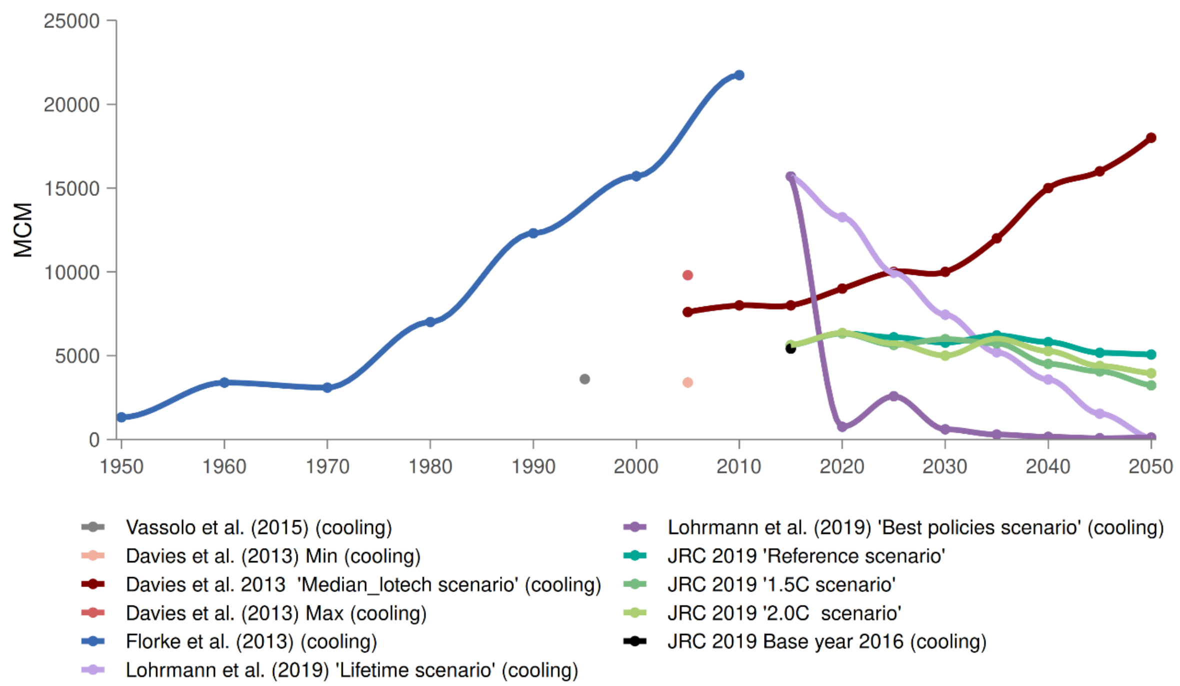
Figure 20, Figure 21, and Figure 22 show the comparison among the different studies analysed. It is important to consider factors such as the distinction between freshwater and seawater and the energy production processes included in each study to understand the differences between them.

Figure 20 - Comparison of water consumption with previous studies not including hydropower



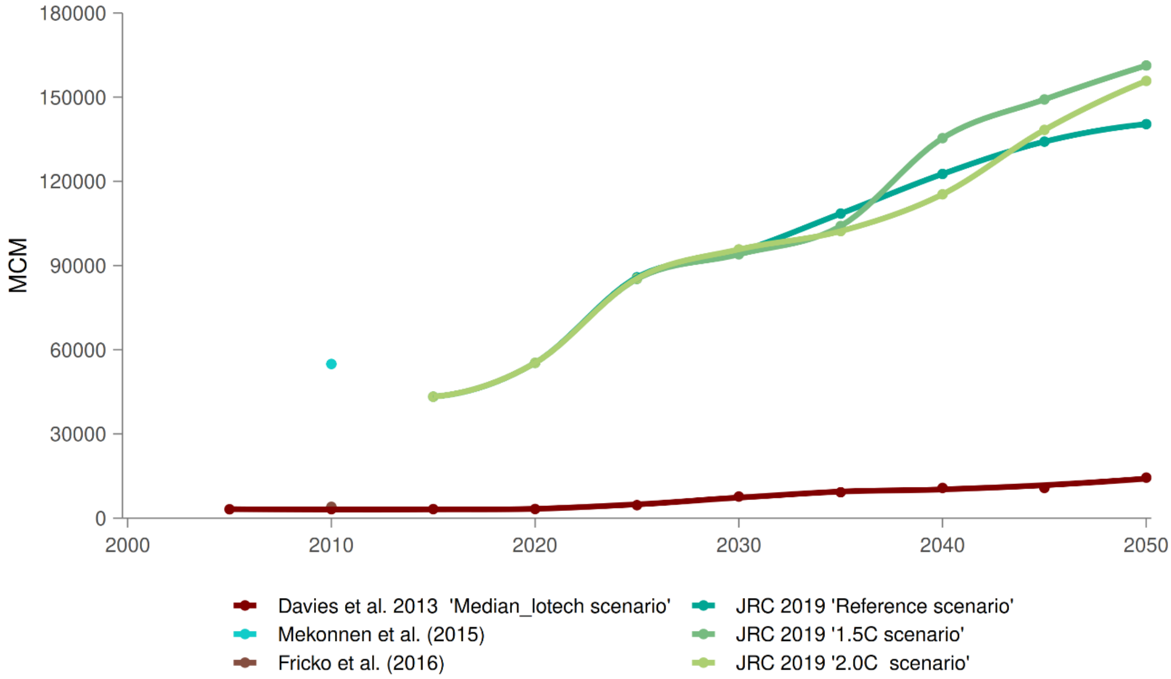
Source: JRC, 2020

Figure 21 - Comparison of water withdrawals with previous studies



Source: JRC, 2020

Figure 22 - Comparison of water consumption with previous studies including hydropower



Source: JRC, 2020

Figure 22 depicts the comparison among studies that consider water loss through evaporation in hydropower reservoirs in their calculations. An in-depth comparison has been done at reservoir level with two studies that include some of the African reservoirs analysed in this study. Table 2 shows the comparison among the two studies analysed and the results presented in this report.

Table 2. Comparison of water loss in hydropower reservoirs with previous studies.

Study	Reservoir	Akosombo	Cahora Bassa	Itezhi Tezhi	Kariba	Kiambere
	Country	**Ghana**	**Mozambique**	**Zambia**	**Zambia / Zimbabwe**	**Kenya**
(Mekonnen and Hoekstra, 2012)	**IC**	1180	2075	600	1320	150
	A	8502	2660	370	5100	25
	EV	2185	3059	2572	2860	2356
	WL	18580	8140	950	14590	60
(Hogeboom, Knook, and Hoekstra, 2018)	**IC**		-	-	-	-
	A	6044	-	328	5276	-
	EV	1418	-	1258	1289	-
	WL	4820	-	232,5	3826	-
	WL*	8569	-	413	6801	-
JRC (2020)	**IC**	1020	2075	120	1760	144
	A	5601	2293	348	4820	24
	EV	1587	1888	1646	1667	1544
	WL	8889	4329	572	8037	37

IC (MW): installed capacity

A (km^2): area of the reservoir

EV (mm/year): evaporation

WL (mcm/year): water loss

WL*(mcm/year): Water loss removing the k-factor applied in Hogeboom et al. (2018).

The results are not directly comparable, since the extension of the reservoirs, the time reference, the evaporation values and the shared uses allocation method present differences in each study, being in some cases significant. It is important to investigate where the discrepancies come from to perform correct comparisons among studies. First of all, the areas in the two previous studies analysed (as well as in many others that analyse a big number of reservoirs) are taken from global databases such as GRanD (Lehner et al., 2011) or ICOLD (ICOLD, 2013). When using global databases, it is not always clear the moment in which these areas have been measured and, in many cases, the maximum areas recorded are used in the studies. In (Hogeboom, Knook, and Hoekstra, 2018) for instance, these maximum areas are used for the calculations and a correction factor of 0.5625 is applied. As mentioned in the introduction, the methodology used in this report aims to overcome the difficulties in the collection of accurate values of the areas by using the Global Surface Water dataset, based on Landsat imagery and for which the timeframe of the measurements is very well defined. The evaporation in these two articles, on the other hand, is obtained using different methods leading for example to significant discrepancies with (Mekonnen and Hoekstra, 2012) in which the evaporation values are up to 42% higher than the values used in our study for the reservoirs compared. In this case, (Hogeboom, Knook, and Hoekstra, 2018) presents values of evaporation more similar to the ones used in our study (maximum 24% difference). However, in (Hogeboom, Knook, and Hoekstra, 2018) some of the discrepancies arise from the use of the correction factor without which the final water loss for the reservoirs compared are more consistent with our results (see WL* in Table 2). Regarding the shared uses allocation, (Hogeboom, Knook, and Hoekstra, 2018) performs an allocation based on the economic value of the different uses, while in our study we use a ranking-based allocation as explained in 2.6. In (Mekonnen and Hoekstra, 2012), an allocation of water loss to the different shared uses is not mentioned, therefore, we assume 100% of the water loss was allocated to hydropower in all cases. Electricity production is the first use for all the reservoirs analysed in Table 2, as indicated by GRanD (Lehner et al., 2011) and ICOLD (ICOLD, 2013). Consequently, this factor should not be a source of discrepancy between (Mekonnen and Hoekstra, 2012) and our study since 100% of the water loss would be allocated to hydropower in these five reservoirs. In (Hogeboom, Knook, and Hoekstra, 2018), no water loss has been allocated to other uses as a result of their economic allocation for the three reservoirs included in their study, therefore, no discrepancies should arise from this factor either.

5. Conclusions and discussion

In the current study, the present and future freshwater consumption and withdrawals of the African energy sector have been estimated. The processes analysed include primary energy production, energy transformation in oil refineries, power plant construction and operation. A comparison with previous studies has also been performed, showing a good alignment with our results, taking into account factors such as the distinction between freshwater and seawater and the energy production processes included in each study. However, fuelwood and hydropower are normally not addressed, despite being the highest water consumers. The methodology used in this report to obtain the water lost by evaporation in hydropower reservoirs differs significantly from the ones applied in other studies in the literature, in which global databases are used to obtain the reservoir areas. In this study, the areas are obtained using the Global Surface Water Dataset (Pekel et al., 2016), a JRC product based on satellite data, which provides monthly water surfaces at 30 m spatial resolution.

The overall total water consumption of all energy types (including fuelwood production and hydropower) in 2016 for the African continent has been estimated at 47.7 bcm. For primary energy production, most of the water is used for oil extraction. Gas on the other hand, regardless of being the second fuel type more used in the continent, has a minimal water impact due to a much less water intensive extraction process. Biomass use in households, especially in Sub-Saharan Africa, has also an important impact on water associated to fuelwood production. Regarding power plant operation, in most of the countries, evaporation in hydropower reservoirs is several orders of magnitude higher than the total water use of other energy activities combined, estimated at 42 bcm of water lost in 2016 (88% of the total water consumption for energy in Africa). Factors such as climate, extension of the reservoirs and allocation of shared uses are key for the estimation of water loss. Results of our study show that, for countries with similar installed capacities, the ones with a high number of small reservoirs seem to be more efficient in terms of water loss per MW installed than those with a few large reservoirs. Beyond hydropower, most of the freshwater is consumed for cooling thermal power plants, with important variations depending on the cooling system used. Water impact of renewable energies on the other hand is almost negligible compared to the rest of the energy sources.

Future freshwater use has also been analysed in three energy scenarios compatible with GECO (Keramidas et al., 2020; Pappis et al., 2019): reference, 2.0 °C and 1.5 °C scenarios. The results obtained indicate that in 2030, the total water consumption will reach 102.4 bcm, 103.4 and 101.8 bcm and in the year 2050 these amounts will grow to 147.6 bcm, 163.2 bcm and 169.2 bcm, in the reference, 2.0 °C and 1.5 °C scenarios respectively.

In the reference scenario, despite observing an appreciable increase in penetration of renewable energies (wind, solar and geothermal) from 1% to 9% by 2050, the energy sector continues to be dominated by fossil fuels. Increasing amounts of coal used for electricity production in power plants will raise water consumption due to mining and cooling. Water withdrawals remain stable, caused by a switch in cooling technologies in gas power plants from open-cycle to close-cycle systems. By 2030 and 2050, the water loss associated to hydropower has been estimated at 93.8 bcm and 139 bcm; the water consumption for fuelwood production at 7.6 bcm and 7.2 bcm; and the water consumption for other energy types at 1 bcm and 1.3 bcm.

In the 2.0 °C and 1.5 °C scenarios, we start observing decreasing trends in water use, both for consumption and withdrawals. An increase of renewable energies in the energy mix substituting coal and oil will be the main reason for this. Gas power plants will continue to account for the largest share of water withdrawals due to their cooling needs. A growing nuclear energy penetration with power plants mainly located in coastal areas (using seawater for cooling), as assumed in the energy scenarios used to estimate the freshwater requirements, will also contribute to the decrease in total water use for electricity generation. The total water consumption decreases by 48% and 56% while water withdrawal decreases by 36% and 47% in the 2.0 °C and 1.5 °C scenarios respectively. The use of biomass is expected to continue to increase due to fuelwood use in households, especially in the 1.5 °C scenario where by 2050 it will cover 48% of the total primary energy supply. This causes an important increase in water use, reaching 7934 mcm by 2050 in the 1.5 °C scenario, mainly originated in WAPP. Hydropower generation will continue to increase in all scenarios and while we observe a similar evolution in hydropower generation for all the power pools except NAPP, in terms of water losses, WAPP will account for the highest share due to the high values of evaporation per MWh in the region. In summary, in the 2.0 °C scenario, by 2030 and 2050, the water loss associated to hydropower has been estimated at 94.8 bcm and 155 bcm; the water consumption for fuelwood production at 7.7 bcm and 7.4 bcm; and the water consumption for other energy types at 0.9 bcm and 0.7 bcm. In the 1.5 °C scenario, the water consumption in 2030 and 2050 becomes: 93.1 bcm and 160.7 bcm for hydropower; 7.8 bcm and 7.9 bcm for fuelwood; and 0.86 bcm and 0.55 bcm for other energy types.

The growing energy demand in Africa presents an opportunity to develop the energy sector in more sustainable ways, not only aiming towards decarbonisation but also towards water savings. The results of this study show that freshwater use in the energy sector could be reduced in a number of ways. Increasing the use of less water -intensive fuels like gas or the use of salt/brackish water for oil extraction can help to decrease the use of freshwater during fuel extraction. The choice of appropriate cooling systems based on the availability of local water resources can also contribute significantly to water use for power plant operations. The shift from open-cycle to close-cycle cooling systems that we currently observe in new power plants can aid in solving some of their environmental issues and high withdrawals from the water sources; however, it is also important to consider the impacts of cooling systems on costs. Lack of data is generally a problem when studying Africa. Better data availability, for instance regarding the electricity production at power plant level, would further improve the quality of the results. Country-specific water factors would also provide an important added value to the results of this study or similar studies in other regions in which global average water factors are normally used.

Africa is characterised by a large untapped hydropower potential; however, new developments should pay attention to the importance of water loss through evaporation and consider factors such as water availability, climate (evaporation) and size of the projected reservoir. This study sets the base for further work on hydropower in Africa. Future studies could focus on evaluating the net water losses in which less water loss may be allocated to hydropower as a result of accounting for the natural evaporation of the river before the dam construction. Additionally, seasonal variation studies of the reservoirs 'extents over time can also be performed in order to try to forecast periods of water scarcity using the GSW. The methodology presented in this analysis can certainly be applied to other regions similarly, both to assess the current water lost through evaporation in a reservoir as well as to estimate the water losses of future developments. The reservoir uses allocation methodology applied in this study, can also be further developed by integrating several aspects such as priority of uses, regulations and economic and social valuations.

Non-hydro renewable energies such as solar PV and wind have small water use both for operations and construction, being almost negligible compared to fossil fuels. A wider installation of renewable energies can reduce drastically the water use, especially in Africa where there is a substantial potential of renewable sources (mainly wind and solar) highly untapped. One of the deterrents for the wider installation of renewable energies in Africa is the power grid infrastructure. Interesting interconnection opportunities among the power pools can be put in place to take advantage of the differences in the potential of each region. These interconnections may also have positive impacts on the use of water resources. Unlike in the past, today's cost-competitive renewable technologies are a feasible and competitive solution to substitute fossil fuels.

The use of existing infrastructure for energy generation should be improved, including for instance the retrofitting of non-powered dams to meet the proper criteria for electricity production. Installing floating solar panels in hydropower reservoirs can be another interesting solution, not only to produce electricity by taking advantage of the present grid infrastructure but also to help reduce evaporation in the reservoirs.

Biomass use should also be looked at carefully, since it is a very water intensive resource. The use of modern appliances with higher efficiencies in households would help reducing water use and deforestation at the same time. Additionally, it is important to analyse the evolution of renewable resources in view of climate change as well as to consider the availability of fossil fuels to ensure a steady transition to a more sustainable energy mix in the continent. Socio-economic barriers to the development of renewable energies in Africa can also play an important role for a broader installation. These barriers need to be addressed to ensure the stable long-term presence of renewable energies and the universal access to electricity in the continent.

Finally, despite the overall positive trends in future freshwater use, resulting from the three scenarios, the water-energy nexus in Africa will remain a challenge. Economic and demographic growth combined with increased scarcity of water resources due to climate change will induce further competition between energy and other non-energy uses (e.g. irrigation, public water supply, etc.) that will require appropriate policy measures.

References

AFREC, 'Africa Energy Database.', 2017. https://africa-energy-portal.org/database.

Africa-ME, 'Drought Plunges Kariba Dam Hydropower to Record Lows', 2016. http://africa-me.com/drought-plunges-kariba-dam-hydropower-to-record-lows/.

Alfieri, L., V. Lorini, F. Hirpa, S. Harrigan, E. Zsoter, C. Prudhomme, and P. Salamon, 'A Global Streamflow Reanalysis for 1980-2018', *InReview*, 2019.

Bakken, T.H., Å. Killingtveit, and K. Alfredsen, 'The Water Footprint of Hydropower Production-State of the Art and Methodological Challenges', *Global Challenges*, Vol. 1, No. 5, August 2017, p. 1600018.

Bakken, T.H., I.S. Modahl, K. Engeland, H.L. Raadal, and S. Arnøy, 'The Life-Cycle Water Footprint of Two Hydropower Projects in Norway', *Journal of Cleaner Production*, Vol. 113, 2016, pp. 241–250.

Burek, P.A., J. Van Der Knijff, and V.N. Ntegeka, *LISVAP Evaporation Pre-Processor for the LISFLOOD Water Balance and Flood Simulation Model*, *Joint Research Center*, 2013.

Coelho, C.D., D.D. da Silva, G.C. Sediyama, M.C. Moreira, S.B. Pereira, and Â.M.Q. Lana, 'Comparison of the Water Footprint of Two Hydropower Plants in the Tocantins River Basin of Brazil', *Journal of Cleaner Production*, Vol. 153, 2017, pp. 164–175.

Davies, E.G.R., P. Kyle, and J.A. Edmonds, 'An Integrated Assessment of Global and Regional Water Demands for Electricity Generation to 2095', *Advances in Water Resources*, 2013.

EEA, 'Water Use by Sectors.', 2018. https://www.eea.europa.eu/archived/archived-content-water-topic/water-resources/water-use-by-sectors.

Energydata.info, 'Africa - Power Stations.', 2012. https://energydata.info/en/dataset/africa-power-stations-2012.

FAO, 'Evaporation from Artificial Lakes and Reservoirs', *FAO AQUASTAT*, 2015.

FAO, 'Geo-Referenced Dams Database', 2016. http://www.fao.org/nr/water/aquastat/dams/index.stm.

FAO, 'Irrigation in Africa in Figures: AQUASTAT Survey.', Vol. 29, 2005.

Flörke, M., E. Teichert, I. Bärlund, S. Eisner, F. Wimmer, and J. Alcamo, 'Domestic and Industrial Water Uses of the Past 60 Years as a Mirror of Socio-Economic Development: A Global Simulation Study', *Global Environmental Change*, Vol. 23, February 1, 2013, pp. 144–156.

Fricko, O., S.C. Parkinson, N. Johnson, M. Strubegger, M.T.H. van Vliet, and K. Riahi, 'Energy Sector Water Use Implications of a 2° C Climate Policy', *Environmental Research Letters*, Vol. 11, No. 3, 2016, p. 34011.

Gleick, P.H., 'Water and Energy', *Annual Review of Energy and the Environment*, Vol. 19, No. 1, 1994, pp. 267–299.

Gonzalez Sanchez, R., R. Seliger, F. Fahl, L. De Felice, T.B.M.J. Ouarda, and F. Farinosi, 'Freshwater Use of the Energy Sector in Africa', Applied Energy, Vol. 270, 2020, p. 115171.

Harvard, 'Africa Power Plants.', 2010. http://worldmap.harvard.edu/data/geonode:africa_power_plants_gd4.

Hidalgo González, I., Medarac, H. and Magagna, D., Projected freshwater needs of the energy sector in the European Union and the UK, EUR 30266 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-19829-1 (online), doi:10.2760/796885 (online), JRC121030.

Hogeboom, R.J., L. Knook, and A.Y. Hoekstra, 'The Blue Water Footprint of the World's Artificial Reservoirs for Hydroelectricity, Irrigation, Residential and Industrial Water Supply, Flood Protection, Fishing and Recreation', *Advances in Water Resources*, Vol. 113, 2018, pp. 285–294.

ICOLD, 'World Register of Dams (WRD).', 2013. https://www.icold-cigb.org/GB/world_register/world_register_of_dams.asp.

IEA, *Energy Access Outlook. From Poverty to Prosperity.*, 2017.

IEA, 'World Energy Balances', 2018. https://www.oecd-ilibrary.org/energy/data/iea-world-energy-statistics-and-balances/world-energy-balances_data-00512-en.

IEA, 'World Energy Outlook', *World Energy Outlook*, November 13, 2014.

IEA, *World Energy Outlook 2016*, *World Energy Outlook*, OECD, November 16, 2016.

Keramidas, K., A. Diaz Vazquez, M. Weitzel, T. Vandyck, M. Tamba, Tchung-Ming, J. S., Soria-Ramirez, A., Krause, R. Van Dingenen, S. Chai, Q., Fu, and X. Wen, *Global Energy and Climate Outlook 2019: Electrification for the Low Carbon Transition, Luxembourg: Publications Office of the European Union, 2020, ISBN 978-92-76-15065-7, Doi:10.2760/350805, JRC119619. Https://Ec.Europa.Eu/Jrc/En/Geco*, 2020.

Lee, U., J. Han, A. Elgowainy, and M. Wang, 'Regional Water Consumption for Hydro and Thermal Electricity Generation in the United States', *Applied Energy*, Vol. 210, 2018, pp. 661–672.

Lehner, B., C.R. Liermann, C. Revenga, C. Vörösmarty, B. Fekete, P. Crouzet, P. Döll, et al., 'High-resolution Mapping of the World's Reservoirs and Dams for Sustainable River-flow Management', *Frontiers in Ecology and the Environment*, Vol. 9, No. 9, November 2011, pp. 494–502.

Liao, X., J.W. Hall, and N. Eyre, 'Water Use in China's Thermoelectric Power Sector', *Global Environmental Change*, Vol. 41, 2016, pp. 142–152.

Lohrmann, A., J. Farfan, U. Caldera, C. Lohrmann, and C. Breyer, 'Global Scenarios for Significant Water Use Reduction in Thermal Power Plants Based on Cooling Water Demand Estimation Using Satellite Imagery', *Nature Energy*, Vol. 4, No. 12, 2019, pp. 1040–1048.

Macknick, J., R. Newmark, G. Heath, and K.C. Hallett, 'Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies: A Review of Existing Literature', *Environmental Research Letters*, Vol. 7, No. 4, 2012.

Mekonnen, M.M., P.W. Gerbens-Leenes, and A.Y. Hoekstra, 'The Consumptive Water Footprint of Electricity and Heat: A Global Assessment', *Environmental Science: Water Research & Technology*, Vol. 1, No. 3, 2015, pp. 285–297.

Mekonnen, M.M., and A.Y. Hoekstra, 'The Blue Water Footprint of Electricity from Hydropower', *Hydrol. Earth Syst. Sci.*, Vol. 16, No. 1, 2012, pp. 179–187.

Meldrum, J., S. Nettles-Anderson, G. Heath, and J. Macknick, 'Life Cycle Water Use for Electricity Generation: A Review and Harmonization of Literature Estimates', *Environmental Research Letters*, Vol. 8, No. 1, 2013, p. 15031.

Paladin Energy LTD, 'Sustainability Report', *ACN061681098*, 2016.

Pappis, I., M. Howells, V. Sridharan, W. Usher, A. Shivakumar, F. Gardumi, and E. Ramos, *Energy Projections for African Countries*, 2019.

Pekel, J.F., A. Cottam, N. Gorelick, and A.S. Belward, 'High-Resolution Mapping of Global Surface Water and Its Long-Term Changes', *Nature*, Vol. 540, No. 7633, 2016, pp. 418–422.

Pekel, J.F., A. Cottam, N. Gorelick, and A.S. Belward, 'High-Resolution Mapping of Global Surface Water and Its Long-Term Changes', *Nature*, Vol. 540, No. 7633, 2016, pp. 418–422.

Reuters, 'Zimbabwe's Main Hydro Power Dam Running out of Water after Drought.', 2016. https://www.reuters.com/article/us-zimbabwe-drought-powerstation/zimbabwes-main-hydro-power-dam-running-out-of-water-after-drought-idUSKCN0VS1GM.

Rodriguez, D., A. Delgado, P. DeLaquil, and A. Sohns, 'Thirsty Energy', *Water Papers;. World Bank, Washington, DC. © World Bank. Https://Openknowledge.Worldbank.Org/Handle/10986/16536 License: CC BY 3.0 IGO*, 2013.

Rystad Energy., 'UCUBE', 2018. https://www.rystadenergy.com/products/EnP-Solutions/ucube/.

S&P Global Platts, 'World Electric Power Plants Database', 2016. https://www.platts.com/products/world-electric-power-plants-database.

Scherer, L., and S. Pfister, 'Global Water Footprint Assessment of Hydropower', *Renewable Energy*, Vol. 99, 2016, pp. 711–720.

Schyns, J.F., M.J. Booij, and A.Y. Hoekstra, 'The Water Footprint of Wood for Lumber, Pulp, Paper, Fuel and Firewood', *Advances in Water Resources*, Vol. 107, 2017, pp. 490–501.

Spang, E.S., W.R. Moomaw, K.S. Gallagher, P.H. Kirshen, and D.H. Marks, 'The Water Consumption of Energy

Production: An International Comparison', *Environmental Research Letters*, Vol. 9, No. 10, October 1, 2014, p. 105002.

Srinivasan, S., N. Kholod, V. Chaturvedi, P.P. Ghosh, R. Mathur, L. Clarke, M. Evans, et al., 'Water for Electricity in India: A Multi-Model Study of Future Challenges and Linkages to Climate Change Mitigation', *Applied Energy*, Vol. 210, January 2018, pp. 673–684.

Tinto, R., *Rossing Uranium. Report to Stakeholders.*, 2017.

UN, 'UN Data.', 2016. http://data.un.org/.

UN Water, 'Water for Life Decade.', 2014. https://www.un.org/waterforlifedecade/africa.shtml.

Vassolo, S., and P. Döll, 'Global-Scale Gridded Estimates of Thermoelectric Power and Manufacturing Water Use', *Water Resources Research*, Vol. 41, No. 4, April 1, 2005.

WNA, 'Uranium Country Profiles.', 2019. https://www.world-nuclear.org/information-library/country-profiles.aspx.

World Electric Power Plants Database (WEPP), S&P Global PLATTS, 2018.

WRI, 'Global Power Plants Database.', 2018. https://www.wri.org/publication/global-power-plant-database.

Wu, M., and Y. Chiu, 'Consumptive Water Use in the Production of Ethanol and Petroleum Gasoline-2011 Update', *Center for Transportation Research*, 2011.

Zhao, D., and J. Liu, 'A New Approach to Assessing the Water Footprint of Hydroelectric Power Based on Allocation of Water Footprints among Reservoir Ecosystem Services', *Physics and Chemistry of the Earth, Parts A/B/C*, Vol. 79–82, 2015, pp. 40–46.

List of figures

List of tables

Annexes

Annex 1. Water factors

Further details on the data and methodology can be found in (Gonzalez Sanchez et al., 2020)

Table 3 - Water consumption and withdrawal factors for primary fuel production

		Consumption (m^3/MWhf) [1]			Withdrawal (m^3/MWhf) [1]			
Fuel	**Processes**	**Median**	**Min**	**Max**	**Median**	**Min**	**Max**	**Source** [2]
Coal	**Extraction and processing** [3]	0.0523	0.0154	0.1916	0.0529	0.0154	0.1916	[1]
Crude oil	**Extraction (first and secondary recovery)** [4]	0.2011	0	0.5271	0.2011	0	0.5271	[2], [5]
	Refining	0.1710	0.0988	0.1828	0.1710	0.0988	0.1828	[2], [5]
Natural gas	**Extraction and processing** [5]	0.0019	0	0.0386	0.0019	0	0.0405	[1]
Uranium [6]	**Surface mining and milling**	0.0059	0.0005	0.0083	0.0059	0.0005	0.0083	[1], [3], [4]
	Underground mining and milling	0.0028	0.0002	0.0184	0.0028	0.0002	0.0184	[1], [3],[4]

(1) Water factors for coal, natural gas and uranium extraction provided by (Meldrum et al., 2013) are expressed as m^3/MWhe (electric) and are converted to m^3/MWhf (fuel) by removing the corresponding harmonization parameters used by the authors.
(2) Sources: (Meldrum et al., 2013) [1]; (Wu and Chiu, 2011) [2]; (Tinto, 2017) [3]; (Paladin Energy LTD, 2016) [4], (Gleick, 1994) [5].
(3) Calculated as the average of the water factors for surface and underground mining due to lack of information regarding the mining method used in the coal production data sources.
(4) Calculated as the weighted average (based on US production) of first and secondary recovery due to lack of information on the oil extraction methods used in each African country.
(5) Includes conventional natural gas extraction and processing
(6) For Namibia, the water consumption in the two main uranium mines is provided by the yearly mining reports (Tinto, 2017; Paladin Energy LTD, 2016) while for the third uranium mine in the country, an average of the water intensity factors of the other two is applied. The water factors in the table are applied in Niger and South Africa and are obtained from an average of the water consumption from the Namibian mines in combination with data from (Meldrum et al., 2013).

Source: (Gonzalez Sanchez et al., 2020)

Table 4 - Water consumption factors for fuelwood production

	Climate zone	Water consumption (m^3 water/m^3 roundwood) [1]	Blue water consumption (m^3 water/m^3 roundwood) [2]
North Africa	**Subtropics, summer rainfall**	65	2
South Africa	**Subtropics, winter rainfall**	57	2
Rest of Africa	**Tropical**	93	4

Source: (Schyns, Booij, and Hoekstra, 2017)
(1) Estimated as water lost by evaporation and water retained as moisture content in the harvested wood.

(2) Blue water represents the fraction of water consumption that originates from capillary rise.

Source: (Gonzalez Sanchez et al., 2020)

Table 5 - Water consumption and withdrawal factors for power plant operation based on fuel type, cooling system and technology

			Consumption (m^3/MWh)			Withdrawal (m^3/MWh)			
Fuel	**Cooling system**	**Technology type**	**Median**	**Min**	**Max**	**Median**	**Min**	**Max**	**Source[1]**
Coal	**CT**	**SUB**	2.008	0.758	4.924	2.500	1.742	4.545	[1]
	Dry	**SUB**	0.417	0.250	0.591	0.367	0.252	0.517	[3]
	Dry	**SUP**	0.322	0.211	0.456	0.322	0.211	0.456	[3]
Natural gas/ Oil/Waste heat [2]	**OT**	**SUB/SUP [3]**	1.098	0.720	1.553	136.364	132.576	140.152	[1]
	OT	**CC**	0.379	0.076	0.871	34.091	27.273	79.545	[1]
	CT	**SUB**	2.765	2.121	4.167	4.545	4.545	4.545	[1]
	CT	**CC**	0.795	0.178	1.136	0.947	0.568	2.879	[1]
	Dry	**CC**	0.015	0.015	0.455	0.015	0.000	0.015	[1]
	Dry [4]	**SUB**	0.417	0.250	0.591	0.367	0.252	0.517	[3]
	N/A	**GT/IC [5]**	0.189	0.189	1.288	1.629	1.629	1.629	[1]
Nuclear	**OT**	**SUB**	1.515	0.379	1.515	178.030	87.121	227.273	[1]
Geothermal	**CT**	**SUB [6]**	0.042	0.019	1.364	0.068	0.042	0.095	[1]
	Dry	**SUB [6,7]**	0.000	0.000	0.000	0.000	0.000	0.000	[2]
	Dry	**ORC [8]**	1.098	1.023	2.386	1.098	1.023	2.386	[1]
Biomass	**CT**	**SUB**	2.095	1.818	3.655	3.326	1.894	5.530	[2]
	OT	**SUB**	1.136	1.136	1.136	132.576	75.758	189.394	[2]
	N/A	**GT/IC [5]**	0.189	0.189	1.288	1.629	1.629	1.629	[1]
Solar	**CT**	**Fresnel**	3.788	3.788	3.788	3.788	3.788	3.788	[1]
	CT	**Trough**	3.371	2.121	7.197	3.636	3.295	4.167	[1]
	Dry	**Power tower**	0.098	0.098	0.098	0.098	0.098	0.098	[1]
	Dry	**Trough**	0.295	0.121	0.530	0.295	0.125	0.299	[1]
	N/A	**PV**	0.023	0.004	0.098	0.023	0.004	0.098	[1]
Wind	**N/A**	**Wind turbine**	0.001	0.000	0.008	0.004	0.004	0.004	[1]

OT: Once-through, CT: cooling tower, SUB: steam turbine subcritical, SUP: steam turbine supercritical, GT: gas turbine, IC: internal combustion engine, CC: combined cycle, ORC: Organic Rankine Cycle.

(1) (Sources of water factors: (Meldrum et al., 2013) [1]; (Macknick et al., 2012) [2]; (Zhang et al., 2016) [3];

(2) The water factors of natural gas power plants are applied to oil and waste heat power plants due to data limitations.

(3) (Meldrum et al., 2013) does not differentiate between subcritical and supercritical steam turbines, therefore the same value is applied in both cases.

(4) The water factors of "Coal-Dry Cooling- SUBCR" are applied due to the lack of specific values for natural gas.

(5) The water factors of GT provided by (Meldrum et al., 2013) are applied due to data limitations on the water use for IC.

(6) (S&P Global Platts, 2016) does not provide the type of technology used, therefore the water factors of flash technology are used since it is the most commonly used technology in geothermal plants.

(7) Due to data limitations it is assumed that withdrawal and consumption are equal.

(8) Rankine cycle is the commercial binary cycle used in the United States, therefore and due to data limitations, the water factors of binary power plants in (Meldrum et al., 2013) does not differentiate between subcritical and supercritical steam turbines, therefore the same value is applied in both are applied..

Source: (Gonzalez Sanchez et al., 2020)

Table 6 - Water consumption and withdrawal factors for power plant construction

		Consumption (m^3/MWh)			Withdrawal (m^3/MWh)		
Fuel	**Technology type**	**Median**	**Min**	**Max**	**Median**	**Min**	**Max**
Coal	**ST**	0.0039	0.0012	0.0986	0.0039	0.0012	0.0473
Oil [1]	**ST**	0.0058	0.0017	0.0058	0.0058	0.0017	0.0058
	GT	0.0077	0.0023	0.0077	0.0077	0.0023	0.0077
	IC	0.0058	0.0018	0.0058	0.0058	0.0018	0.0058
	CC	0.0056	0.0017	0.0056	0.0056	0.0017	0.0056
Natural gas	**ST**	0.0059	0.0018	0.0059	0.0059	0.0018	0.0059
	GT	0.0063	0.0019	0.0063	0.0063	0.0019	0.0063
	IC	0.0052	0.0016	0.0052	0.0052	0.0016	0.0052
	CC	0.0043	0.0013	0.0043	0.0043	0.0013	0.0043
Nuclear	**ST**	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007
Geothermal	**ST**	0.0076	0.0076	0.0076	0.0114	0.0011	0.0379
Solar	**PV** [2]	0.2896	0.0367	0.7488	0.3386	0.0036	6.0112
	CSP	0.6057	0.3028	0.6435	0.6057	0.3748	0.6435
Wind		0.0038	0.0004	0.0341	0.0984	0.0492	0.3142
Hydropower		0.0011	0.0011	0.0011	0.0011	0.0011	0.0011
Waste heat/gas [a]	**ST**	0.0059	0.0018	0.0059	0.0018	0.0018	0.0059
	IC	0.0052	0.0016	0.0052	0.0016	0.0016	0.0052
Biomass [3]	**ST**	0.0039	0.0012	0.0986	0.0039	0.0012	0.0473
	GT	0.0039	0.0012	0.0986	0.0039	0.0012	0.0473
	IC	0.0039	0.0012	0.0986	0.0039	0.0012	0.0473

ST: steam turbine, GT: gas turbine, IC: internal combustion engine, CC: combined cycle, CSP: concentrated solar power.

Source: water factors obtained from (Meldrum et al., 2013) in combination with thermal efficiencies from EIA (2017).

([1]) The water factors for natural gas are applied to oil due to lack of specific data.

([2]) A weighted average of crystalline-silicone and thin-film are applied (94% crystalline-silicone and 6% others) based on (Jäger-Waldau, 2018)

([3]) Water factors are assumed the same as for coal.

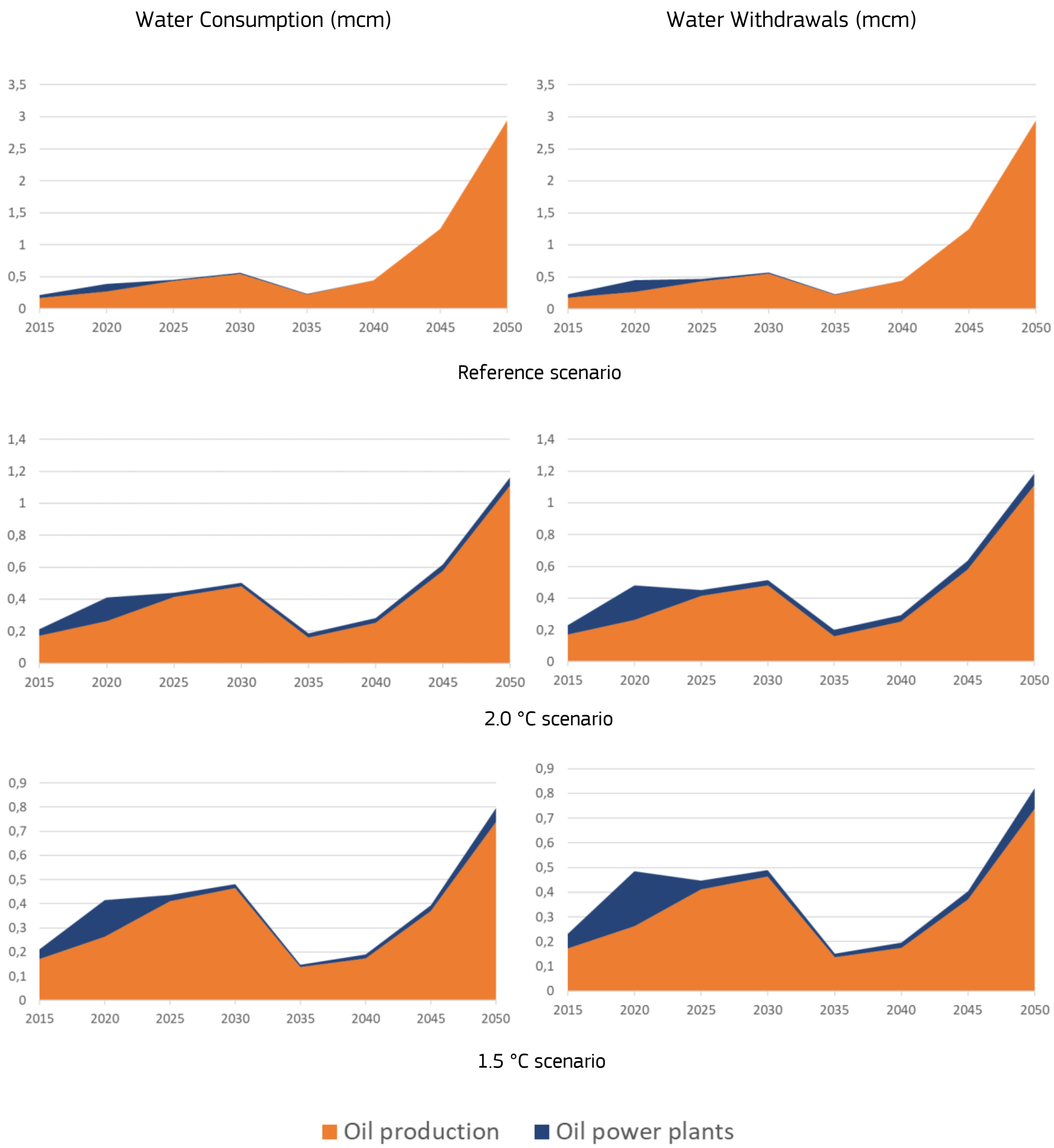
Source: (Gonzalez Sanchez et al., 2020)

Annex 2. Data for future water use per power pool by fuel type and scenario.

Figure 1. WAPP water consumption and withdrawals by fuel type for the three scenarios

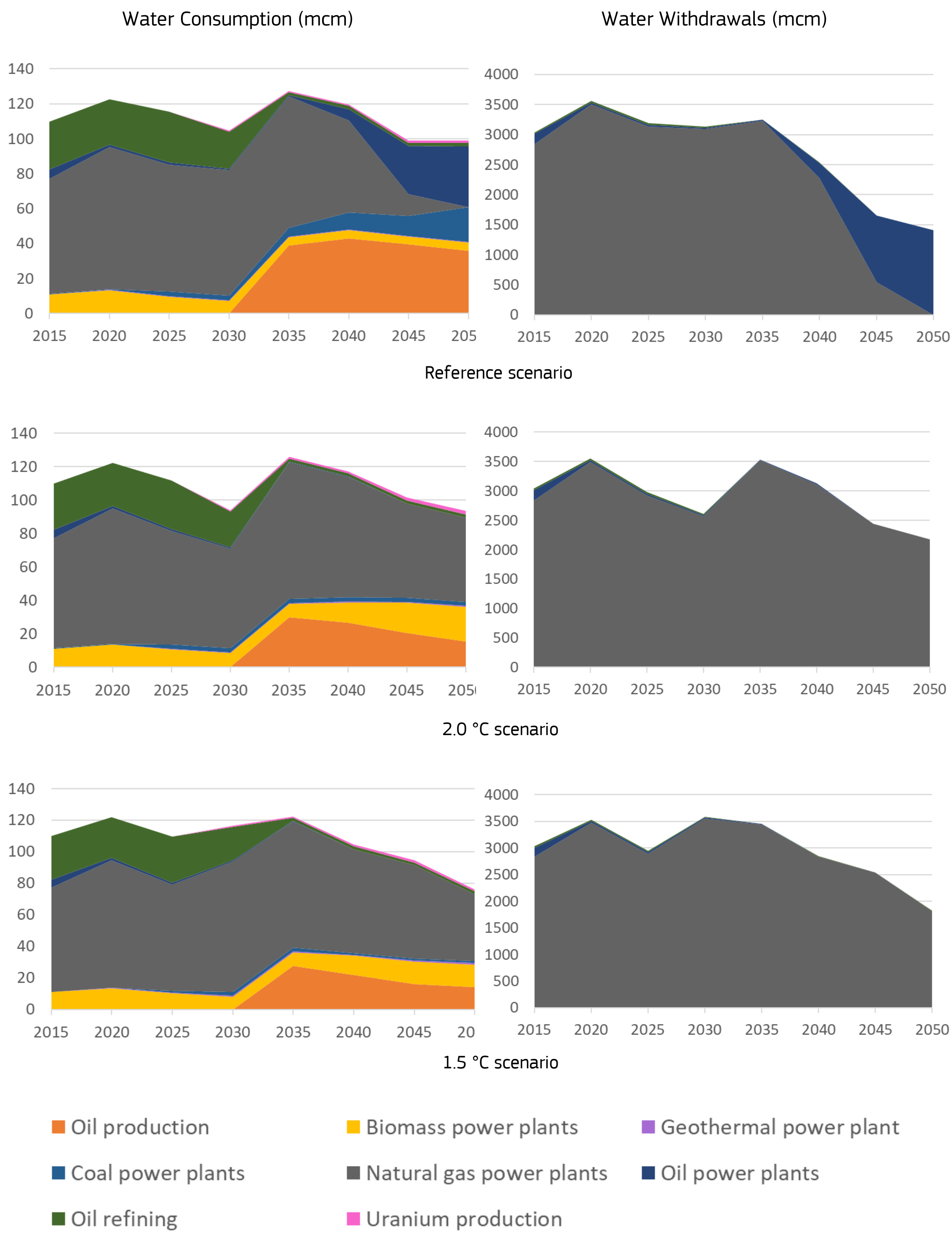
Source: JRC, 2020

Figure 2. CAPP water consumption and withdrawals by fuel type for the three scenarios



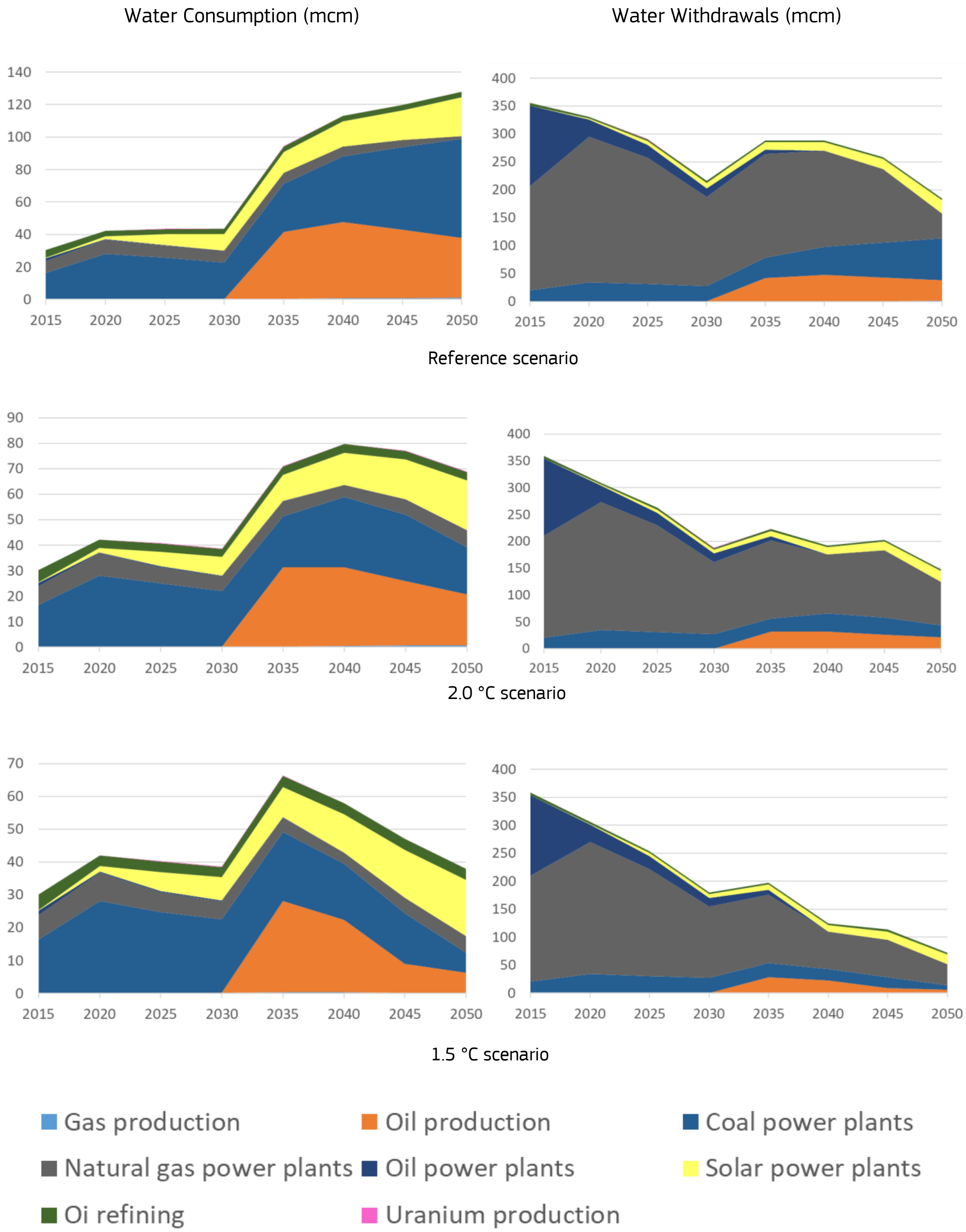
Source: JRC, 2020

Figure 3. EAPP water consumption and withdrawals by fuel type for the three scenarios



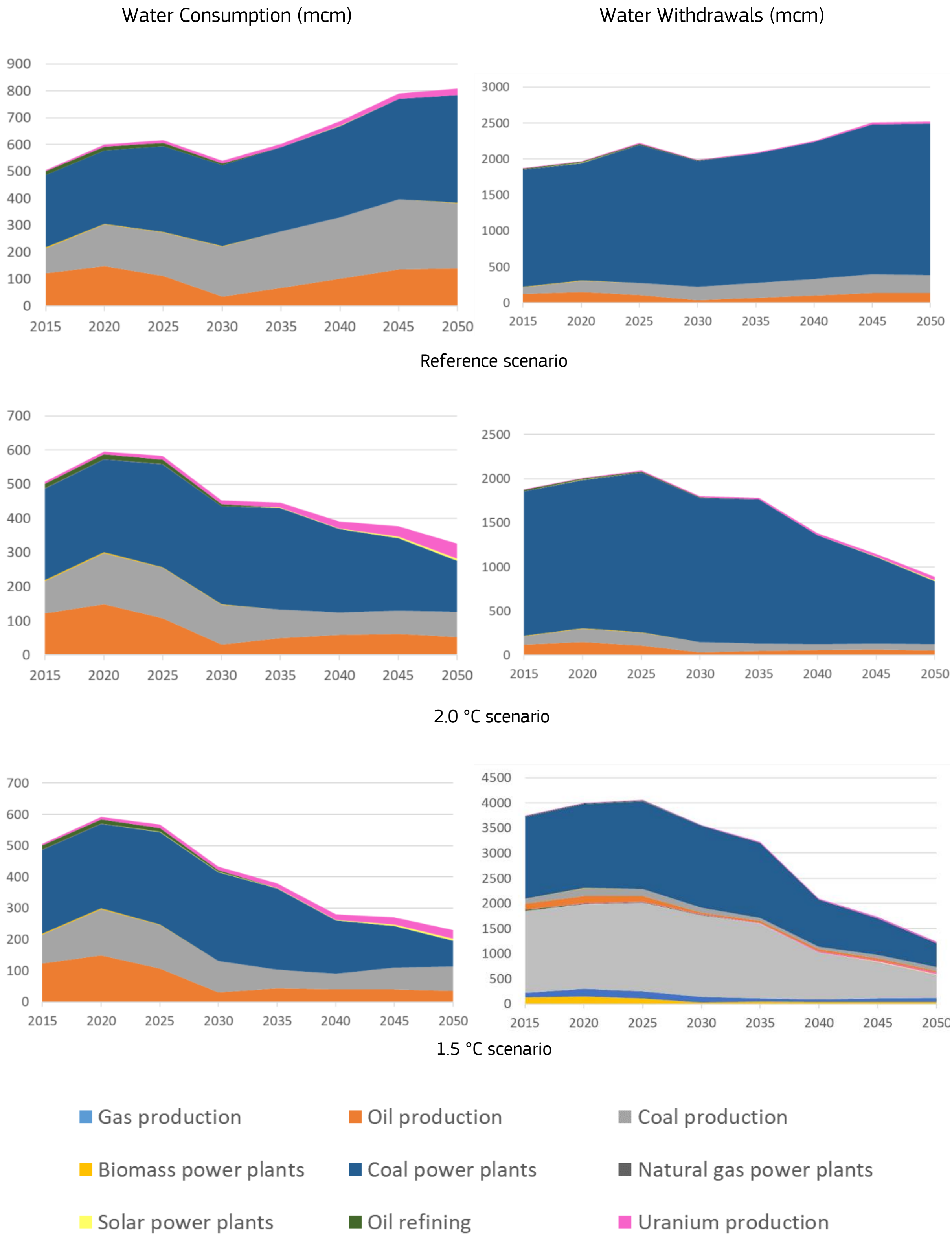
Source: JRC, 2020

Figure 4. NAPP water consumption and withdrawals by fuel type for the three scenarios



Source: JRC, 2020

Figure 5. SAPP water consumption and withdrawals by fuel type for the three scenarios



Source: JRC, 2020

KJ-NA-30278-EN-N

The European Commission's science and knowledge service

Joint Research Centre

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub

EU Science Hub - Joint Research Centre

EU Science, Research and Innovation

EU Science Hub

Publications Office
of the European Union

doi:10.2760/808928

ISBN 978-92-76-19977-9