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Review

Applying the Water-Energy Nexus for Water Supply—A Diagnostic Review on Energy Use for Water Provision in Africa

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Abstract: This work explores the application of the Water-Energy Nexus concept for water supply in the African context, where its operationalization is quite limited compared to developed regions. Furthermore, water supply and demand drivers and their influence on energy use are examined. This study found that there is limited literature available on the operationalization of the concept, and energy use is not considered a key performance indicator by water regulators and utilities. Regionally, most of the studies were carried out in the northern and southern Africa, where energy demand for water supply through desalination is high. An analysis of water supply and demand drivers show diminishing quantities of available freshwater, and increased anthropogenic pollutant loads in some areas are projected. Consequently, utilities will likely consider alternative energy-intensive water supply options. Increased population growth with the highest global urban growth rate is projected, with about 60% of the total population in Africa as urban dwellers by 2050. This implies huge growth in water demand that calls for investment in technology, infrastructure, and improved understanding of energy use and optimization, as the largest controllable input within utilities boundaries. However, it requires a data-driven understanding of the operational drivers for water supply and incorporation of energy assessment metrics to inform water-energy policies and to exploit the nexus opportunities.

Keywords: demand-side/supply-side drivers; energy use; key performance indicators; water-energy-nexus; water supply; water utilities

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1. Introduction

Water and energy resources are intricately connected in their production and consumption [1–3]. On a global scale, water and energy are placed as Goals Six (6) and Seven (7) in the 2015 launched United Nations Sustainable Development Goals (SDGs), with targets 6.1 and 7.1 emphasizing increased universal access to water and energy, respectively, while 6.4 and 7.3 focus on improving water efficiency and energy efficiency [4]. Consequently, global efforts to address the role of water and energy resources in a coordinated manner through research and policy for sustainable development have increased steadily with the application of the Water-Energy Nexus framework [5,6]. This close intrinsic interconnection between production, consumption, and management of water and energy resources commonly referred to as the Water-Energy Nexus was discussed in the Bonn 2011 Water-Energy-Food Nexus conference [7], as a framework to address the complex global water and energy needs, interactions, synergies, conflicts, and trade-offs, which were traditionally considered independently in their utilization, governance, and policy formulation [8,9]. Since then, the application of the Water-Energy Nexus concept in the drinking water sector has received increased attention from researchers, water utilities, development partners, and regulators in the last decade. This is to enhance the understanding of the role of energy in water supply and energy saving potentials through technical assessments [10,11] and synergistic water and energy policy formulation [5,12].

Energy is required in the water supply cycle for abstraction, treatment, and distribution of drinking water, as well as collection and treatment of wastewater in the urban water cycle [3,8,13]. On the other hand, water is required for energy production, directly for hydroelectric power production or indirectly for cooling of thermal power plants [1,14,15]. Energy consumption for municipal water supply is a major driver of operational performance accounting up to 44% or more of the total operational costs, only coming second after labor costs [16,17]. However, energy costs are the largest controllable expenditure within the internal boundaries of water utilities; with up to 40% potential savings on investment with short payback periods, through optimization of pumps and motors, which are the main energy consumers, accounting for up to 90% of the energy use in water supply [11,18].

Several comprehensive reviews on energy use for water supply in different regions and cities have been conducted since the beginning of the last decade, for instance, For instance, on the energy consumption and associated greenhouse gases in water distribution systems [2], the energy consumption for water use cycles in selected countries [3], the assessment of the Water-Energy Nexus in the Middle-east and North Africa (MENA) region [13], the energy intensity for municipal and agricultural water supply processes [19], and the opportunities for improvement of energy efficiency for water supply [20–22]. In addition, several studies have undertaken assessments to quantify energy use for different water source options such as groundwater [22], surface water [23], and sea water desalination [24,25]. Others have presented future scenarios of energy use for various water supply options [12,26] and focus on performance assessment and benchmarking efforts for energy use in water supply in several countries have also been emphasized, for instance, Chile [17,27,28], the Nordic region [29], Australia [30,31], China [32,33], and Canada [34–36].

However, to the best of the knowledge and understanding of the authors, there is a paucity of research and available case studies on the application of the Water-Energy Nexus concept and its influencing factors for water supply in utilities in Africa. Such assessments have not received much attention in the performance assessment of water utilities by the utilities and water services regulators, or are publicly unavailable, coupled with the growing water demand and increased energy costs. Yet, there is growing evidence that improvement in energy efficiency has potential to yield substantial returns for water utilities within a short payback period [11,37–39]. This is especially crucial for water utilities with very weak operational efficiencies and limited ability to recover their full operational costs or generate revenue, which results in a delayed expansion of water supply and consistent provision of unsatisfactory services.

Literature on energy use and energy efficiency optimization for drinking water supply and the drivers of energy demand for water supply is also scant in Africa, with very few studies available to provide a comprehensive assessment in the region. In addition, an assessment carried out by the authors on energy use for drinking water supply in selected drinking water utilities in Kenya disclosed that, even though water utilities collect large amounts of data on their operations, there is a huge challenge in obtaining that data through open calls, especially where such data are not required as a performance indicator by water services regulators (Macharia et al., unpublished). Furthermore, where such energy data are present, the energy metering and billing in most cases is not disaggregated to reflect actual energy use for each treatment process in the water supply cycle. This makes it difficult to undertake a comprehensive qualitative analysis of energy use for water treatment and invariably identify any potential energy-saving opportunities in the water distribution system.

Research Scope

Efficient operational performance of water utilities is key in the delivery of water services, revenue generation, and expansion of coverage. However, insufficient real-time data on energy use and lack of fast, robust, and flexible feedback mechanisms as decision support tools on energy efficiency limits optimization of energy-intensive devices and processes within the water distribution network. Consequently, assessment of energy use is essential to understand the close linkage between energy and water use, cost and savings, and associated management implications of energy efficiency to support efforts towards universal access to water services. In addition, water utilities in Africa are faced with increased water demand from population growth and rapid urbanization, but also deteriorating water quality from increased pollution, which influences the energy input for water supply. Hence, it is crucial to explore the interaction of water supply and demand drivers and the extent to which they influence energy use now and in the future for improving operational efficiency of water utilities.

This paper therefore makes a diagnostic review on accessible literature to explore the level of application of the Water-Energy Nexus concept to address dynamics of energy use and efficiency for water supply in Africa. In addition, the operational performance of water utilities in Africa is explored, and available energy use performance indicators applicable in the context of limited availability of consistent data highlighted. Lastly, provision of water services is influenced by several internal and external supply and demand drivers, which in turn affect the energy demand for water supply. This work therefore synthesizes a selection of water supply-side and demand-side drivers and examines how they influence energy demand for water supply processes in the African context. This works makes an important contribution in highlighting the role of energy as a major input of operational efficiency of water utilities and the benefits of operationalizing the Water-Energy Nexus concept to improve performance of water utilities and enhance access to water services in Africa.

This paper is organized as follows: the first section presents a brief overview of available literature on the application of the Water-Energy Nexus concept and its operationalization in the African context; next, performance of water utilities in Africa highlighting the energy use for water supply processes and available energy use indicators is provided; furthermore, a synopsis of water supply and demand drivers and how they influence energy demand for water supply in Africa is presented; in conclusion, implications of the assessments of energy use for water utilities in Africa is explored.

2. Methodological Approach

A literature search to identify the existing literature on the water-energy-nexus as it applies to water supply in different regions was conducted in peer reviewed journal articles and publicly available reports and books, mostly retrieved from the Science Citation indexes of the Web of Science Core Collection database, Google Scholar and Elsevier. The definition of the 'Water-Energy Nexus' was adapted from [7], which defines the Water-Energy Nexus as the inter-linkage and dependence of production and use of water and energy resources on each other and the associated trade-offs and synergies of considering this connectedness. In this context, the focus was on the water sector's dependence on energy. The literature search on the 'Water-Energy Nexus' was narrowed to the context of water supply, with literature focusing on the energy demand in the drinking water treatment and supply processes commonly referred to as 'energy embeddedness' [21], for different raw water options and optimization processes.

Particular emphasis on assessment and quantification of energy use for drinking water supply in Africa from peer-reviewed journals, country and regional level performance assessment reports by the utilities, the water service provision regulators and the International Benchmarking Network for Water and Sanitation Utilities (IBNET). Furthermore, available literature on drivers of water supply and water demand in selected countries in Africa was sought and synthesized.

3. Results

3.1. Literature on Energy Use for Water Supply in Africa

Although compilations of best practices for energy use in municipal supply are available at least for Kenya, South Africa, and Zambia; energy use for the drinking water supply itself is not considered among the key performance indicators for water utilities. Instead, available energy data for most utilities solely reflect the operational costs associated to energy use. Literature on the application of the Water-Energy Nexus concept for water supply as well as assessment of energy use in the water sector in most of Africa is quite limited. A summary of available literature retrieved and the area of study is presented in Table 1. There was increased attention in the last decade with available studies mostly carried out in South Africa and the Northern Africa regions (50% of the literature retrieved), focusing on life cycle assessments of water supply [25,40,41], while the authors in reference [13] provided an analysis of the application of the Water-Energy Nexus in water supply in the Middle East and North Africa (MENA) region. Few studies explored the use of renewable energy sources for water supply in rural areas in Ethiopia [42], Nigeria [43], and Tanzania [44], and the adoption of solar-powered borehole pumps to replace diesel-powered pumps for water supply in refugee settings [45–47] Furthermore, reference [48] compared the energy demand for different water supply options in the informal water supply chain in Kisumu, Kenya. At the level of water utilities, publicly available efforts to assess energy use for water supply were available for Zambia [49]. In addition, energy use per unit volume sold (kWh/m^3) as a key performance indicator has recently been made available on IBNET, but only data for utilities in Nigeria were available during the study (available online at www.ib-net.org in January 2020).

Table 1. Summary of available literature on energy assessment for water supply in Africa.

Reference	Description	Country
[50]	Compared the environmental burdens of water supply through conventional water treatment and through membrane filtration.	South Africa
[51]	Outlined benefits of concentrating solar power for large-scale desalination over fossil fuels in the long term to enhance water security in the Middle-east and North Africa (MENA) region.	North Africa
[40]	Provided a life cycle assessment of urban water provision and a comparison of the environmental consequences of treating virgin portable versus recycled water.	South Africa
[52]	Assessed the sustainability of selected urban water treatment plants in Alexandria.	Egypt
[41]	Provided a review of life-cycle assessments of the South African water sector, outlining the potential application of life-cycle assessments to improve efficiency of the water sector in the future	South Africa
[43]	Explored the feasibility of using different alternative renewable energy options for clean water pumping.	Nigeria
[13]	Assessed application of the water energy nexus in the MENA region, bearing in mind desalination as the treatment process.	North Africa
[53]	Conducted a life cycle assessment of portable water production and associated impact to the environment.	Algeria
[42]	Explored the use of solar powered pumps for rural water supply.	Ethiopia
[48]	Compared the energy use for water supply in the informal settlements from different water sources.	Kenya
[54]	Conducted a systems analysis to examine the energy requirements of the water supply for different alternatives of urban water supply.	South Africa
[55]	Assessed the impact of variable energy prices on the financial stability of drinking water utilities in Accra and Ashanti regions.	Ghana
[47]	Assessed the potential of high-capacity solar-powered boreholes compared to diesel-powered pumps in an emergency context.	Kenya, Somalia

Table 1. *Cont.*

Reference	Description	Country
[56]	Provided the rationale for promoting energy efficiency for water utilities.	Tanzania
[46]	Outlined the benefits of switching from fuel-powered to solar-powered pumps in refugee camps.	East and Horn of Africa
[45]	Presented a cost-benefit analysis of switching from diesel-powered to a hybrid diesel-solar powered generator system for water pumping in refugee camps.	Kenya
[57]	Provided a design for solar-power operated water pumping system for water provision in Niger Delta.	Nigeria
[24]	Provided an energy and operational cost optimization model for seawater desalination.	South Africa
[44]	Demonstrated the potential of small-scale photo-voltaic powered water treatment system for brackish-water to enhance water supply in remote areas.	Tanzania
[25]	A life cycle assessment of desalination and mine-water reclamation as alternatives for portable water supply.	South Africa
[58]	Assessed the energy and carbon footprints of using centralized, decentralized or desalination options in treating brackish groundwater, Cape Town.	South Africa

3.2. Operational Performance of Water Utilities in Africa

Water supply coverage in Africa is still lagging, with only about 27% of the total population having access to safely managed water services, and a further 34% with access to basic water supply [59]. In a bid to expand water coverage, improved quality of service delivery and enhanced operational efficiency, performance benchmarking, and ranking of water utilities in Africa is routinely monitored by water services regulators through key performance indicators. In this context, several studies on the performance of water utilities in Africa exist. For instance, the performance assessment and benchmarking of the Uganda water supply [60], while reference [61] compared the urban water efficiency and effectiveness for different regions in Africa and reference [62] assessed the performance assessment of urban water supplies in Mozambique. Furthermore, reference [63] analyzed the performance of state water agencies in Nigeria, while references [64,65] provided an analysis of the performance of water utilities in Africa aimed to inform decision on water sector development and investment. The overall performance of water utilities in Africa based on financial, operational, and customer satisfaction indices was reported as weak [64,65]. Most water utilities report consistently unsatisfactory customer service delivery, often struggling to meet their operational costs, with over-reliance on government subsidies, as most utilities struggle to exploit their self-financing capacity. Consequently, the inability to meet full operational cost coverage hinders or delays the expansion of service coverage and delays the maintenance of aging infrastructure, especially pumps and motors, and hence, their operational efficiency. In addition, water losses remain the greatest challenge to water services delivery, highest among the largest utilities, serving over 1 million people across the region, as they often have the oldest infrastructure [64,66]. In Kenya, the Water Services Regulatory Board Kenya (WASREB) [67] estimates an average of 58% non-revenue losses among the largest utilities in Kenya, and an average of 42% at the national level, translating to an annual water loss of about 90 million M^3, assuming an acceptable 20% water loss. This, as the regulator reports, is large enough to meet the daily water demand for Nairobi City for about four months. Furthermore, in response to the increase in population growth, i.e., urbanization, resulting in an increased demand for water services, water utilities are increasingly constrained by huge operational costs, rising energy costs and low self-financing of the sector to allow expansion of water services.

To benchmark and monitor the performance of water utilities aimed at improving the quality of water service delivery and expansion of water coverage, a set of key performance indicators is used, as presented in Table 2. The choice of performance assessment indicators depends on the local operating environment and the priority areas of performance for each country. A comprehensive list of various key performance indicators is provided in [68].

Table 2. Summary of clusters of Key Performance Indicators (KPIs) for assessing the water service performance in selected countries; number of KPIs within cluster in brackets.

Country	No of KPIs	Clusters of Key Performance Indicators (KPIs)	Literature Source
Kenya	9	Quality of service (3) Economic efficiency (3) Operational sustainability (3)	[67]
Lesotho	18	Water quality (2) Customer care (5) Network disruptions (4) Continuity of supply (1) Metering (4) Water supply (2)	[69]
Malawi	11	Access to water services (2) Sustainability of companies (4) Customer Care Service (3) Water quality (2)	[70]
Nigeria	16	Level of service (6) Technical indicators (3) Financial indicators (3)	[63]
Tanzania	11	Protection of users' interest (3) Sustainability of the operator (6) Environmental sustainability (2)	[71]
Uganda	10	Technical indicators (4) Financial indicators (3) Service indicators (4)	[72]
Zambia	15	Operational indicators (5) Staff efficiency (2) Service level (3) Financial indicators (3) Corporate governance and management (2)	[49]

3.2.1. Energy Demand as an Operational Performance Indicator in Africa

As observed from the cluster of key performance indicators presented, energy use for water supply is not considered among the key performance indicators during routine monitoring of water utilities. Among all the publicly available reports on utilities performance that were reviewed, energy use was only reported in Zambia [49], as specific energy in kWh/m^3 for water production in the cluster of operational indicators. However, assessment of energy demand for water supply provides opportunities for water utilities to understand the drivers of their operational performance and make necessary interventions to reduce the cost of energy or increase its efficiency [73]. Furthermore, utilities need to develop an energy use management plan through a comprehensive assessment of energy-consuming devices, i.e., the embedded energy which provides insights into how much energy is consumed and dissipated within the system [27,74–76]. Bearing in mind the huge non-revenue water losses of up to 60% as observed in some utilities (www.ib-net.org), linking energy use and associated costs to water losses through the treatment and distribution process can inform water utilities on how much energy is lost with water losses and the associated revenue loss at each water supply process. However, the main challenge of such estimations is the disaggregated data on energy use and energy cost reflected in the electricity bills in most utilities, as observed in an assessment by the authors of selected water utilities in Kenya (Macharia et al., unpublished).

Since monitoring, benchmarking, and ranking of water utilities in Africa at a country and regional level exists, regulators and utilities should seek to incorporate appropriate energy use metrics in their routine performance assessments to assess, monitor, optimize, and benchmark their energy use. A summary of the available energy use indicators, which can be incorporated in the routine performance assessment and benchmarking, are outlined in Table 3. The choice of key performance indicators is guided by the ambition to boost revenue generation, optimize and reduce energy costs, reduce water and energy losses, expand water services delivery, and reduce greenhouse gases emissions [73]. However, the unique operational factors that influence energy demand for water supply including terrain, size, age, and configuration of the water distribution network should not be overlooked while formulating the objectives for performance assessments. Hence, as outlined in [68], before settling on the appropriate indicators, regulators and utilities are required to set achievable objectives, provide a strategy to achieve the objectives, outline the drivers to achieve the set objectives, and lastly establish an energy performance indicators system. Several indicators exist for the assessment of energy use for water supply including those provided by the International Water Association (IWA) in [68], which, as reference [73] noted, although they provide a good starting point for energy assessment and management, they do not provide for cost-benefit analysis of implementing energy efficiency measures. In addition, some of the proposed indicators, for instance a pump energy indicator that considers the energy use and the working hours of the pump expressed as kWh/m^3/m, has been used for nation-wide water utilities benchmarking in Australia [77]. Others including the indicator for energy in excess per unit of authorized consumption, energy loss due to dissipation in the pumps, energy loss embedded in leaks, and energy loss due to network operations and system layout applied in pressurized systems [75], require knowledge of hydraulic models and only run online [78,79]. This limits their application in water utilities, with limited access to the internet and with frequent power interruptions.

Table 3. Energy use metrics for energy use assessment for water services provision.

Metric	Description	Remarks	Source
Ph5 (kWh/m^3/100 m)	Standardized energy consumption. Assesses the average pumping energy use per unit volume at 100 m of head.	Provides information on minimum energy used.	[68]
E1 (kWh/m^3)	Energy in excess per unit of input volume Represents the potential for energy reduction per unit of total input volume.	Provides information on the impacts of energy management measures. No provision for the assessment of impact of leakage control measures.	[76]
E2 (kWh/m^3)	Energy in excess/unit of revenue water Represents the theoretical potential for energy reduction per unit of billed water.	Allows for assessment of impact of leakage control measures on the energy demand. Requires a hydrological model.	[76]
WSEE	Water Supply energy efficiency Defined by the ratio between the minimum energy required by a pump and the actual energy used.		[74]
PEI kWh/ML/m	Pump energy indicator Normalizes the pump energy consumption against work done (pump operating hours).	Possibility to benchmark pump energy use for several utilities. Does not provide for the measurement of efficiency of individual pump stations.	[77]
I1 and I2 (Structure, and quality) indicators (kWh/m^3)	I1 shows the influence of the difference in elevation between source and consumers on energy demand. I2 shows the difference between actual energy used and the minimum energy required for water supply processes.	Do not require the use of complex hydraulic models. Do not consider frictional energy losses.	[80]
Fi 10 (% cost of electrical energy)	Provides the percentage share of electricity cost as a proportion of total operational cost.	Provides information on cost trends useful for management decisions.	[68]

Table 3. *Cont.*

Metric	Description	Remarks	Source
D1 (€/m^3 sold) D3 (€/m^3 distributed)	Specific energy costs per volume of water sold. Specific energy cost per volume of distributed water.	D1 Provides cost estimates of energy for each billed unit of water. D3 estimates of energy cost (water distributed).	[81]
D2, (€/m^3 sold)	Specific energy cost in peak hours.	D2 provides cost estimates of energy during the peak hours/during high tariffs hours.	[81]
D4, (kWh/m^3 sold)	Specific energy consumption per volume of water sold.	Can be used to make an inventory of energy use for each pumping station/treatment plant.	[82]
WNEE, Water Network Energy Efficiency	Ratio of the minimum required energy and the actual consumed energy.		[83]
UME, Unavoidable Minimum Energy	Minimum energy required at the tap.	Applicable to one or more pumps/pump stations.	[83]
EEI, Energy Efficiency Indicator	Ratio between UME and the actual energy consumed by each device.	Accounts for the possible daily volume left in the reservoir (considered as excess energy).	[83]

3.2.2. Data Required Energy Use for Drinking Water Supply

As the call to examine the benefits of operationalizing the Water-Energy Nexus in the water supply intensifies, water utilities and regulators should harmonize the definition of metrics of energy used to standardize their data collection. Several terms are used interchangeably in most papers including 'energy intensity,' 'embedded energy,' embodied energy,' and 'associated energy.' In most papers, the energy used for the abstraction, treatment, and distribution of water in pressurized water distribution systems is reported as the sum of the direct and indirect embodied energy required to produce a certain unit volume of water [16,23,84]. Direct energy is defined as the onsite energy for the operation, water treatment, and distribution of water in terms of electricity and fuel, while indirect energy comprises the off-site administrative energy and chemical usage [3,22]. The embodied energy demand estimated through life-cycle assessments, input-output analysis or process-based hybrid approaches, vary with the water supply options either groundwater supply systems, surface water systems, or reclaimed water systems as outlined in [3,19]. Direct energy use for supplying ground water is estimated at 20–30% higher than that of surface water per unit of water supplied depending on the well yield, the height over which the water is lifted and the efficiency of the pumping devices [22]. In surface water supply options, the main determinants of direct energy include the pipe characteristics, the treatment technology, the quality of raw water and the distance from the source [3,30].

Estimates of the total direct and indirect energy use for different water treatment processes is provided as the unit of energy required (kWh) to produce one-unit volume (1 m^3) of water, expressed in most papers as kWh/m^3, as summarized in other reviews [3,13,30]. Consequently, to demonstrate the broad span of energy used for the supply of different water types, a summary for selected countries is provided in Table 4. Note that the expression of energy use for water supply varies, with several authors using different metrics. For instance, the energy consumption is expressed as kWh acre/foot [85], in kWh/annum^3 [86], in kWh/KL [41], or Petajoules/year [86].

Table 4. A summary of studies on energy use for drinking water supply processes.

Water Type	Process	Energy Intensity kWh/m^3	City/Country	Reference
Mine water	Reclamation	2.16 **	South Africa	[25]
Sea water	Reverse osmosis	2.5–7.0	Libya	[13]
Sea water	Reverse osmosis	3.69	South Africa	[25]
Sea water	Multistage flash distillation	3–5	Libya	[13]
Surface water	Water supply	0.29	China	[87]
Surface water	Water distribution	0.41	Toronto, Canada	[23]
Surface water	Water distribution	0.31	Turin Italy	[23]
Surface water	Water treatment	0.07–0.21	Chile	[27]
Surface water	Water supply	0.02	Alexandria, Egypt	[52]
Surface water	Water supply	0.02–0.14	Kenya	Macharia et al. (Unpublished)
Groundwater	Water extraction	0.14–0.69	California, USA	[19]
Groundwater	Water extraction	2.87	Florida, USA	[22]
Groundwater	Water extraction	0.32–0.47 *	South Africa	[58]
Groundwater	Water abstraction	1.1–2.4	Kenya	Macharia et al. (Unpublished)

* Converted from MJ/m^3 and ** converted from kWh/kL.

3.3. Drivers of Water Demand and Water Supply on Energy Use and their Relevance for Africa

Analyses of water scarcity, defined as the gap between the freshwater resource available and the demand under prevailing conditions, have revealed that about 54% of countries in Africa, especially in the Northern and Southern regions, are either water scarce or severely water stressed, with 20% of the 2016 population living under water scarcity conditions. It is projected that approximately 37% and 57% of the total population in the continent will live under severe water crisis by 2025 and 2050, respectively, as presented in Figure 1 [88]. This is largely driven by water insecurity largely driven by physical shortage, lack of infrastructural capacity, and economic vulnerabilities, which influences water supply and availability. As the population increases and demand for water services soars among African utilities, an understanding of the interdependence of water and energy and their interaction is crucial in the water supply sector. This will ensure the sustainability of water supply services, reduction of water and energy losses, as well as mitigation of greenhouse gas emissions and guiding water-energy policy formulations and future implications of investment in energy efficient systems [6,89]. Population growth, high rates of urbanization, and effects of climate change have been observed as the major drivers of water demand in Africa, where water utilities should incorporate water supply planning in their future [90,91]. The increase in urban population, especially in urban informal and peri-urban settlements, pose a major challenge in the operations of water utilities due to huge non-revenue water losses arising from illegal connections and increased pressure to the already ageing infrastructure. Several drivers of water supply and demand influence the energy demand for the water treatment processes and their influence on energy use for water supply have been explored.

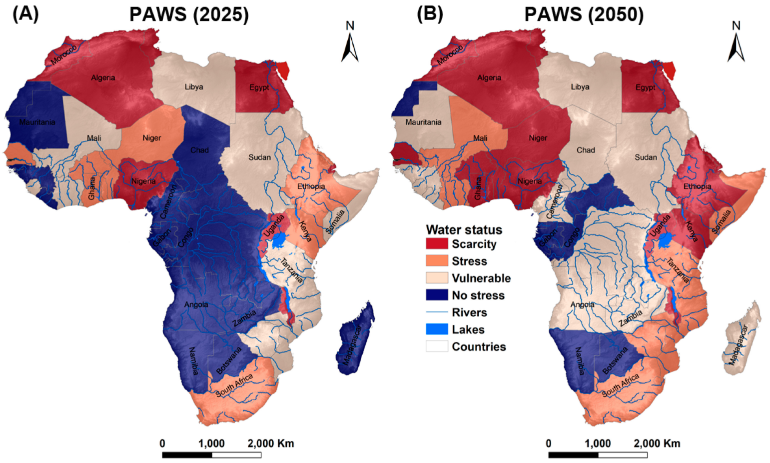

Figure 1. (**A**,**B**) Projected available water status showing total available renewable freshwater per capita in African countries in the year 2025 (**A**) and 2050 (**B**) [88].

3.3.1. Demand-Side Drivers

This chapter explores the influence of selected water demand drivers on water utilities energy demand, crucial for future planning of expansion and sustainability of service coverage, especially in the metropolitan areas of large cities where utilities need new infrastructure for service expansion as the cities expand.

- Population Growth and Accelerated Urbanization

The United Nations Department of Economic and Social Affairs (UNDESA) projects that the total population in Africa will be approximately 2 billion by 2050. Furthermore, about 50% of the population in low-income countries and 59% in lower middle-income countries will be city-dwellers in 2050 compared to only 30% and 41%, respectively, in 2018 [92]. This is a 20% increase in about three decades from the current population estimates. In addition, the rate of urbanization in low-income and lower middle-income countries is expected to be two times that of the global rate (0.6%) between 2030 and 2050, the highest among the world's income categories.

As reported in reference [90], eight out of 10 countries with the highest rates of urbanization in the world are in Africa. Furthermore, reference [91] noted that countries in sub-Saharan Africa that have achieved continued growth in gross domestic product (GDP) have the fastest rate of urbanization, among them Ethiopia, Nigeria, Mali, and Burkina Faso. The urban growth is expanding into the metropolitan areas, most of which do not have an existing water supply infrastructure. This results to low rates of piped water supply coverage, as water utilities are already struggling to meet current demand which outpaces the speed of service expansion. The challenge is further exacerbated by the rise in unplanned urban settlements of low-income households where most of the non-revenue water losses and hence energy losses occur through vandalism and poor management [93]. This has pushed water utilities to increase water production and exploit new raw water sources, such as groundwater and sea water desalination, which often increase the energy demand [24,25].

The 2018 performance assessment report, WASREB, Kenya, indicated that most water utilities in Kenya recorded an average 27% increase in energy costs, attributed to an increase in water production, a rise in national energy prices, and prolonged drought, which resulted in reduced surface water levels; hence, most utilities sought more energy-intensive groundwater options. Increased demand for water implies more energy to abstract and supply water but also require utilities in areas with limited water supplies to explore additional alternative sources, including groundwater and desalination, which are often highly energy intensive. On the other hand, the expanding metropolitan areas present water utilities opportunities to make informed planning of the infrastructure especially with respect to water harvesting and storage structures, renewable energy sources, and energy saving technologies to reduce over-reliance on the grid [91,94].

- Per Capita Consumption

The daily per capita water consumption is influenced by socioeconomic status, meteorological conditions, household behavior, and characteristics and restriction of supply through conservation measure, tariffs, price, and metering technology [95,96]. On the supply side, water utilities influence the water demand through the enforcement of smart metering and pre-paid options for access to water services, which reduces non-billed water and enhances increased revenue collection. In the African utilities' context, there is a huge variation in the daily per capita consumption between and within countries and even among utilities within the same country [64,97]. The average daily water production and consumption for the largest utilities in the country and for those with multiple large utilities, serving a population above 5,000,000, were selected as presented in Figure 2 for the years between 2013 and 2017, for which most data were available at IBNET except for Sudan (latest data available was for 2009), 2005 for Namibia and Madagascar, and 2010 for Mauritius [98]. Huge intra-country variations in production and consumption were observed among utilities in Nigeria and South Africa, attributed mainly to variations in income level. The expansion of the middle-class in most urban areas in Africa with the ability to pay for quality water services have led to increased demand for domestic water supply, and hence, a need for increased production [67]. Consequently, water utilities need to plan for such increase in demand, which is highly dependent on quality data on trends of residential per capita water use within the supply area essential for demand forecasting, pump scheduling, and optimization.

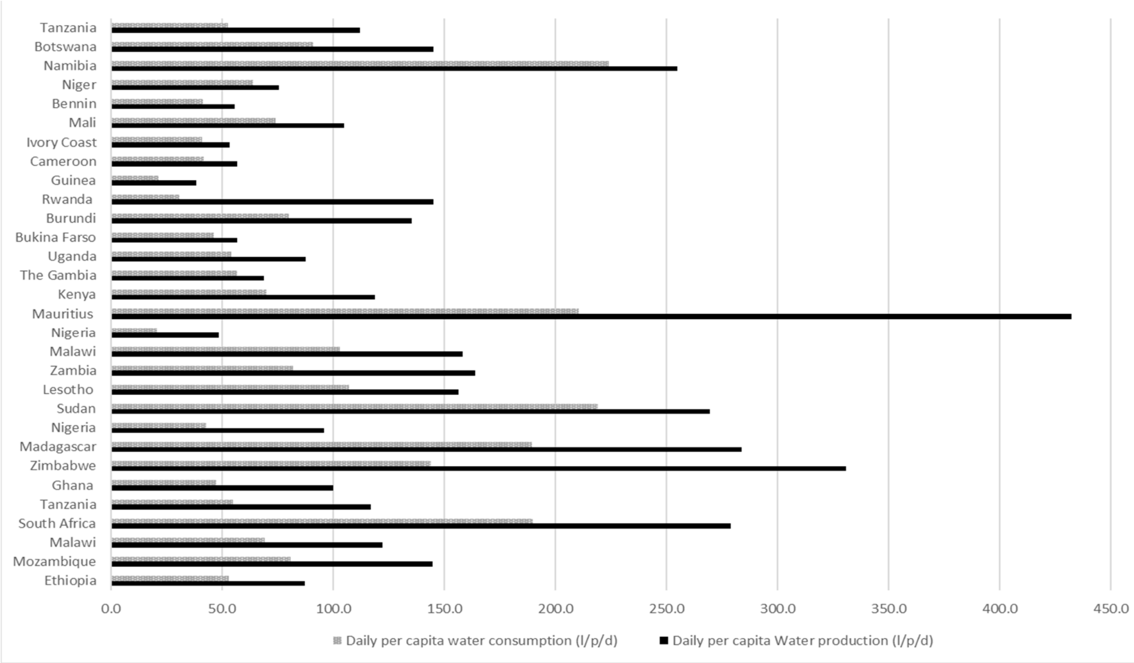

Figure 2. Daily per capita water production and consumption for selected countries in Africa. Data obtained from [98].

3.3.2. Supply-Side Drivers

The supply-side drivers are mostly external factors that influence the quantity and quality of raw water entering the boundaries of water treatment and distribution systems. Projections of water supply drivers are crucial in the long-term planning of water utilities regarding water sources and possible exploration of alternative sources, which would be energy-intensive. In addition, a clear understanding of the water supply drivers outlined below is crucial in the management of water losses along the water distribution network where the bulk of non-revenue water occurs. Operationalization of the Water-Energy Nexus thus presents opportunities to save water and energy, with energy management measures such as correct sizing of the pumps and motors reported to have as much as 30% energy savings within a 3–6 months payback periods [11].

- Variation in Precipitation Patterns

Climate change and its influence on precipitation patterns in Africa is widely reported [99–102]. Of interest to water supply is the future projections of the spatio-temporal distribution of rainfall, which would influence the balance between water supply and demand, and consequently, the energy requirement to abstract, transfer, or lift the water. Several studies project prolonged drought and reduced groundwater recharge rates of about 30–70% in the northern and southern regions, compared to the increased precipitation and groundwater recharge in the eastern, western, and central part of Africa under the high-emission and low-emission climate change scenarios [100,101]. In addition, increased flooding events are projected along the Niger delta and the Blue Nile by an over 10% increase in high flows under the global climate low-emission scenarios of 2 °C [101]. It is further noted that the effects of climate change are likely to be more severe, especially in Sub-Saharan Africa due to low adaptive capacities [101,102]. Water utilities in areas facing more frequent severe droughts have to adjust their production to cope with the growing demand by seeking alternative water sources such as sea water desalination and mine-water reclamation, often with huge energy intensities [25]. Furthermore, longer pumping hours, and hence higher energy demand, may be required to meet the increased water demand during drought periods. Therefore, more investment is required to increase water harvesting and storage capacity to meet the growing demand.

- Water Losses within the Systems

Water loss within the water supply network is categorized as either physical losses through leakages in the storage and pipe network or real losses that occur through incorrect customer meter billing, vandalism, or any unauthorized consumption [103]. These losses pose one of the greatest challenges of water supply sustainability, both in hindering expansion of supply to the unserved areas, thus weakening the utilities operational efficiency. As reported in [64,66], large utilities, serving more than 1 million persons, tend to report higher non-revenue losses, since in most cases their infrastructure is quite old, with frequent bursts and leakages where energy is lost too. Based on the data submitted to IBNET, non-revenue water losses in participating utilities in Africa were reported as a percentage of billed water and as volume lost per kilometer of connection. The percentage non-revenue water ranged on average from 54% in Gabon and to about 20% in Burkina Faso, with the continent's lowest non-revenue water losses as in Figure 3. However, values as high as 72% have been reported in Nigeria. Additionally, non-revenue water loss reported as volume lost per km of connection per day in 2018/2019, ranged from 73 m^3/km/day in Nigeria, 61 m^3/km/day in Zambia, 4.7 in Burkina Faso, and 10 m^3/km/day in Lesotho.

As noted in [104], reducing and managing non-revenue losses and hence energy losses requires comprehensive supply and demand side programs that are both sustainable and realistic. Although it is not technically possible to reduce the water losses to zero especially in systems with aged infrastructure, means to reduce the losses in the system starts with thorough assessment of the system to prioritize management options. Hence, keeping in mind the close linkage between water and energy, utilities can exploit a joint wholistic water-energy balance where a link between energy consumption in water supply processes and associated water and energy losses can be quantified [82,105,106].

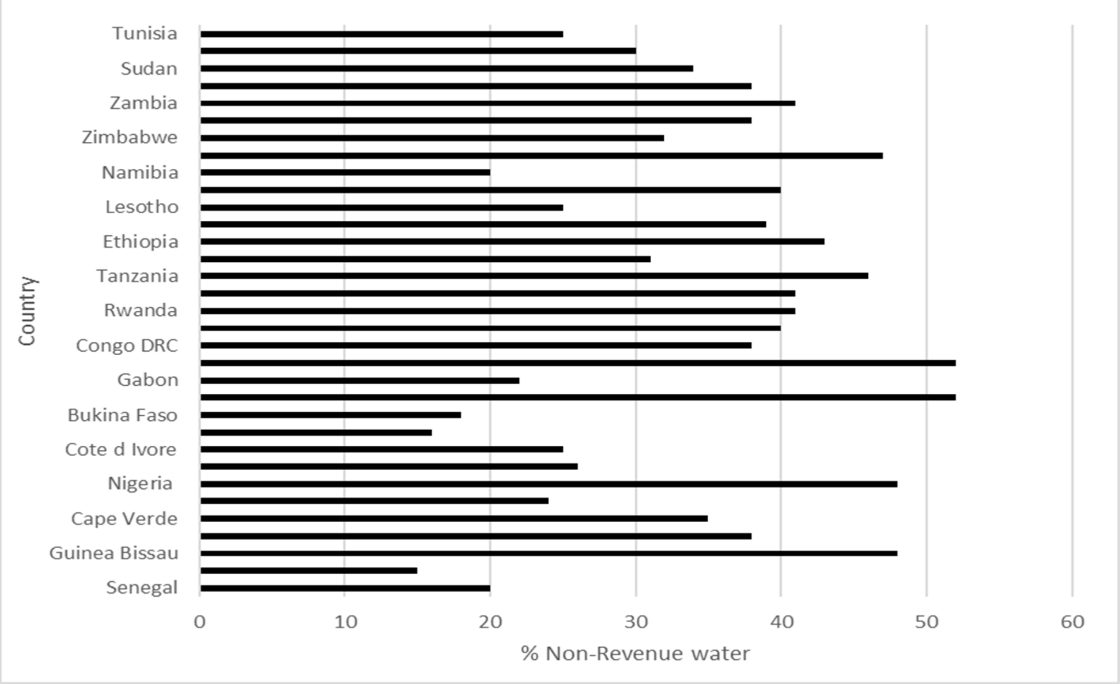

Figure 3. Levels of % non-revenue water (NRW) for selected countries in Sub-Saharan Africa. Data obtained from [98].

- Nature and Type of Pumps and Motors

The nature of pumps and the associated pipe network largely determines the energy demand and energy and water losses within the system. In addition, these are the highest consumers of energy within the water supply networks, accounting for over 90% of the total water utilities energy consumption, but also present the utilities' greatest energy-saving potential [11,83]. Pumping accounts for about 30% of the total energy consumption for groundwater extraction, and about 80% of the clean water transmission and distribution; hence, their operational efficiency is crucial in energy savings and reducing water losses through leakages [11]. The amount of energy consumed is highly dependent on the nature, age, and pump running hours and the maintenance schedules, but poor sizing and installation, as well as high variability in pressure and head losses, can greatly increase the energy consumption due to increased inefficiencies. In an unpublished study carried out by the authors in water utilities in Kenya, most utilities have not invested much in improving or optimizing their energy efficiency. Similarly, most utilities had no separate metering and billing of individual pumping station and none of the utilities under study had an energy management plan, although strategic plans to explore renewable energy sources were mentioned. Separation of energy consumption by energy-intensive consumers provide valuable disaggregated trends of energy use and efficiency crucial for the detection of inefficiencies responsible for energy losses and establishment of maintenance schedules.

- Water Source and Water Quality

Different raw water sources require varying amount of energy to abstract, treat, transmit, and distribute clean water. As already outlined in [22], groundwater extraction accounts for about 31% of total direct energy compared to surface water. Furthermore, surface water supply systems have a higher indirect energy requirement due to higher amounts of chemicals required to treat the water. The type and quality of raw water entering a water treatment system influences inputs such as energy and treatment chemicals where in a typical conventional water treatment that employs coagulation/flocculation and uses filters, the energy intensity is largely influenced by the concentration of the total suspended solids and the nature of the filters [107]. Furthermore, land-use activities, population density in the catchment areas, and possible effects of climate change influences the quality of water from the catchment areas. The concentration of suspended matter, total organic carbon, and water conductivity, which are highly influenced by seasonality, have been identified as water quality parameters that contribute to a high energy intensity in the water treatment system [17].

4. Discussion

Since the beginning of the last decade, Water-Energy Nexus research has gained a lot of attention both in the application of the nexus concept and models to address the nexus challenges. However, as noted in [108], in one of the latest reviews on the Water-Energy Nexus, there are challenges in the application of the framework for decision support, since there is no singular framework for conducting a nexus research. In addition, research on the methods and tools for the assessment of the Water-Energy Nexus framework at different scales even in developed economies is still at the 'understanding stage.' This necessitates a further analysis of the water-energy framework towards the 'implementing stage,' where effects on water energy policies trade-offs and synergies would be evidenced. The authors further note that there is potential in the adoption of the Water-Energy Nexus framework to address sustainable and wise-use of energy and water resources through informing decision-makers on policy and governance structures in the water sector in Africa.

Upward shifts in the supply side and demand side drivers of energy use for drinking water supply are expected in the future. On the supply side, the quality of raw water is likely to deteriorate or reduce due to increased pollutant loads from various users; moreover however, the water treatment technologies will need to change to cater for higher efficiency and maintenance of required water quality standards. Additionally, water utilities will be required to consider alternative water supply options including desalination and re-use, which will likely increase their energy demand. On the demand side, Africa is expected to have the highest growth rate in the cities, with about 60% of the total population living in urban areas in 2050 [109]. This implies a huge growth in the water demand, which calls for investment in technology, infrastructure and labor as well as improved understanding of the water supply system inputs and how they can be optimized.

Estimation of the energy use for drinking water among water utilities in Africa is a key enabler of universal water access through sustainable and resilient operations of water utilities; it should be a requirement that water utilities and regulators are implemented in the existing performance assessment data collection, considering differences in their operating environments. Several indicators do exist for the assessment of energy use for water supply [76]. Such indicators are based on the concept of the minimum energy required to deliver a unit volume of water between a point of source and delivery point, considering the terrain, the nature of the water supply system, and areas of losses within the system, all of which influences the system operational energy requirements. For instance, for the assessment of energy use in small and medium sized water utilities, reference [80] proposed two indicators that do not require hydrological modeling: the structure indicator I1 and the quality indicator I2. Structure indicator (I1) represents the energy consumption to lift water from a water source to consumers, while quality indicator (I2) shows how well a utility is utilizing the energy for water supply processes compared to minimal energy required to lift a unit volume of water, maintaining the operational pressure required at the end user tap.

Water utilities needs to prepare to be 'fit for the future' by adapting ways to achieve maximum operational cost recovery, expand service connectivity and transform into customer-oriented service providers through innovative solutions that address water supply and energy reduction [110]. Water utilities in cities such as Kampala (Uganda), Lagos (Nigeria), Bamako (Mali), and Niamey (Niger) have been projected to experience exponential growth in water demand due to high rates of urbanization, since they are located in areas of high-risk water stress [90,111]. Planning for increased water harvesting and storage is thus paramount. However, as already reported in reference [112], the water storage facilities within the distribution network influence the energy intensity for water pumping, which should be considered to optimize energy use for pumping, especially when water utilities need to invest in new pumping and storage systems.

Transformation into smart utilities will help utilities to leverage the vast amount of data they generate to optimize their service delivery [113–115]. Availability of comprehensive data on the performance of water utilities and energy use for water supply is not a unique situation to water utilities in Africa, as already discussed in reference [116]. However, the quality of data remains a significant challenge for water utility operations research in areas without a comprehensive database, thus, limiting such research efforts to utilities willing to provide the data, and more often those performing relatively well. In addition, most of the data provided through open calls to utilities is largely siloed, disintegrated into files or computer systems that rarely communicate with each other [115].

5. Conclusions

There is a compelling need to assess energy use in water utilities in Africa to properly inform their decisions for water service provision and improve the understanding of the application of the Water-Energy Nexus concept by water utilities and water services regulators. There are still very few studies on the application of the concept in the region and energy data is quite difficult to obtain through open calls, given that many water services regulators do not consider energy use as a key performance indicator. There are indications of an upward shift in the demand-side drivers of water supply, especially population growth and urbanization, while on the supply-side, available water sources are continuously being depleted and/or increasingly being polluted. These trends have triggered an increase in energy requirements for water utilities as they switch to remote water sources and/or abstracting and treating increasingly polluted sources that are often more energy intensive. Despite these challenges, it is clear that accelerated structural and organizational reforms in the water sector in Africa and increased investment in water infrastructure since the 1990s have demonstrated great potential for water utilities to meet their operational costs. Furthermore, it shows the possibility to deliver water services and at the same time expand coverage in a sustainable manner towards the achievement of the SDG goal on universal access to water in Africa. Moreover, several opportunities exist for water utilities to adequately understand their energy consumption and the extent to which the supply-side and demand-side drivers for water supply affect energy demand for efficiency and sustainability considering the increasing demand for water and the associated obligations to provide quality services in the region. This review supports the ambition of regulators of water services to incorporate energy use assessment indicators through which utilities can be evaluated and benchmarked in their routine monitoring and reporting. However, accurate understanding of the operational drivers for water supply lies in data collection, which will help to inform water-energy policies.

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