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Research article

Quantifying water-energy nexus for urban water systems: A case study of Addis Ababa city

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Abstract: The complex interdependency between water and energy poses new challenges for policymakers to achieve a safe, secure, and sustainable supply of water and energy in the future. The water-energy nexus can be typically characterized by efficient use of energy and water resources. Hence, this paper aims to explore quantitative results of the nexus in terms of energy intensity on existing water systems within urban water cycles. The energy requirement for water treatment and water conveying to the city (from Legadadi water treatment, Gefersa water treatment and wastewater treatment area) as well as the energy requirement for water distribution within the city were quantified. The energy intensity for groundwater extraction, water transmission and water distribution were computed using Energy Intensity method. This led to identify the best technologies to insure the security of water-energy nexus. The annual energy demand and energy intensity values for groundwater extraction were estimated to be 0.6 PJ and 1.2 kWh/m^3 respectively. These values for operating all pumps in the water transmission were 0.13 PJ and 0.32 kWh/m^3 respectively. Similarly, the energy intensity value for water distribution was 0.27 kWh/m^3 and distributes water to residential, commercial and industrial end-users. Determining the energy intensity predicts the future energy demand in urban water system. In 2030 and 2050, the predicted energy demand will be 0.50 and 0.83 PJ respectively for water transmission whereas it will be 0.41 and 0.67 PJ for water distribution.

Keywords: urban water; energy demand; energy intensity; water supply; water-energy nexus

1. Introduction

Urban water service provision includes the planning and delivery of water supplies for residential, commercial and industrial uses as well as water collection, treatment, and recycling of wastewater. Energy is used throughout the water cycle of urban when water is pumped, treated, or pressurized. Energy demand varies from city to city, due to local factors like location, quality of water sources, topography, pipe dimensions and its configurations, and treatment standards required. Operational strategies and technology selection of water use in industry can also significantly influence energy demand. The increased treatment standards, the use of more marginal water qualities and increased distance of pumping for raw and treated waters also increased the energy consumption or use in water services provision [1]. According to UNICEF [2] the urban population share for most developing countries will be more than 50% by 2050. The high population with urban growth and global economic development will cause great pressure on the resources in the planet, such as water and energy. With growing demand of resources, water crisis is a present and future risk of the city. By 2035, the world's primary energy demands will grow by 40%, compared with that in 2010 [3]. Saving water and energy resources becomes an important premise of sustainable development around the world. The increase in water efficiency by end-users can achieve the greatest reductions in energy consumption of water cycle in urban [4] in part because a reduction in urban water demand will reduce the energy required in sourcing, treating and pumping water to end-users. With the growing concern for water and energy security globally, detailed exploration of interlinks between energy and water, known as WEN has drawn great attention in recent years.

The water-energy nexus (WEN) analysis can support water and energy planning and understanding of potential options for both policy and technology. The water-energy nexus assists policy makers and resource managers in water and energy conservation [5]. Water and energy are essential for human survival and intimately intertwined [6]. This interdependence or interlinkage between two resources is defined as the Energy Intensity (EI) [7]. The energy for water has been less researched [8] and the water systems in urban are frequently managed separately [9]. Urban water systems are one of the users of energy resources [10]. The processes involved and the water quality level before end-use affects quantity of energy intensity required per unit volume of water [11]. As example, in Spain, the level of energy consumption per unit of delivered water is stated as 0.21 and 0.56 kWh/m^3 for urban users and wastewater treatment for recycling respectively [11]. Differences in these values also reflect the variety of boundary conditions of the studies, as well as other influential factors such as the type and quality of the raw water and the efficiency of the water treatment and delivery system [12]. This suggests that a greater focus on the energy requirement of the water systems will be a crucial point of the policy response to the sustainable management of the systems. Sustainable management of urban water systems can achieved through improving the water and energy use efficiency, which can reduce their environmental associated impacts [13].

Water-energy efficiency improvement has a win-win contribution to human being and environmental sustainability for future generations [14]. The United States, Australia and European countries have provided suggestions for future policy directions for water-energy resource management [15] and the need to study sustainability of water and energy within an urban water system. According to the study of energy use in urban water system in Australian cities, the electricity consumption could increase remarkably, if alternative water sources such as wastewater recycling were implemented [16].

Technologies for WEN: Underlying the motive for new energy technology, a strong drive comes from ensuring security by extracting resources that before were technologically or economically unviable. Notwithstanding, new technologies also provide innovative applications for WEN. For example, applying solar heating systems would significantly save energy for supplying domestic hot water [17]. Photovoltaic (PV) solar power plants are built in order to produce energy that could be either sold or consumed for part of the electricity needed for processing water [18]. Reverse osmosis and capacity deionization processes are energy efficient methods to desalinate blackish wastewater [19]. Integrating solar PV systems inside the water treatment section, leads the water-energy nexus more energy efficient [20]. During the desalination process, voltage variation has a substantial effect on the performance of electro-sorption of anions [21]. Hence, the PV system should be convenient to manage with the required voltage.

A number of scenarios for attaining both energy and water security are proposed, taking advantage of technologies that are relatively new; for example, low-flow fixtures, energy-efficient appliances, rainwater collection for non-potable uses, solar hot water heating, electricity peak shaving as a demand response method, solar PV power, and converting municipal waste to energy [17]. Rainwater harvesting would not only provide water to residents but also offers solutions for energy conservation [22]. A list of emerging water service infrastructures and energy sources is provided in Table 1.

Table 1. Water service infrastructure and energy sources [23].

Purpose	Technology
Water efficiency	Low flow showerheads, dual flush toilets, tap flow regulators and etc.
Source substitution	Rainwater and storm water harvesting, wastewater recycling
Pumps	Rain tank pumps, more efficient water pumps, and house pumps
Alternative energy sources	PV energy production and biogas production from sewage treatment

Energy for water: water supply is the fundamental application in the studies of energy for water that is an alternative side of WEN story. In the USA and China, it is quantified that energy use for water is 4% of the country's electricity generation [24]. Energy intensity for all water uses is not similar; it depends on the geographical attribution, quality, quantity, and distribution of the water source, as well as the type of technologies used in water system. Energy for water also called 'energy intensity' or 'energy embeddedness', is calculated by computing the energy required per unit of water volume measured (kWh/m^3) for each stage. The energy consumed varies in specific stages of the water systems conditioned by their geological conditions, technologies, and infrastructures [25]. The stage of urban water cycle system is given in Figure 1.

Source and conveyance systems: For surface water extraction and transmission, the physical environment exerts a basic influence on energy requirements. Groundwater pumping has different energy intensities depending on the depth of the aquifer, the pressure and flow rate of the output water, and the efficiency of the pumping system. Commonly, it is assumed that the efficiency of pumping is around 50% [27]. Based on a different approach, EPRI [28] estimates the energy intensity of source and conveyance systems according to the sector in which the water is used. For example, the unit electricity consumption for groundwater is 0.18 kWh/m^3, whereas for surface water source it is 0.08 kWh/m^3 for domestic and commercial sectors. For the industrial and mining sectors, 0.19 kWh/m^3 were assumed for groundwater pumping with additional energy requirements such as frictional losses or higher pressures. In the power generation sector, values of 0.21 kWh/m^3 for groundwater pumping and of 0.04 kWh/m^3 for surface water supply were estimated [28]. When conveyance is required over long distances with elevations, local treatment and distribution, and wastewater collection and treatment, water becomes more energy intensive [15]. Energy requirements at this stage of water provision depend on the number and performance of pumping systems required to transfer water from the source to the water treatment or purification plant.

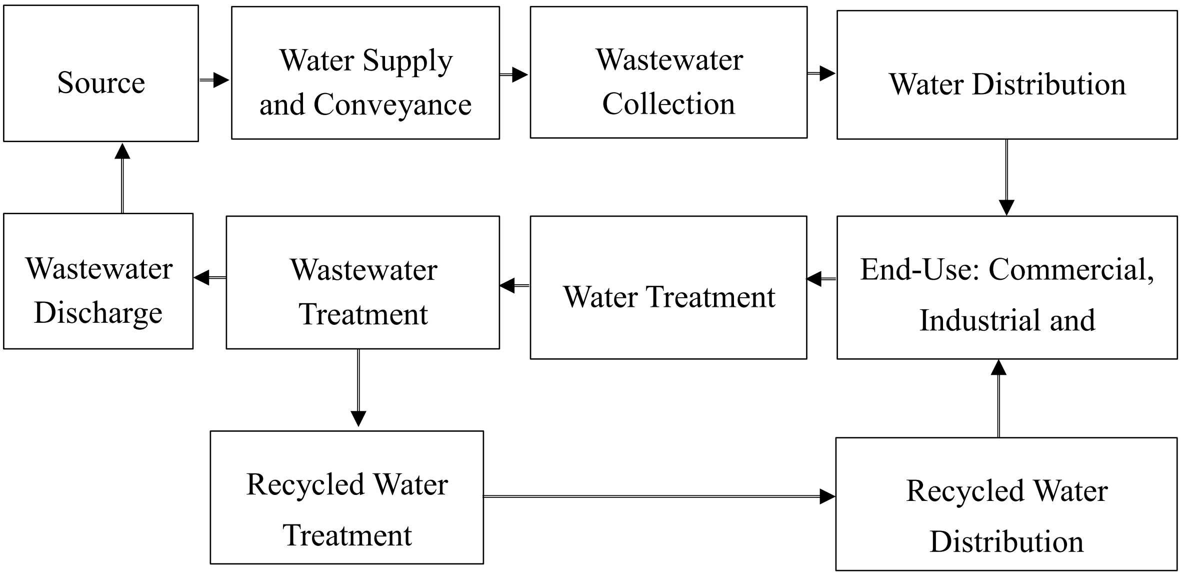

Figure 1. Urban water use cycle scheme [26].

Water treatment: The local environments and regulations affect the energy use for water and wastewater treatment in urbans [16]. More concretely, cases from the United States have shown that surface water treatment facilities that use processes including rapid mix, flocculation, sedimentation, and filters of 37,850 m^3/d has an estimated total electricity consumption of about 14,057 kWh/d, which is equivalent to a unit energy consumption of 0.4 kWh/m^3 [28]. This found that variations are driven primarily by economies of scale, particularly in the case of small facilities, where unit electricity consumption decreases as the size of the treatment plant decreases. Regardless of size, however, electricity is primarily used for pumping treated water into the distribution system, which normally accounts for between 80 and 85% of the total electricity consumption for surface water treatment [28].

Distribution to end-users: Energy is required to distribute water to the end-users. These distribution systems are usually equipped with chlorination points to meet the regulations on chlorine levels at the faucet for potable uses. When the reservoirs are located in at higher elevation, water can distribute through gravity pressurized system and which is possible to reduce the energy demand [29].

Wastewater treatments: Studies have shown that the average energy consumption per cubic meter of wastewater treated ranges from 0.36 to 2.0 kWh/m^3 [30,31]. However, when the volume of water treated in each country is considered, the difference in the net energy use could be significant. Economies of scale can generally be achieved at this stage. The higher degree of treatment and complexity of the process increases due to salinity and other organic material contents in the wastewater can increase the unit electricity energy consumption [32].

It demands significant amount of energy to supply water to Addis Ababa city from its sources to the end users. The energy is required for water extraction, water treatment, and wastewater treatment, water distribution to the end use and for water transmission. Therefore, quantifying water-energy nexus is needed for policy and decision making for water and energy scarcity. For this reason, this study quantifies water and energy nexus in urban water system to recommend alternative options for improving water and energy availability of the city.

The aim of the study is to quantify the WEN in urban water system using the method that has been used in water-energy nexus (WEN) studies. There are different methods to enumerate the water-energy nexus, such as the Energy Intensity (EI), Linkage analysis, MRNN, UWOT method, etc. In this study, the EI method is used to quantify the WEN in Addis Ababa City.

2. Materials and method

2.1. Data collection

Data of from 2016 are used as a baseline in this paper; these are collected from AAWSA office, these data includes pumping station (which includes, status of pump, head and flow rate of pump) of water transmission and distribution network. The power for ground water pump at various stations and water treatment for Gefersa and Legadadi station was gathered from AAWSA office. Additionally, wastewater treatment data was taken from wastewater treatment final report. The data are discussed in this sub-section.

2.1.1. Groundwater pump (extraction)

Akaki phase II and I use power of 4701 kW (a design capacity of 126000 m^3/d), Akaki phase IIIA consume a power of 2773 kW (for a design capacity of 70,000 m^3/d) and Akaki phase IIIB used a power of 4089 kW (capacity of 70,000 m^3/d). Legadadi deep well used a power of 1034 kW (42,000 m^3/d), Addis Ababa Pocket Borehole consumed a power of 6386 kW (with a capacity of 62,000 m^3/d) and Koye Feche and Kilinto Deep Well has a power of 1814 kW (a capacity of 55,000 m^3/d).

2.1.2. Water transmission

The pumping station at water transmission network branch are taken from AAWSA, which includes Legedadi water treatment plant, Legedadi deep wells phase I, Terminal rising, Gefersa water treatment plant (WTP), Akaki Phase I and II, Akaki Phase III-A (PIIIA), Akaki Phase III-B (PIIIB) and Koye Feche transmission network. The pumping station data at each water transmission network used for water-energy nexus analysis in urban Addis Ababa. The detail of pumping station including lift head (H) in m, flow (Q) in m^3/h and status of the pump for water transmission network is summarized in Table 2.

Table 2. Water transmission network pumping stations.

Legedadi water treatment plant transmission pump						
Station	Ayat booster			CMC	Kara 1 PS1	Kara 1 PS2
Pumps	P1	P2	P3	P1	P1	2 parallel
Flow (m^3/h)	14	30	30	30	35	72
Lift (m)	244	150	150	187	200	196
Status	Operation	Operation	Operation	Operation	Not	Operational
Legedadi deep wells phase I transmission						
Station	T2		T2		T3	
Pumps	2 parallel		3 parallel		2 parallel	
Flow (m^3/h)	362.5		331.2		80	
Lift (m)	68		140		100	
Status	Operational		Operational		Operational	
Terminal rising transmission branch pumping						
Station	Terminal	Jan Meda			Teferi Mekonen	
Pumps	3 parallel	3 parallel	3 parallel	3 parallel	P1	P1
Flow (m^3/h)	1125	188	270	360	95	310
Lift (m)	76	57	55	32	69.5	63
Status	Operational	Operation	Operation	Operation	Operation	Operation
Terminal rising transmission pump						
Station	Shiromeda	Entoto R1	Entoto R2		XMO	
Pumps	2 parallel	2 parallel	2 parallel		2 parallel	P1
Flow (m^3/h)	71	31	21		270	300
Lift (m)	89	55	65		160	33
Status	Operational	Operational	Operational		Operational	Operational
Gefersa WTP transmission branch						
Station	Asko Giorgis		Iyassu Minch New		Ras Hailu 1	Ras Hailu 2
Pumps	P1	P2	2 parallel		2 parallel	2 parallel
Flow (m^3/h)	108	163	80		320	250
Lift (m)	125	140	130		105	55.5
Status	Operational	Operational	Operational		Operational	Operational

Continued on next page

Akaki phase I and II transmission pump							
Station	CT	CT2		GWI and GWAII	GWII Old	GWII New	GWIII
Pumps	5 parallel	2	8	5	5	6 parallel	5 parallel
Flow (m^3/h)	651	455	507	651	587	417	750
Lift (m)	58	75	192	120	100	98	125
Status	4 operation	All	All	3 operation	3 operation	5 operation	4 operation

Akaki phase III-A transmission pump		
Station	CT2 (PIIIA)	Hana Mariyam (PIIIA)
Pumps	8 parallel	8 parallel
Flow (m^3/h)	486	486
Lift (m)	178	137
Status	Operational	Operational

Akaki Phase III-B Transmission pump						
Station	CT2	Hana Mariam	Fana Booster	Mexico square	Police Hospital Old	Police Hospital New
Pumps	8 parallel	8 parallel	8 parallel	3 parallel	2 parallel	2 parallel
Flow (m^3/h)	510	510	510	700	270	162
Lift (m)	192	180	195	30	98	140
Status	Operation	Operation	Operatio n	Operation	Operation	Operation

Pump station of Koye Feche (KF) transmission	
Station	Collection Tank (CT5)-KF
Pumps	6 parallel
Flow (m^3/h)	450
Lift (m)	200
Status	Operational

2.1.3. Water distribution

Pumping station at distribution network branch are collected from AAWSA; these distribution network branch includes the terminal rising branch, terminal gravity branch, Gefersa WTP branch, Akaki Phase III-Borehole branch and terminal small pumping station (PS). The data collected for each water distribution branch concerning to pumping station is used in this study. Summary of pumping station including its status, lift head (H) in m, flow (Q) in m^3/h for water distribution network is given in Table 3.

2.1.4. Water and wastewater treatment

According to AAWSA data; the power used in treatment technology for Gefersa WTP including air blower, aluminium sulphate, chlorination, mixer and steered are 24, 3.4, 44,8 and 22 kWh, whereas for Legadadi WTP which includes air blower, backwash, chlorination, service water 1 and 2 are 19.38, 150, 28.05, 9.35 and 7.65 kWh respectively is considered. The daily water flow and power capacity of the Wastewater Treatment Plant is 113,659 m^3/day and 2652 kW respectively.

Table 3. Water distribution branch pumping stations.

Terminal rising branch distribution pump					
Station	Terminal PS1	Angorcha PS1		Kenya Embassy PS	Gabriel PS1
Pumps	3 parallel	2 parallel		2 parallel	2 parallel
Flow (m^3/h)	540	27	36	20	17.5
Lift (m)	75	185	200	155	100
Status	Operational	Operational	Operational	Operational	Operational

Terminal rising branch distribution				
Station	Belay Zeleke PS1	Belay Zeleke PS2	Ras Kassa PS1	Ras Kassa PS2
Pumps	2 parallel	3 parallel	1	1
Flow (m^3/h)	30	17.5	30	30
Lift (m)	150	100	130	130
Status	Operational	Operational	Operational	Operational

Terminal gravity pumping station			
Station	Jakrore PS1	Urael PS1	
Pumps	3 parallel	3 parallel	
Flow (m^3/h)	70	(2x) 178	188
Lift (m)	80	(2x) 39	57
Status	Not operational	Operational	Operational

Gefersa WTP pump stations		
Station	Ras Hailu	Iyassu Minch Old
Pumps	3 parallel	2 parallel
Flow (m^3/h)	62	13
Lift (m)	47	130
Status	Not operational	Operational

Akaki phase III-borehole distribution station			
Station	Augusta Booster		Radio Fana Booster
Pumps	1	1	3 parallel
Flow (m^3/h)	30	27	120
Lift (m)	130	185	140
Status	Operational	Operational	Operational

Terminal small pumping station (PS) distribution zone pump				
Station	Terminal PS4	Terminal PS5	Terminal PS3	
Pumps	2 parallel	2 parallel	2 parallel	
Flow (m^3/h)	50	80	20	43
Lift (m)	230	180	200	130
Status	Operational	Operational	Operational	Operational

2.2. Energy intensity method

The water and energy resources supply and use in the cities are complicated and intensive. In the perspective of urbanization, city is the core system for WEN research around the world, and indeed, the selected city-scale comprehensive case studies include case cities around the globe, from the United States to cities in Africa with a nexus method used is indicated in Table 4.

Table 4. Property of methods about the WE nexus scope [33].

Method	Model type	Developer and software	Geographical scale	Purpose	Nexus challenge level
EI	Quantitative analysis model	No	City level	Quantify energy flows in urban water systems	Understanding
Linkage analysis	Quantitative analysis model	No	City level	Explore the structure and interconnection of both water and energy resources in cities	Understanding
MRNN	Quantitative analysis model	No	City level	Explore the interconnections of energy consumption and water use for urban agglomerations	Understanding
UWOT	Quantitative analysis model	UWOT	City level	Quantify energy use in urban water supply systems	Understanding

The tools include those that are focusing on the water-energy nexus (WEN), which is nexus fundamentals are limited to urban water-energy. In this paper, the most methods that used to quantify the energy use for water are the Energy Intensity (EI) method or quantitative analysis model. This is a top-down and bottom-up hybrid model that was mainly for quantifying the energy flows in urban water system. The high-level monthly energy intensity of the urban water system can be estimated using a top-down model. The bottom-up model is developed to calculate detailed energy estimates for a subset of urban water service area or sites. In the case study of the East Bay Municipal Utility District in Northern California [34] this method is used, but there was no scenario function and no applicable software for this method.

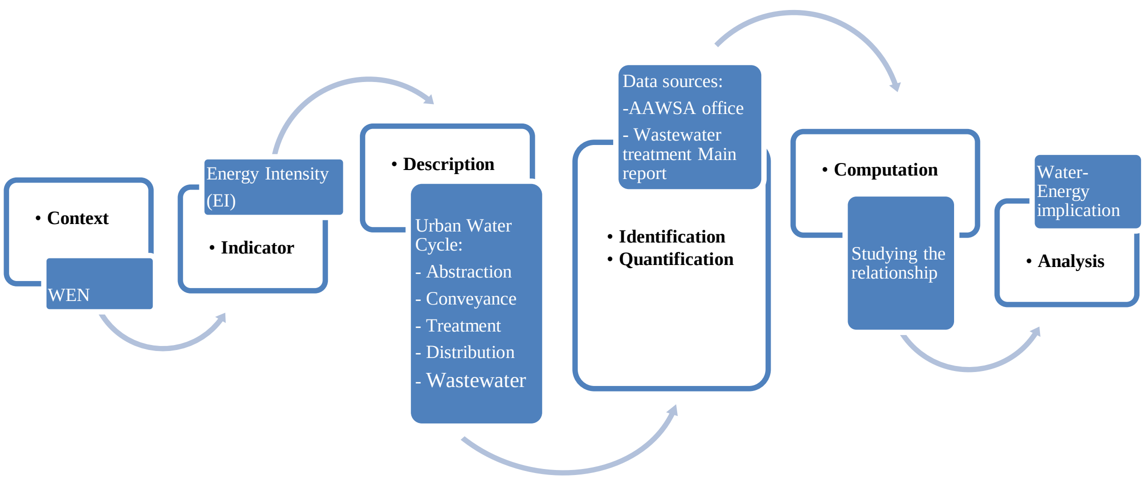

Figure 2. Framework of the WEN for urban water systems.

Characterization of the WEN for urban water systems can be conducted at regional or city levels. This paper looks into the energy intensity of water systems and the total energy used to for the total water. The energy intensity method is selected as the major measurements for the water-energy nexus in urban water system of Addis Ababa City. Detailed framework of the WEN analysis within and around the city is illustrated in Figure 2.

The energy use boundary of the study within and around the urban water system cycle is indicated in Figure 3 considering water abstraction and conveyance, water treatment, water distribution, wastewater treatment.

Figure 3. Typical energy use in water cycle within and around the study.

Quantification of the WEN is usually characterized in resource use efficiency terms. In this study, the nexus term was quantified as energy intensity and energy, which is defined as energy consumption (in kWh) per unit volume (in m^3) of product water and in kWh respectively. For groundwater abstraction, the energy required for water is estimated when the system operate annually and the energy intensity estimated by dividing the total energy at the station or site for the total water. In case of estimating the energy consumption for distribution and transmission, only discharge and head is considered as a data for computing the power.

The energy is estimated annual for water transmission and distribution to the end-user of Addis Ababa City, when the system operates for a 24 hr. In similar case, estimating energy used for wastewater and water treatment is considered. According to the data information, some of pumps are not operating and while other is operational, this causes urban water scarcity. To improve the water scarcity all technology should operate efficiently. Generally, the water-energy nexus in urban water system of Addis Ababa City is quantified using the following steps of Eqs 1, 2 and 3: The ideal hydraulic power to drive a pump is a function of volume flow rates, the liquid density and the differential height. Either it is the static lift from one height to another or the total head loss component of the system can be calculated like Eq 1:

$$P_h = \rho\, g\, Q\, H \tag{1}$$

Where, Ph = power (kW), Q = flow rate (m^3/s), ρ = density (kg/m^3), g = gravity (9.81 m/s^2) and H = head (m).

The following are used for quantifying water-energy nexus using the energy Eq 2:

$$E = P_h \times t \tag{2}$$

Where E = Energy (kWh) or it can be in GWh or in PJ, t = annual operational time (hr)

The energy intensity consumption in urban water cycle system is estimated by using Eq 3:

$$\mathrm{EI} = \frac{\mathrm{E}}{\mathrm{V}} \tag{3}$$

Where, EI = Energy intensity (kWh/m^3) or it can be in GWh/m^3 or in PJ/BCM, V = volume of water (m^3) or in BCM.

2.3. Energy prediction for water

Energy consumption is calculated in terms or energy intensity, with the units being kilowatt-hours of electricity consumed per generated volume of water (kWh/m^3). Energy is consumed throughout the water cycle, and depending on the source of water and the distance and topography over which it is transported, it is possible that large amounts of energy are required to move water from its source to its final destination.

The future energy demand of water transmission and distribution for Addis Ababa city in 2030 and 2050 will be predicted based on the water demand of the city in 2030 and 2050. Additionally; the energy intensity required for water transmission and distribution is the factor in the prediction of energy demand for water. The Eq 4 is used to predict and plan the future energy demand of water transmission and distribution.

$$\text{Energy demand} = \mathrm{EI} \times \mathrm{V} \tag{4}$$

Where; energy demand is the future energy required for water transmission and distribution in PJ or GWh or kWh, EI is energy intensity in PJ/BCM or kWh/m^3; V is the volume of water in BCM or m^3.

3. Result and discussion

This paper particularly looks into the relationship between the energy intensity of water systems in urban Addis Ababa. The water-energy nexus (WEN) can be measured using the energy intensity. Quantification of the water-energy nexus in terms of energy intensity in Addis Ababa City is discussed in this section. Quantification of the water-energy nexus is usually characterized in resource use efficiency terms. In this study, the nexus term was quantified as energy intensity, which was defined as energy consumption (kWh) per unit volume (m^3) or (PJ) per unit volume (BCM) of product water. Quantification of the nexus was conducted for the urban water system, including the majority of the urban water cycle from a water supply, wastewater treatment, transmission, water treatment to distribution. The challenges of energy and resources availability is turning society to a more sustainable direction are tremendous and urgent. The demand for sustainable development derives from the growing world population and its demand for increasing living standards, which generates a huge demand for water and energy.

The energy intensity for groundwater pumping at the site of Addis Ababa was estimated by considering the total water pumped at each site. The sum of energy per sum of water extracted at each site or area indicates the energy intensity of the water use cycle. Quantifying the interconnections among energy and water is an initial step toward integrated WE systems, which will further contribute to robust WE security management. Energy consumption is inevitable for water services, including water treatment, and distribution, and the energy footprint of water provision significantly varies among different water sources. Quantifying of energy requirement in urban water systems would provide a more appropriate basis for planning, management and policy. Understanding the water-energy nexus can lead decision-makers to explore new opportunities to conserve water, energy and costs, as well as achieve maximum benefits. In response to the dependence of water systems on energy, future integrated system designs may favor water conservation or reuse in end-use sectors. It is encouraging that policy makers are recognizing the potential of efficient water and energy use [35].

The energy consumption of urban residential water in Addis Ababa city, driven by rapid urbanization and continuously rising living standards, will increase dramatically from 0.27 PJ in 2030 to 0.46 PJ in 2050. Therefore, improving the water efficiency of household water-consuming fixtures and fittings, such as toilets, showerheads, faucets, and water heaters, contributes to wastewater reduction, and more importantly, wastewater treatment energy and water embodied energy.

3.1. Energy implication in groundwater extraction

Due to the accessibility of water source (surface water or groundwater) that had a strong impact on its energy demand and commissioning of alternative water sources such as desalination and wastewater recycling would also increase the total urban energy requirement [36]. According to Wakeel study, groundwater supplies typically require approximately 30% higher direct electricity consumption and 27% more embodied energy than surface water supplies. Groundwater pumping requires energy consumption and tends to be more energy-intensive. Groundwater pumping has different energy intensities depending on the depth of the aquifer, the pressure and flow rate of the output water, and the efficiency of the pumping system. Energy requirements at this stage of water provision depend on the number and performance of pumping systems required to transfer water. The total energy used for ground water extraction in Addis Ababa and its surrounding which includes Akaki phase I and II, Akaki phase IIIA, Akaki phase IIIB, Legadadi deep well, Addis Ababa pocket borehole and Koye Feche deep well were estimated. The average energy in used to pump a volume of water at the stage of groundwater extraction is 1.2 kWh/m^3 or 4.3 PJ/BCM with the energy of 0.6 PJ.

3.2. Implication of energy in water transmission

According to AAWSA, new water sources are scheduled to be commissioned to secure a fully supplied adequately pressurized system. A new concept of the transmission network will need to be developed, incorporating the new supply sources to meet the future water demand of the city. Commissioning of new supply sources can be expected to additional service reservoir capacity; the provision of new supply routes involving new pipelines and pumping stations; as well as changes in operating heads and flow direction at parts of the system. The energy required for water transmission was increased due to the future water supply expansion of the city and based on the water demand of the city; the energy (PJ) required for water conveyance is indicated in Figure 4. The water-energy nexus indicate, the more water needed, the further energy is also required for water transmission, and the nexus has a direct relationship in magnitude. The energy intensity used in transmission is quantified as 0.32 kWh/m^3 or 1.2 PJ/BCM with the corresponding energy of 0.13 PJ. The energy growth rate required for water transmission will be increasing from 2025 by 14% in 2030 and from 2030 by 65% in 2050.

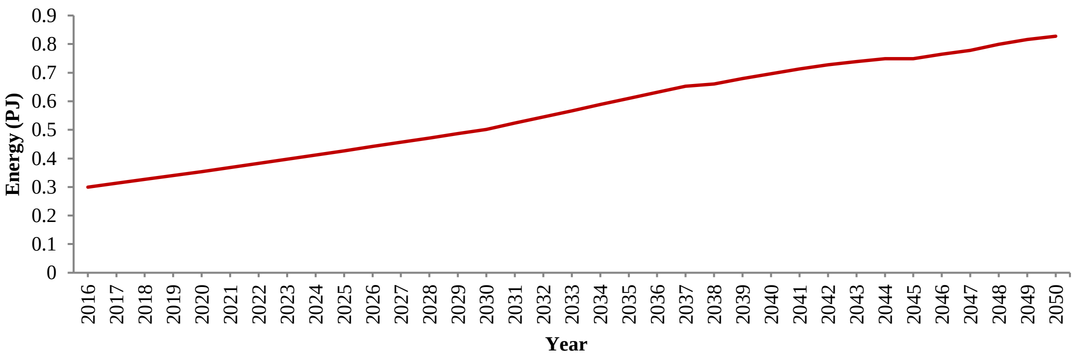

Figure 4. Energy for water transmission based on city water demand.

Energy requirement at different stages within an urban water system may be site specific [37], being influenced by the technologies used for water abstraction, water and wastewater treatment including the level of treatment, transport distance, local orography and efficiency of the system [38]. In Addis Ababa city and its surrounding, the highest share of average energy intensity was attributed to the groundwater extraction (1.2 kWh/m^3) followed by the water transmission (0.32 kWh/m^3) and water distribution system (0.27 kWh/m^3) as most of the water is gravity fed from reservoirs. The energy requirement for lifting groundwater mostly depends on the groundwater elevation, volume, and the efficiency of the pump and energy requirements for various water sectors at a global level are 0.0002 to 1.74 kWh/m^3 for surface water supply and 0.37 to 1.44 kWh/m^3 for groundwater pumping (Wakeel M, 2016). The groundwater extraction value in this study is in the range of global scale that is 1.2 kWh/m^3.

3.3. Energy related to water distribution

The energy requirements for water supply system has remained constant (0.21 kWh/m^3), even though the population and water volume supplied have exhibited steady growth [36]. The energy consumption for water distribution (residential, industrial, and commercial sectors) is comparatively lower energy intensities than those of groundwater extraction, water transmission and wastewater treatment that has highlighted in this study. Energy is required to distribute water to the end-users (residential, industrial and commercial) of Addis Ababa city, therefore to distribute one billion cubic meters of water to residential, commercial and industrial the embodied energy is 0.98 PJ or 0.27 kWh/m^3. The energy for water distribution zone networks was quantified for the 2016 water consumption, considering 2016 energy used as the baseline, the energy desired for water distribution to the end-users based on the city future water demand was quantified as indicated in Figure 5. The future water consumption and demand of the city for residential, commercial and industrial sectors is based on the rapid population and low GDP growth rate scenario. The water-energy nexus for water distribution were indicating; the more water required, the further energy also desired. The water future demands scenarios are analyzed based on the population of 6.8 and 18.8 million in 2030 and 2050 respectively with a growth rate of 5.2% [39].

The energy required in 2030 and 2050 for different end-users (commercial, industrial and residential) is provided in Table 4.

Table 4. Energy demand for the stage of water distribution.

Year	Water demand (BCM)	Energy required (PJ)
	Residential water	Energy
2030	0.28	0.27
2050	0.47	0.46
	Commercial water	Energy
2030	0.07	0.06
2050	0.12	0.11
	Industrial water	Energy
2030	0.06	0.058
2050	0.10	0.10

The analyzed energy (PJ) demand for water distribution in Addis Ababa city is indicated in Figure 5. The result shows the linearly increasing trend of energy demand for water end-users described in this study.

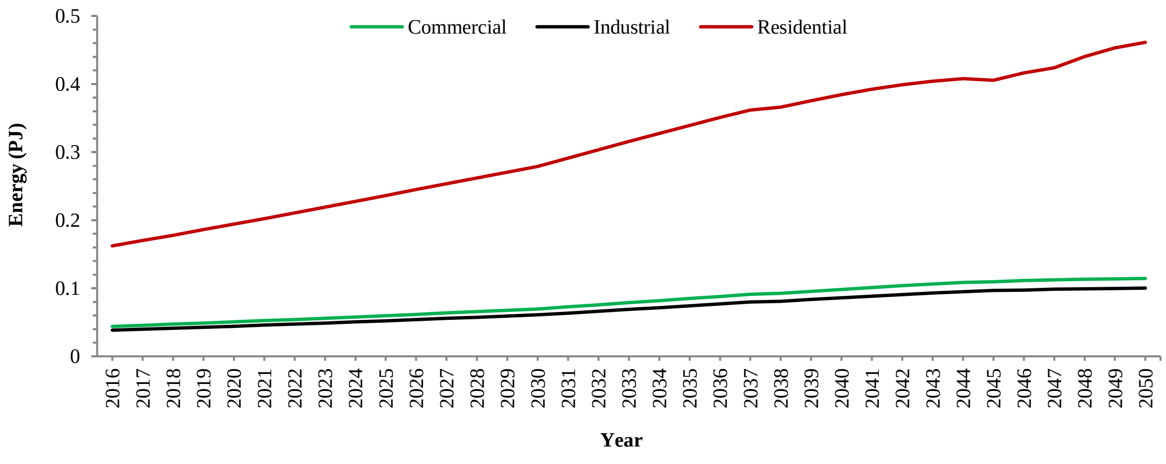

Figure 5. Energy for water distribution to end-users.

The energy required in the residential, commercial and industrial sectors has grown linearly. The residential, industrial and commercial water demand management strategies should be target at energy-intensive end-uses can significantly reduce energy demand.

3.4. Implication of energy related to water treatment system

Energy use for water treatment significantly varies between treatment plants and cities depending on design discharge, level of treatment, the technology used, and scale of treatment plant and source of energy. Energy consumption is expected for water treatment technology that includes air blower, aluminum sulphate mixing and water chlorination, the energy footprint is significantly varied among different water treatment technology. The total energy used for Gefersa water treatment (including air blower, aluminum sulphate, chlorination and mixer treatment technology) is 690000 kWh or 0.003 PJ and Legadadi water treatment (air blower, backwash, chlorination, service water and vacuum pump technology) is 2050000 kWh or 0.007 PJ.

3.5. Energy intensity for wastewater treatment systems

The energy demand for wastewater treatment plants vary substantially, depending on the capacity of the plant and technology requirements for the treatments. The energy and energy intensity for wastewater treatment of was estimated based on the power used for wastewater treatment technology. The total quantified energy and intensity for wastewater treatment is 23.23 GWh and 0.6 kWh/m^3 respectively. Urban wastewater treatment aims to protect the environment from adverse effects of urban wastewater discharges, as well as discharges from certain industrial sectors, most of the participating countries have attempted to maximize their wastewater reuse [40].

The energy intensity of the wastewater treatment appeared to be affected through effluent quality, treatment level and water treatment technology. Wastewater treatment is generally the greatest contributor to energy consumption [41]. In this paper, the energy intensity for wastewater treatment is around 0.6 kWh/m^3 which is within the range of the result of other studies (0.36 to 2.0 kWh/m^3).

4. Conclusion and recommendation

4.1. Conclusion

The aim of the study was investigated to quantify water-energy nexus in the urban water cycle system and to visualize how water and energy interact in the cycle. Data from Addis Ababa Water and Sewerage Authority (AAWSA) and reports are used for estimating the energy intensity. The water-energy nexus, a general term used to detail the interdependence between water and energy was characterized as energy intensity in this paper. Systematic quantification of the water-energy nexus and analysis for urban water systems, including water conveyance or transmission, distribution, groundwater, water treatment and wastewater treatment systems, for Addis Ababa city is conducted. The energy is embedded in every step of the urban water supply process and Addis Ababa water utilities use energy to provide water to customers today. The energy intensity of water supplies for five of the systems is described in prior sections.

This paper further confirmed that investigation of the water-energy nexus should be conducted at a city or regional level to ensure a better understanding of the use of energy for water and water for energy. Energy-intensive sections in urban water systems also optimized based on the water-energy nexus perspective. The energy and energy intensity for water in urban Addis Ababa for water treatment, wastewater treatment, water distribution; groundwater extraction and water transmission was quantified based on available data. The energy was estimated based unit weight of water, flow rate, head and operational time; whereas energy intensity was estimated based on energy and flow rate and the water intensity in the energy system is estimated as a function of water and energy. The energy for water in the transmission network was assessed in terms of its capacity to satisfy the specified consumer demands and its capacity to fully convey available supplies from water sources (well fields and treatment plants). The energy required for water distribution to end-user and transmission was quantified based on city water demand for up to 2050. The energy demand growth rate from 2025-2030 and 2025-2050 for residential will be 18 and 95%, whereas for commercial and industrial water demand distribution it will be 16 and 91% respectively. The energy demand for water distribution and transmission for up to 2030 and 2050 will be linearly increasing. According to the study; from urban water system stage, groundwater extraction and water transmission required energy intensive than water distribution stage.

4.2. Recommendation

The governing equation for the pumping power, energy and energy intensity will use for estimation of water-energy nexus in water cycle system of Addis Ababa City and its surrounding area. The paper was focused on a technology that is operational in urban water cycles, some of the technology are malfunctioned (out of function) according to the data, this causes water scarcity. Therefore, to achieve the availability of water and energy simultaneously it will need new advanced appropriate alternative technology, such as rainwater harvesting, using a photovoltaic solar panel, etc. The underlying the motive for new energy technology; a strong drive comes from ensuring security by extracting resources that will technologically or economically unviable. The new technologies provide innovative applications for WEN. Some of win-win alternative scenarios for attaining both energy and water security will propose, taking new technologies; such as, providing low-flow fixtures, energy-efficient appliances, rainwater collection for non-potable uses. Source substitution such as rainwater harvesting, storm water harvesting, and wastewater recycling used to attain water and energy security. An alternative energy source like as solar reservations is the energy scenarios.

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All authors equally contributed to this paper. All authors revised and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Zakkour PD, Gaterell MR, Griffin P, et al. (2002) Developing a Sustainable Energy Strategy for a Water Utility. Part I: A Review of the UK Legislative Framework. *J Environ Manage* 66: 105–114.
2. UNICEF, Annual Report. 2013.
3. IEA, Emissions from fuel combustion. International Energy Agency. 2012.
4. Cohen R, Nelson B, Wolff G (2004) Energy Down the Drain: The Hidden Costs of California's Water Supply. Natural Resources Defence Council and Pacific Institute. USA.
5. Healy RW, Alley WM, Engle MA, et al. (2015) The water-energy nexus: an earth science perspective. US Geological Survey.
6. Voinov A, Cardwell H (2009) The Energy-Water Nexus: Why Should We Care? *J Contemp Water Res Educ* 143: 17–29.
7. Scott CA, Pierce SA, Pasqualetti MJ, et al. (2011) Policy and Institutional Dimensions of the Water–energy Nexus. *Ener Pol* 39: 6622–6630.
8. Lundie S, Peters GM, Beavis PC (2004) Life cycle assessment for sustainable metropolitan water systems planning. *Environ Sci Technol* 3465–73.
9. Loubet P, Roux P, Loiseau E, et al. (2014) Life cycle assessments of urban water systems: a comparative analysis of selected peer-reviewed literature. *Water Res* 67: 187–202.
10. Kenney DS, Wilkinson R, editors (2011) The water-energy nexus in the American west. Edward Elgar Publishing.
11. Hardy L, Garrido A, Juana L (2012) Evaluation of Spain's water-energy nexus. *Int J Water Resour Dev* 28: 151–70.
12. W. W. Griffiths-Sattenspiel B, 2009.
13. Stillwell AS, King CW, Webber ME, et al. (2011) The energy-water nexus in Texas. *Ecol Soc* 16.
14. Ringler C, Bhaduri A, Lawford R (2013) The nexus across water, energy, land and food (WELF): potential for improved resource use efficiency? *Curr Opin Environ Sustain* 617–624.
15. Wilkinson R K W (2006) An analysis of the energy intensity of water in California: providing a basis for quantification of energy savings from water system improvements. ACEEE Summer Study on Energy Efficiency in Buildings, ACEEE, Pacific Grove, CA, 123–33.
16. Kenway SJ, Priestley A, Cook S, et al. (2008) Energy use in the provision and consumption of urban water in Australia and New Zealand. Water for a Healthy Country Flagship: CSIRO.
17. King CW, Duncan IJ, Webber M (2008) Water Demand Projections for Power Generation in Texas.
18. Siddiqi A, Anadon LD. The Water–Energy Nexus In Middle East And North Africa. *Ener Pol* 39: 4529–4540.
19. Pan SY, Haddad AZ, Kumar A, et al. (2020) Brackish water desalination using reverse osmosis and capacitive. *Water Res* 183: 1-23.
20. Kumar A, Pan SY (2020) Opportunities and Challenges for Renewable Energy Integrated Water-Energy. Water-Energy Nexus.

21. Tsai SW, Hackl L, Kumar A, et al. (2021) Exploring the electrosorption selectivity of nitrate over chloride in capacitive deionization (CDI) and membrane capacitive deionization (MCDI). *Desalination* 497: 1-11.
22. Chiu YR, Liaw CH, Chen LC (2009) Optimizing Rainwater Harvesting Systems as an Innovative Approach to saving energy in Hilly Communities. *Renew Energ* 34: 492–498.
23. Retamal ML, Abeysuriya K, Turner AJ, et al. (2008) The Water energy Nexus: Literature Review. [Prepared For CSIRO]. Sydney: Institute For Sustainable Futures, University Of Technology "The Water energy Nexus: Literature Review". [Prepared For CSIRO]. Sydney: Institute For Sustainable Futures, University .
24. Copeland C, Carter NT (2017) Energy-Water Nexus: The Water Sector's Energy Use. Congressional Research Service.
25. Wakeel M, Chen B, Hayat T, et al. (2016) Energy consumption for water use cycles in different countries: a review. *Appl Energy* 178: 868–85.
26. CEC. (2005) Comparison of Alternate Cooling Technologies for California Power Plants: Economic, Environmental and Other Tradeoffs" California, USA: California Energy Commission.
27. Yoon H (2018) A Review on Water-Energy Nexus and Directions. Documents d'Anàlisi Geográfica, 64: 365-395.
28. Goldstein R, Smith WE (2002) Water & Sustainability (Volume 4): US Electricity Consumption for Water Supply & Treatment – The Next Half Century". Palo Alto, California, USA.
29. Cohen R, Nelson B, Wolff G (2004) Energy Down the Drain-The Hidden Costs of California's Water Supply. Oakland, California: Natural Resources Defense Council, Pacific Institute.
30. Hernández-Sancho F, Molinos-Senante M, Sala-Garrido R (2011) Energy Efficiency in Spanish Wastewater Treatment Plants: A Non-Radial DEA Approach. *Sci Total Environ* 409: 2693–2699.
31. Lam KL, Kenway SJ, Lant PA (2017) Energy use for water provision in cities. *J Clean Prod* 143: 699–709.
32. Hancock NT, Black ND, Cath TY (2012) A Comparative Life Cycle Assessment of Hybrid Osmotic Dilution Desalination and Established Seawater Desalination and Wastewater Reclamation Processes. *Water Res* 46: 1145–1154.
33. Dai J, Wu S, Han G, Weinberg J, et al. (2018) Water-energy nexus: A review of methods and tools for macro-assessment. applied energy, 15: 393–408.
34. Spang ES, Loge FJ (2015) A high-resolution approach to mapping energy flows through water infrastructure systems. *J Ind Ecol* 19: 656–65.
35. Cohen R, Nelson B, Wolff G (2004) Energy down the drain: the hidden costs of California's water supply. Cousins, Emily, Natural Resources Defense Council, Oakland,. Researchgate,applied energy.
36. Kenwa y, S. P (2008) Energy Use in the Provision and Consumption of Urban Water in Australia and New Zealand. Water Services Association of Australia. Canberra: CSIRO.
37. Mo W, Wang R, Zimmerman JB (2014) Energy-water nexus analysis of enhanced water supply scenarios: a regional comparison of Tampa Bay Florida, and San Diego, California. *Environ Sci Technol* 48: 5883–91.

38. Lemos D, Dias AC, Gabarrell X, et al. (2013) Environmental assessment of an urban water system. *J Clean Prod* 54: 157–65.
39. MUDHCo (2015) National Report on Housing and Sustainable Urban Development. Federal Democratic Republic of Ethiopia.
40. EEA (2013) Urban waste water treatment. European Environment Agency, Denmark.
41. Racoviceanu AI, Karney BW, Kennedy CA, et al. (2007) Life-cyle energy use and greenhouse gas emissions inventory for water treatment systems. *J Infrastruct Syst* 13: 261–70.