# POLITECNICO DI MILANO

## School of Civil, Environmental and Land Management Engineering

## Master of Science in Environmental and Land Planning Engineering

**WATER FOOTPRINT OF KENYA'S ELECTRICITY SYSTEM FROM 2016 TO 2021**

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**Academic Year 2020/2021**

# Acknowledgements

First, I would like to acknowledge both my very able supervisors, Professor Maria Cristina Rulli and Dr. Andrea Cominola for their unwavering tutelage and support throughout all the stages of this research. Second, I would like to convey my sincere gratitude to the Italian Agency for Development and Cooperation – Partnership for Knowledge program and Ide3a - DAAD program for their steadfast financial support towards the accomplishment of this work. Last but not least, I would like to acknowledge Kenya Power for their important contribution in the provision of the base data useful in accomplishment of the objectives of this research.

# Abstract

Harnessing of natural resources around the world is dependent on the existence of other natural resources. The interdependence between the world's natural resources warrants the need to view them and if possible manage them not in isolation but as an interconnected system to be able to effectively steer away from problems caused by their poor management. Specifically, the interlinkages between energy resources (electricity) and water resources has led to interests and research by scientists around the world leading to the formulation of the term *electricity-water nexus*. Kenya is a country facing water scarcity with half of its population lacking adequate access to safe and sufficient water for domestic use. Despite this, Kenya has not benefited from studies related to *electricity-water nexus* which are geared towards understanding and improving the management of water resources. The focus of this study is therefore to analyze the water use in Kenya's entire electricity system in order to provide a starting point for water use optimization in the sector and to try and inform the government of Kenya's plan to increase its renewable portion of electricity consumption to 80% of the total electricity generated in the country by 2030.

This is achieved in this study by first analyzing the status quo of Kenya's electricity system yearly from 2016 to 2020 with the aim of establishing the quantity of electricity consumed within the borders of Kenya. Secondly, the estimation of water use due to the electricity consumed in Kenya is undertaken. This is accomplished with the application of the water footprint concept which is an indicator of amount of freshwater consumed by a unit amount of a product or service. Electricity in Kenya is the product of focus in this study and its water footprint is estimated in units $m^3$/MWh or $m^3$/GWh in a specified amount of time say year. Next is the estimation of the amount of electricity related virtual water flow between Kenya and its neighboring countries with the application of the water footprint concept once again. The aim of this step is to identify the main protagonists in terms of electricity exchanges among the neighboring countries of Kenya and to try and get an idea of how much environmental impact Kenya is having on its neighbors and vice versa.

The annual electricity consumption changes seen from the year 2016 to 2020 in Kenya shows an overall increase of approximately 16% with an individual change of +5843% for solar sources, +2259% for wind sources, +13% for geothermal sources, +8% for hydropower sources, -48% percent for thermal sources and -78% for biomass sources. The corresponding trend of water footprint of electricity in Kenya displays a huge oscillation but with a slight decline in its overall value from 39 $m^3$/MWh (392 MCM) in the year 2016 to 37 $m^3$/MWh (426 MCM) in 2020. This is a -7% change in the water footprint and a +9% change in overall annual water use. Looking at the 2030 energy projections, Kenya's electricity generation is projected to grow by about 42% from with a 95% confidence interval. The corresponding trend of water footprint and overall annual water use of electricity consumption respectively is estimated to reduce by 30% and 46%. This reduction is due to the ambitious plan by the government to shift the energy mix to 80% renewable energy by 2030.

This research proposes the need to carb the dominance of hydroelectricity and to promote other non-hydro renewable sources of electricity due to their apparent benefit of minimal pressure on water resources. This study also demonstrates how the patterns of electricity flows and the corresponding virtual water flow between Kenya and its neighboring countries and underpins the dominance of exchanges between Kenya and Uganda as compared to other countries in all the study periods. It therefore proposes the development of an electricity exchange framework that will give a better-informed direction towards better and informed future exchanges with water needs of both countries at the center of considerations. Some of the proposed future developments anticipated for this research include establishment of more precise water intensity factors for all electricity generation plants in Kenya, inclusion of river based hydroelectric plants future water footprint calculation, incorporation of energy losses during electricity transmission phase to water footprint calculations, inclusion of green and grey water footprints and the undertaking of an optimization problem exercise to establish the ideal mix that will give the best water footprint results for the electricity system in Kenya.

# Sommario

Lo sfruttamento delle risorse naturali nel mondo dipende dall'esistenza di altre risorse naturali. L'interdipendenza tra le risorse naturali del mondo giustifica la necessità di considerarle e, se possibile, gestirle non in modo isolato, ma come un sistema interconnesso per poter evitare efficacemente i problemi causati dalla loro cattiva gestione. In particolare, l'interconnessione tra le risorse energetiche (elettricità) e le risorse idriche ha suscitato l'interesse e la ricerca di scienziati di tutto il mondo, portando alla formulazione del termine "nesso elettricità-acqua". Il Kenia è un Paese che deve far fronte alla scarsità d'acqua e metà della sua popolazione non ha accesso ad acqua sicura e sufficiente per uso domestico. Nonostante ciò, il Kenia non ha beneficiato di studi relativi al nesso elettricità-acqua che sono orientati alla comprensione e al miglioramento della gestione delle risorse idriche. L'obiettivo di questo studio è quindi quello di analizzare l'uso dell'acqua nell'intero sistema elettrico del Kenia per fornire un punto di partenza per l'ottimizzazione dell'uso dell'acqua nel settore e per cercare di informare il piano del governo del Kenia di aumentare la quota rinnovabile del consumo di elettricità all'80% dell'elettricità totale generata nel Paese entro il 2030.

Per raggiungere questo obiettivo, il presente studio analizza innanzitutto lo status quo del sistema elettrico del Kenia dal 2016 al 2020, con l'obiettivo di stabilire la quantità di elettricità consumata all'interno dei confini del Kenia. In secondo luogo, viene effettuata una stima dell'utilizzo di acqua dovuto all'elettricità consumata in Kenia. Ciò è possibile applicando il concetto di impronta idrica, che è un indicatore della quantità di acqua dolce consumata da un'unità di prodotto o servizio. L'elettricità in Kenia è il prodotto oggetto di questo studio e la sua impronta idrica è stimata in unità di m3/MWh o m3/GWh in un determinato periodo di tempo, ad esempio un anno. Successivamente si procede alla stima della quantità di flusso di acqua virtuale legata all'elettricità tra il Kenia e i Paesi limitrofi, applicando ancora una volta il concetto di impronta idrica. L'obiettivo di questa fase è identificare i principali protagonisti in termini di scambi di elettricità tra i Paesi limitrofi del Kenia e cercare di farsi un'idea dell'impatto ambientale che il Kenia ha sui suoi vicini e viceversa.

Le variazioni annuali del consumo di energia elettrica osservate dal 2016 al 2020 in Kenia mostrano un aumento complessivo di circa il 16% con una variazione individuale di +5843% per le fonti solari, +2259% per le fonti eoliche, +13% per le fonti geotermiche, +8% per le fonti idroelettriche, -48% per le fonti termiche e -78% per le fonti di biomassa. La corrispondente tendenza dell'impronta idrica dell'elettricità in Kenia mostra un'enorme oscillazione, ma con un leggero calo del suo valore complessivo da 39 m3/MWh (392 MCM) nel 2016 a 37 m3/MWh (426 MCM) nel 2020. Si tratta di una variazione del -7% nell'impronta idrica e di una variazione del +9% nell'uso annuale complessivo di acqua. Se si considerano le proiezioni energetiche per il 2030, si prevede che la produzione di elettricità in Kenia crescerà di circa il 42%, con un intervallo di confidenza del 95%. La tendenza corrispondente dell'impronta idrica e dell'uso complessivo annuo di acqua del consumo di elettricità è stimata ridursi rispettivamente del 30% e del 46%. Questa riduzione è dovuta all'ambizioso piano del governo di spostare il mix energetico all'80% di energie rinnovabili entro il 2030.

Questa ricerca propone la necessità di ridurre il predominio dell'energia idroelettrica e di promuovere altre fonti rinnovabili non idroelettriche per il loro evidente vantaggio di ridurre al minimo la pressione sulle risorse idriche. Questo studio dimostra anche come i modelli dei flussi di elettricità e i corrispondenti flussi di acqua virtuale tra il Kenia e i Paesi limitrofi siano alla base della predominanza degli scambi tra Kenia e Uganda rispetto agli altri Paesi in tutti i periodi di studio. Si propone quindi lo sviluppo di un quadro di riferimento per gli scambi di energia elettrica che dia una direzione più informata verso scambi futuri migliori e consapevoli, con le esigenze idriche di entrambi i Paesi al centro delle considerazioni. Alcuni degli sviluppi futuri previsti per questa ricerca includono la definizione di fattori di intensità idrica più precisi per tutti gli impianti di produzione di energia elettrica in Kenia, l'inclusione nel calcolo dell'impronta idrica futura degli impianti idroelettrici fluviali, l'inclusione delle perdite di energia durante la fase di trasmissione dell'energia elettrica nel calcolo dell'impronta idrica, l'inclusione dell'impronta idrica verde e grigia e l'avvio di un esercizio di ottimizzazione per stabilire il mix ideale che darà i migliori risultati di impronta idrica per il sistema elettrico in Kenia.

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WF – Water Footprint

WIF – Water Intensity Factor

GDP – Gross Domestic Product

SAGAs - Semi-Autonomous Agencies

IPPs – Independent Power Producers

KenGen – Kenya Electricity Generating Company

GHG – Greenhouse Gases

MCM – Million Cubic Meters

# Chapter 1: Introduction

## 1.1 Background

Harnessing of natural resources around the world is only possible with the existence of other natural resources. The interdependence between energy and water resources has led to the formulation of the term *energy-water nexus* which has been subject to research by scientists around the world (Hussey & Pittock, 2012). For instance, some of the energy related activities that require water include electricity generation and distribution, coal processes, oil processes, natural gas processes, among others. The water sector on the other hand requires energy in activities for handling both portable and non-portable water such as water treatment, pumping, heating, distribution, treatment of waste water and desalination of brackish water (Stillwell et al., 2011). The clear interdependence between the world's natural resources like the one seen between energy and water warrants the need to view them and if possible manage them not in isolation but as an interconnected system to be able to effectively steer away from problems caused by poor management of natural resources.

## 1.2 Problem statement

Kenya is one of the countries currently facing water scarcity with approximately half of its population experiencing lack of adequate and safe supply of water for their domestic use (Mulwa et al., 2021). Better management of water resources can help in improving this situation. This can be realized through the establishment of a better qualitative and quantitative understanding of the interdependence between water and energy which will help in the formulation and implementation of policies and institutions that manage both resources jointly (Newell et al., 2011). On a positive note, the government of Kenya is also looking to increase its renewable portion of electricity consumption to 80% of the total electricity generated in the country by 2030 (Ministry of Energy and Petroleum & Sustainable Energy for All, 2015). Despite this intended positive change, no study has been done to quantify the WF of electricity consumption and to provide an insight of electricity sources that would put minimal pressure on water resources.

The focus of this research is to study the *electricity-water nexus* with the aim of determining the water footprint of Kenya's entire electricity system. The water footprint of electricity varies depending on the technology used in the cooling step of the process of electricity generation (Myhre, 2002), the methods chosen for electricity generation and the location on the globe where the electricity is generated (Li et al., 2011; Liu et al., 2015; Siddiqi & Anadon, 2011; Stillwell et al., 2011). The Gross Domestic Product (GDP) has shown a parallel with the amount of electricity used within a country or region during a specific period. Developed and fast developing countries or regions of the world have depicted high rates electrification coinciding with their growth and economic prosperity (Stern et al., 2017). Increased growth of electricity generation and consumption due to continued development necessitates spatially extensive research to clearly understand and establish dependence of electricity on water resources and in the process ensuring no region or country is left behind in the quest for sustainability.

## 1.3 Main objective

Several studies around the globe have been carried out to establish the interdependence of water and electricity. Most studies of this kind have however been carried out in China, India, Europe and North America. Most of these studies found that generation of electricity can involve substantial amounts of water usage. A study for the state of Texas (USA) for instance found that the annual amount of water required in the generation of electricity in the state was about 595,000 megaliters which is an amount equivalent to annual water needs of about 3 million people (Stillwell et al., 2011). Despite being a country facing water scarcity with half of the population lacking adequate access to safe and sufficient water for domestic use (Mulwa et al., 2021), Kenya has not benefited from studies related to *electricity-water nexus* which are geared towards understanding and improving the management of water resources. This research therefore looks to fill this gap by studying the water footprint of Kenya's electricity system in order to identify what can be done by relevant institutions mandated with the planning, operation and development of the electricity system to optimize water use in the sector. This is going to further inform the plan by the government of Kenya to increase its renewable portion of electricity consumption to 80% of the total electricity generated in the country by 2030 (Ministry of Energy and Petroleum & Sustainable Energy for All, 2015).

The amount of water needed to run the electricity system in Kenya is estimated in this study using the water footprint concept which is an indicator of the volume of freshwater that a product or service consumes and pollutes during the entirety of its life, that is, from cradle to grave. The total water footprint of a product or service is equivalent to the amount of freshwater (grey, blue or green) consumed by a unit amount of that product or service. Blue water refers to the volume of fresh water consumed from surface water bodies such as rivers and groundwater sources such as aquifers. Green water refers to the volume of freshwater consumption from rain water precipitated on the earth's surface less runoff water. Grey water refers to the volume of freshwater needed for purposes of removal of pollutants and contaminants of processes ingrained in the life of the product or service (Hoekstra et al., 2011). In this study, electricity in Kenya is the product of focus. Only the blue water footprint component of Kenya's electricity system is studied in this research based on the fact that data required to study the green and grey water footprint of Kenya's electricity system needs longer time frames of data collection in the study area which is beyond the scope of this research.

## 1.4 Scope of study

The geographical scope of this research is Kenya which has a relatively growing energy sector. For instance, Kenya tops the African charts in the amount of installed capacity and generation of geothermal electricity and is ranked 9th in the world charts as of 2018 (Mangi, 2018). When it comes to the rate of growth of geothermal electricity consumption, Kenya is among the fastest in the world in 2019 (Omenda et al., 2020). According to recent investigations, Kenya has the potential of harnessing between 5000 Megawatts electric (MWe) to 10000 MWe (Simiyu, 2015).

In terms of the temporal scope of this research, the availability and comprehensiveness of data for the satisfaction of the objectives of this research was instrumental. Data from 2016 to 2020 determined the temporal scope of this research which is between January 2016 to December 2020.

## 1.5 Structure of the thesis

The remainder of this thesis consists of six chapters. Chapter two of this paper focuses on the literature review of studies focused on water footprint of electricity consumption around the world. It eventually narrows down to what the status quo is in the country of interest and what gaps are there to be filled potentially by this research. Chapter three describes the case study and identifies and highlights information which are of great relevance to the success of this research. There is for example a look at the water intensity factors (WIFs) which have been employed around the globe to determine the water footprint (WF) of electricity consumption among different sources. This is essential to the estimation of the WIFs that are used in this project. Chapter four describes the specific methods and steps that were taken to achieve the objectives of this research. Chapter five highlights the core data useful for this study. The products of chapter four are displayed in detail in chapter six which are the results of this study. The discussion of the results is also done in depth in the same chapter. This paves way for chapter seven which summarizes the conclusions and opportunities for future development based on the results and discussions of this study.

# Chapter 2: Literature review

In the beginning of this chapter, definition of WF terms and introduction to cooling technologies is given to allow all readers to have a full understanding and comprehension of this research. This is followed by an in-depth review of the literature that helps build into all the aspects of this research. Focus is drawn into electricity WF studies that have been carried out in different regions starting from a worldwide view, followed by Africa and eventually scaling it down to studies related to this aspect that have been carried out in Kenya up to this point. A synthesis paragraph is given at the end of this chapter where all the literature reviewed is synthesized and the gap that this research is trying to fill is highlighted.

## 2.1 The water footprint concept and terminology

The water footprint concept comes in handy in quantifying and optimizing the human influence on fresh water resources. It helps provide a basis that informs policy development by decision makers and all stakeholders within the water resources sector. Given below are the definition of terms used around the WF concept mainly adopted from works of Hoekstra and colleagues (International Organization for Standardization, 2014)

**a) Water footprint**

Water footprint is defined as the volume of freshwater that a product requires during the entire length of its life that is from cradle to grave as used in Life Cycle Assessment.

**b) Blue water**

Defined as the volume of fresh water consumed from surface water bodies such as rivers and groundwater sources such as aquifers.

**c) Green water**

This is defined as fresh water consumption from rain water precipitated on the earth's surface minus runoff rainwater.

**d) Grey water**

This is defined as the volume of fresh water needed for purposes of removal of pollutants and contaminants of processes involved in the product's life.

**e) Water use**

use of water by human activity. This includes water withdrawals, water releases, or any other human activities within a drainage basin.

**f) Water withdrawal**

Water withdrawal is the water removed from its natural setting but returned back after use regardless of the difference in quality.

**g) Water consumption**

Water consumption is defined as the water removed from its natural setting but not returned back to it due to inculcation into the product, evaporation loss and loss to watersheds other than the original or loss to the seas and oceans.

**h) Freshwater degradative use**

This is water removal from its natural setting and returned back to it but in a lower or higher quality than before abstraction (Bayart et al., 2010).

**i) Water scarcity**

A situation whereby the water replenishment in an area compares to its water demand without considering the water quality.

**j) Water availability**

A situation whereby the human population and other living organisms in an ecosystem have adequate access to water for their needs. Quality of the water are factors that influence availability.

**k) Fresh water**

This is our planet's portion of water which has low concentration of dissolved solids. It specifically excludes sea water and brackish waters of our planet.

## 2.2 Thermal electricity production

Thermal electricity consumption dominates other sources of electricity in the world. 75% of the total electricity generated in the world comes from thermal sources (BP, 2018). Consequently, it is leading the pack compared to other source in terms of water use (IEA, 2018). Thermal electricity consumes a lot of water because water is needed in several steps in the generation process. Water is necessary in the conversion of heat energy into electrical energy through steam turbines and in cooling and handling the ash which is a product of the generation process. One of the main water intensive steps of a thermal electricity generating plant is cooling. There are four different types of cooling systems that have different configurations and most importantly different water intensities because of their working principle. Due to the inevitable encounters of the different thermal electricity cooling technologies in this research, it is worth giving the reader an in-depth description of the various cooling technologies available for thermal electricity generation. The four types of cooling technologies used around the world in thermal electricity generating plants are open loop cooling system, closed loop cooling system, dry air-cooling system and hybrid cooling systems (GAO, 2009).

**a) Open loop cooling system**

This is the type of cooling system whereby a huge volume of water is withdrawn from the source, used to condense the steam by passing it through the system's heat exchangers and then released back into the water body which is in most cases rivers. This kind of cooling system requires steady and high-volume supply of water which makes it very vulnerable to water resources competition, high temperature seasons and droughts. Therefore, it is not suitable for drought prone areas (Yang & Yamazaki, 2013). The water released from this kind of system is always in very high temperatures which is detrimental to fish species and other living organisms in the water body involved (Henderson et al., 2011). Open loop cooling system leans more towards the concept of water withdrawal than water consumption.

**b) Closed loop cooling system**

Also known as wet cooling system, this type of cooling system defers from the open loop cooling system in the fact that it consists of a cooling tower where water from the condenser is sent to for cooling before being recycled back to the condenser thus the name closed loop as the same water is circulated around the system with periodic addition to replace the water lost through evaporation. More water is consumed through evaporation in the cooling towers and in the overall system compared to open loop cooling. The positive side of this system is that it doesn't require massive volume of water per unit time and therefore it can be located in dry areas. Nevertheless, this system is still water intensive in terms of water consumption (Yang & Yamazaki, 2013).

**c) Dry air-cooling system**

This cooling system is almost the same compared to the closed loop cooling system but the only difference is that air is used instead of water. It is therefore less water intensive than the two cooling systems above which makes this system very promising in the quest to reduce the amount of water used in thermal electricity generation. The only downside to this system is its low efficiencies due to the Carnot cycle principle that make air less efficient in cooling compared to water. Substantial capital costs (180$/kW) (EPRI, 2007) and power requirements are therefore needed to supply the substantial volumes of air required, making it expensive. Atmospheric whether conditions such as humidity and temperature affect the efficiency of this kind of system (Yang & Yamazaki, 2013).

**d) Hybrid cooling system**

The hybrid cooling system combines components of both the dry system and the wet systems in order to take advantage of the benefits of the two systems and to cut on the demerits of both systems. This makes the hybrid system the most suitable cooling system to be implemented in thermal electricity generation plants due to its overall lower costs, less amounts of water required (up to 80% lower than wet systems) and less power requirements (EPRI, 2007).

## 2.3 Electricity water footprint studies

### 2.3.1 Outside Africa

Several studies related to the topic of water-energy nexus have been carried out around the world. A few factors were taken into consideration in selecting works to review outside Africa. One factor was the stature of the country in terms of economic development and its rank in electricity generation and consumption. Another one was places where extensive research of this kind has been conducted. The population size of the country which sometimes translates to the amount of power generation in the country was also a determining factor. Last but not least was the geographical location of the region or country for purposes of regional balance and comprehensiveness. As a result of these factors, studies from United States of America, China, India, Brazil and the European Union were reviewed.

At the beginning of the last decade, a study done to establish the interdependence between water and electricity generation was undertaken by Stillwell et al. (2011) for Texas (USA). This study found that there is a very deep relationship between the two critical components of our societies. In this study, the amount of water required in the generation of electricity in the state of Texas per year was estimated to be about 595,000 megaliters which is an amount equivalent to annual water needs of about 3 million people. In the same way, the amount of annual electricity required for water and wastewater facilities was estimated to be between 3.9 to 4.7 terawatt-hours equivalent to electricity needs of about 100,000 people per year. This study argued that more in depth studies needed to be done to establish a more comprehensive picture of this relationship between electricity and water which will be achieved through more concerted efforts to collect and avail more specific data on plant processes level. They also gave a recommendation of the improvement of efficiencies of water and energy related processes in order to minimize the overdependence of both resources.

About five years later, another similar study was conducted by DeNooyer et al. (2016) in the state of Illinois (USA). According to the same study, as of 2016, 90% of the total electricity generated in the USA was sourced from thermal based generation plants mainly run using coal as fuel. Based on this fact, the study sought to establish the effect of two possible changes in the process elements of thermal electricity generation to the quantity of water required in the generation process. That is changing the type of fuel used for generation from coal to natural gas and changing the type of cooling technology from open-loop to closed loop. The aim was to establish results for Illinois and then replicating the findings to the entire country. This study found that the amount of water that will be saved in the shift of fuel was 0.10 billion m3/yr (-32%) while there was a tradeoff between water withdrawal and consumption in the shift of the type of cooling technology. The shift of the type of cooling technology was projected to result in a water withdrawal savings of about 21 billion m3/yr (-96%) and a water consumption increase by about 0.18 billion m3/yr (+58%).

Another research done at the turn of the last decade was one by Lee et al. (2018). The main objective was to estimate the water intensity factors of thermal and hydro sources of electricity which are the two major sources in the US led by thermal as we have seen above. The findings of this research showed a major variation of water intensity factors for hydro sources of electricity from region to region in United States. The ranges of the water intensity factors for thermal and hydro sources was found to be from 0.18 L/kWh to 2.0 L/kWh and from 0.67 L/kWh to 1194 L/kWh respectively. A weighted average WIF for the 2015 electricity mix in the US was found to be about 2.18 L/kWh.

Towards the end of the last decade, another study regarding the thermal pollution component of grey WF of thermal electricity generation was conducted by Chini et al. (2020). This was done in order to provide valuable seasonal, spatial and quantitative information regarding the effects of thermal electricity generation in the US. Availability of this information was also expected to help in the improvement of aquatic life and the general suitability of thermal electricity generation return flow to human use downstream of thermal power plants. This research established that the grey WF of thermal electricity generation occurred more during winter and summer seasons than during spring and fall seasons of the year in the US. Regarding the spatial distribution of the grey WF of thermal electricity generation in the US, it was found that the eastern regions of the country where open-loop cooling are more prevalent displayed more grey WF than other parts of the country. Comparing the temporal changes in the grey WF of thermal electricity generation within the period of study of this research (2011-2016), it was estimated that 18% increase occurred. That is from 347 km3 in 2011 to 505 km3 in 2016.

China is well known for its rapid growth into a first world country from its initial third world status within a timeframe of less than half a century. This has meant enormous growth of water intensive energy generating processes to accommodate the ever-rising demand of energy in the country. There have been WF studies related to the energy sector in China especially in the thermoelectricity sector. 80% of China's total electricity generations comes from thermoelectric sources (Zhang & Anadon, 2013). One such study sought to estimate the amount of water use as a result of consumption of thermal electricity in China for the year 2016 and projected quantities for the year 2050 (Liao et al., 2016). It also purposed to narrow down to the individual stages of thermal electricity production and try to understand which phase contributes the most to the total WF of thermal electricity generation in China. This research found that the amount of water consumption in the year 2016 was 4.64 billion cubic meters and the projected amount in 2050 if the business as usual scenario is followed is 15 billion cubic meters. In terms of water withdrawal, this research estimated that the quantity for 2016 to be 62.2 billion cubic meters and the projected value for 2050 to be 280 billion cubic meters.

This research also found that the type of cooling technology for thermoelectric generation power plants dictates water use in the generation process and that different cooling technologies are suitable for different regions due to variations of the availability of water in different regions of the country. The authors argue that the choice of any of the available cooling technologies has both advantages and disadvantages where tradeoffs must be struck in terms of water withdrawal, water consumption and other factors like carbon footprint of the technology. The research proposed rapid changes in terms of efficiency in the production phases of thermal energy production and changes to more renewable options in China's electricity mix as the solutions to current and projected future high-level water use in China's thermal electricity generation and the overall electricity system.

More recently, a WF study was conducted by Xie et al. (2020). This was a more comprehensive study of the entire electricity system in China. The study's aim was to estimate average WF of electricity both nationally and regionally. The study concluded that the national WF of China's electricity system as of 2020 was an average of 4.70L/kWh. In regional terms the WF of electricity consumption varied from region to region ranging from 7.174L/kWh in the east part of China to 0.084 L/kWh in the west. In terms of the individual sources of electricity, the thermal source of electricity was the most significant contributor with a WF of 6.33 L/kWh. The recommendation of this study for improvement of the WF of China's electricity system is the redesign of nationwide electricity mix to favor the dominance of renewable sources at the expense of thermal sources which were found to be the most prevalent.

According to Vandecasteele et al. (2016) 55% of fresh water withdrawn in the European Union (EU) goes to the electricity system. This leaves only 45% of the withdrawn water for other uses which shows the intensity of dependence of the electricity system on water resources of the region. Many studies have been conducted to establish the true picture of the water-energy nexus of the EU. One such study is the one undertaken by Lohrmann et al. (2021). The objective of this study was first to establish the picture in terms of WF of the electricity sector in the EU in 2021 and then using that as a basepoint of comparison with the results of future projections under two different scenarios and one developmental change in EU's electricity system. The two scenarios were, the change of the European electricity mix to 100% renewable sources and the elimination of fossil fuels in thermal electricity generation. The developmental change in the EU's electricity system was the introduction of high voltage electricity transmission between countries in the region. This research established positive outcomes in terms of WF in all the case studies. In the scenario of 100% shift to renewable energy by 2050, a reduction of 28.3% in WF was established while the scenario of the elimination of fossil fuels in thermal electricity generation was estimated to yield a reduction of 1.6% by 2050. The introduction of high voltage electricity transmission was projected to ensure a reduction of water use of about 18.09 km3 from 2015 to 2050.

Another recent study by Roidt et al. (2020) conducted an analysis of the WF of thermal electricity consumption in five countries in Europe. It sought to analyze the impact that the recent COVID-19 pandemic has had on the trend of thermal electricity demand and the associated water burden including changes in the virtual water trade among the selected countries during this period. This study found that the electricity and water relationship is sensitive to short term behavioral and technological changes and provided particular insight and knowledge important for management of future changes in the WF of thermal electricity consumption caused by short term drivers like pandemics similar to the recent devastating pandemic.

India is the second most populous country in the world with a population of 1.38 billion people (World Bank, 2020). India ranks third in the world behind China and USA in terms of the amount of electricity consumption per year with 1229.4 Terawatt-hours (TWh) (Alves, 2022). Among the many studies that have been done about India's electricity sector, one study of interest to this research is one done by Srinivasan et al. (2018). This study was conducted in order to explore the electricity use in the country from 2010 up to the year 2050 coupled with an in depth look at the potential implications of its uses in terms of water use and greenhouse gas emission. The team conducted this research with the application of five different modeling groups using different modelling techniques and assumptions in the analysis of the same system. This was done in order to test the robustness of the results of the study. All the groups narrowed their studies to two potential scenarios in the development of the electricity sector in India. The first was the baseline scenario where the electricity system was developed without efforts to minimize GHG emissions while the second scenario was one in which efforts to minimize GHG emissions was incorporated into the development of the electricity sector.

In comparing between the two scenarios studied, the results of the research showed a 10% difference in the amount of electricity generated in the year 2050. The first scenario gave a projection of a rise from 932 TWh in 2010 to an average of 9000 TWh in 2050 while second scenario gave a projection of a rise from 932 TWh in 2010 to an average of 7920 TWh in 2050. The research indicated that the implementation of GHG emission minimization strategies will help in the overall water reduction of the entire electricity system in India. The study also found that further minimization of water use in India's electricity sector going into 2050 will depend on electricity source-specific alteration. Reduction of water withdrawal will occur if cooling technologies in thermal electricity generation are changed from open-loop to closed-loop cooling systems although this will increase water consumption. To reduce both water consumption and withdrawal the study recommends the switch to dry cooling technologies combined with changes in the energy mix of the system to less water intensive renewable sources of electricity such as wind and solar. This research indicates clearly the fact that better studies in terms of electricity water relationship of India's electricity system can be achieved with availability of more specific water intensity factors for various electricity sources in India. It goes ahead to state that future research of this kind can obtain better results by conducting region specific studies that consider the specific water availability or lack thereof in the different regions of India.

Another study related to water-energy nexus conducted in South America was one done by Coelho et al. (2017) in Brazil. This study sought to expound the knowledge of water use in electricity derived from hydro sources of electricity. This research focused on two reservoirs of hydropower plants in Brazil namely, Tucurui and Lajeado. The aim was to give a clear understanding of the results obtained from three different WF methods applied by different researchers to ascertain the WF of hydropower plants. The difference between the hydroelectricity WF analysis methods was the consideration of evaporation in the area covered by the reservoir before the construction of the dam was done. To explain further, method one incorporated past evaporation from the current dam site before the dam was built without considering difference in evaporation rates between the current and the previous land due to changes in land uses and land cover. The second method incorporated both evaporation from the land before the dam was built and the changes in evaporation between previous and current land. The third method did not incorporate any of the considerations in method one and two. The results showed different WF results in all the methods with the researches recommending method two as the best way to use since it gives a more accurate estimation of WF of hydropower generation.

### 2.3.2 Africa

In comparison to other regions of the world comprising of mainly developed and a few developing regions, not much has been done in Africa in terms of studies on the topic of WF of electricity systems and the water-energy nexus. Most studies conducted in the continent are the WF of other products mostly from agricultural and mining sectors. This research therefore takes a brief look at the only two studies that were retrieved about electricity systems in Africa.

South Africa is one of the leading countries in Africa in terms of economic development. One study related to the water-energy nexus conducted in South Africa was by Thopil & Pouris (2016). The objective of this study was to project the electricity consumption for a period of 20 years in anticipation of diminishing water resources in the country. According to the same study, approximately 90% of electricity generated in South Africa is thermal electricity sourced from coal generation thermal electricity plants. This power plants are based in regions facing water scarcity in the country and utilize both water-based and dry cooling technologies in their generation processes. The results of the study showed that there was an existence of old and water intensive thermal generation power plants which were brought back to life when the country experienced power shortages. It estimated that the coal based thermal electricity generation system in South Africa had a water use amount of 360 gigalitres in 2016 and forecasted that this quantity would increase to 370 gigalitres in 2020. The study proposed a shutdown plan for the water intensive thermal generation plants which would reduce water usage in coal based thermal electricity sector in South Africa by up to 15% (234 gigalitres) by the year 2025. To compensate powers shortages by the shutdowns the study proposes further development of new dry cooling technology based thermal generation plants which are considered less water intensive.

Another study of particular interest to this research was one conducted by Sanchez et al. (2020) whose focus was mainly to quantify WF of the entire energy sector in Africa with special focus on hydroelectricity due to its dominance in the African energy scene. This research found that hydro sources of energy dominates other sources in terms of water use that mainly results from water loss through evaporation from reservoirs used in hydropower generation. The amount of water usage in Africa in 2016 was found to be 42 billion m3 for hydro in relation to 1.2 billion m3 for the rest of the energy sources in Africa all summed up together. The estimation of water usage in the energy sector in Africa was calculated to be 10 million m3 for renewable non-hydro sources of energy. This clearly outlined the direction that Africa should take in terms of energy generation going into the future so as to ensure sustainability in the utilization of water resources in the energy sector. One of the key proposals of this study was the development of a more robust and interconnected power transmission grid in the continent to aid in the anticipated and the much-needed development of less water intensive renewable sources. Another proposal was a solution to curb the high evaporation rates from hydropower reservoirs by laying solar panels on top of the reservoirs which would give a double benefit by generation more energy and saving more water.

### 2.3.3 Kenya

A literature review study on the topic of the overall water-energy nexus of the country together with an in depth look at the WF based studies in Kenya revealed that not much has been done. Most WF studies conducted in the country are those done on products in the agricultural sector such as milk, meat (Bosire et al., 2015) and cut flowers (Mekonnen et al., 2012). One WF study in the water resource management sector was one done on a water basin in Kenya to help in provision of data to be used for better water management at basin level. There is therefore a gap of research in Kenya in this very important concept of any society. This is where this research comes in to help bring awareness on water use in the electricity sector and to help the trajectory of the country's energy mix as we head towards unprecedented times of pandemics, climate change, extinctions among many ills.

### 2.4 Literature review synthesis and wrap up

It is apparent that many countries around the world have research about WF of electricity use and consumption, which is well documented and solutions are sought to ensure that the lowest possible WFs in this area are a focus of the respective responsible institutions. Africa at large has experienced a shift in the last few years towards renewable electricity sources, but research shows that this focus is mainly towards expansion of hydroelectricity sources which is a significant water consumer.

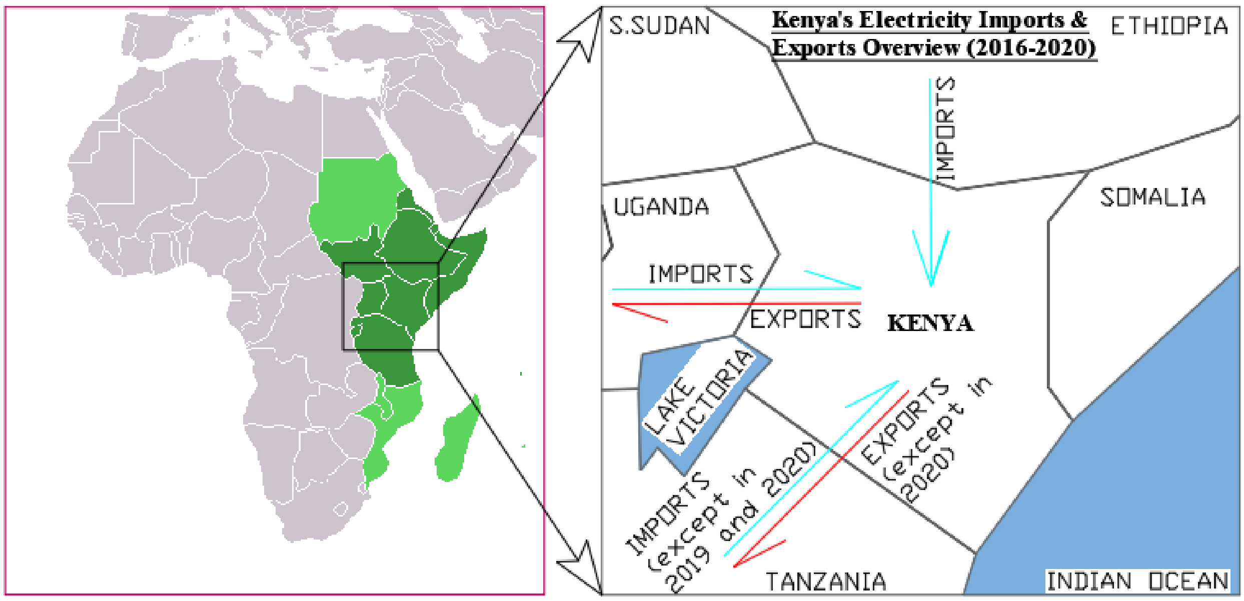
Kenya seems to be leading the way in geothermal electricity sources both in Africa and around the world (International Renewable Energy Agency, 2021) and its government is looking to increase its renewable portion of electricity consumption to 80% of the total electricity generated in the country by 2030 (Ministry of Energy and Petroleum & Sustainable Energy for All, 2015). Despite this positive change that Kenya is experiencing, no study has been done to quantify the WF of electricity consumption and to provide an insight of possible options of electricity mixes that would put minimal pressure on water resources. This is where this study comes in to provide crucial information and solutions to the problem of excessive water use in the sector of electricity use and consumption as Kenya heads into a phase of massive population growth and climate change in the coming decades just like the rest of the world.

The following chapter gives more information about the electricity-water nexus of Kenya, which is the actual case study of your research, and contextualizes it within the African context.

# Chapter 3: Case study

## 3.1 Kenya

**Figure 1.** *Map showing the position of Kenya in Africa (left) and an indication of presence or lack of electricity exchanges for Kenya from 2016 to 2020 with neighboring countries (right).*




As will be seen shortly below, Kenya just like many other countries is trying to steadily move away from fossil fuel electricity sources that are both water intensive and huge CO2 emitters to less water intensive and green renewable energy such as solar, wind and geothermal sources. This change is unfortunately slow and fossil fuel electricity generators still feature prominently as Kenya's energy contributors. This is reinforced by the fact that Kenya just like most of the world experiences extreme seasonal changes such as droughts due to climate change which renders hydroelectricity less reliable. The Kenya's economic situation also does not help in this regard because despite having a high renewable energy potential, a rapid shift to renewable energy requires enormous financial capabilities that Kenya is not endowed with as it is still rated by economic experts worldwide as a 3rd world economy. In this section, we are going to take a glance at the situation of Kenya's energy sector and pick up important information that will be helpful in meeting the objectives of this study. ***Figure 1*** above indicates the electricity import and export exchange patterns displayed on a map which also gives an idea of the geographical position of Kenya in Africa.

### 3.1.1 Potential of renewable energy in Kenya as of 2019

The potential of renewable energy in Kenya is essential to this research because of their significance in the WF of electricity generation and consumption. Most of the statistics give in this segment to support the arguments of the potential of renewable energy in Kenya is adopted from the research by Simiyu, (2015).

**a) Hydro sources of electricity**

Just like most of the African countries, hydroelectricity has been one of the most significant sources of electricity in Kenya. Despite its limitations such as evaporative water loss and the effects of droughts which have been increasingly frequent in the past years, Kenya still has a lot of potential to harness more energy from hydropower. According to the study by Simiyu. (2015), Kenya has a hydroelectricity potential of up to 1670 Megawatts (MW).

**b) Solar sources of electricity**

Kenya is one of the lucky countries to be situated along the equator which guarantees plenty of sunlight throughout the year. This means that Kenya has great solar electricity potential especially on the coastal, Eastern and North-Eastern parts of the country which sums up to an area of about 106,000 $km^2$ that can receive solar insolation of up to 6 $KWh/m^2$/day. Not more than 1 % of this area has been harnessed. That is how large the solar electricity potential is.

**c) Wind sources of electricity**

The wind electricity potential of Kenya is also very promising. Kenya has regions which can have wind speeds of up to 6 m/s. The total area of land where these levels of wind speeds can be achieved is up to 90000 $km^2$. This gives Kenya a wind electricity potential of up to 346 $W/m^2$.

**d) Geothermal sources of electricity**

Geothermal electricity is one of the renewable non-hydro sources of which Kenya has excelled in recently. Kenya tops the African charts in the amount of installed capacity of geothermal electricity plants as of 2019. It also ranks 9th in the world charts which is pretty impressive. When it comes to the rate of growth of geothermal electricity production, Kenya is among the fastest in the world in 2019 (Omenda et al., 2020). According to recent investigations, Kenya has the potential of harnessing between 5000 MWe to 10000 MWe.

### 3.1.2 The target numbers of electricity mix in Kenya (2012-2030)

Kenya has an ambitious plan to increase its electricity production in terms quantity and to shift its energy mix from high dependency on hydroelectricity to a more dependency on geothermal sources. The government targets a change in the country's capacity from 1,645 MW to 14,676 MW in 2012 and 2030 respectively. Another target is with regards with the energy mix of this 14,676 MW of power. As ***Table 1*** below shows, the government is aiming to have approximately 80% of its electricity being sourced from renewable sources (37.13% geothermal, 8.17% solar, 10.22% wind and 20.44% hydropower, 4.08% co-generation/ gasification, 0.07% biogas) and approximately 20% non-renewable sources (3.4% diesel, 16.49% coal). (Ministry of Energy and Petroleum & Sustainable Energy for All, 2015).

**Table 1.** *Target Electricity (Mix change from 2012 to 2030).*

| Sources of Electric Energy | Capacity 2012 | Capacity 2014 | Capacity 2017 | Capacity 2022 | Capacity 2027 | Capacity 2030 |
|---|---|---|---|---|---|---|

| | | **MW** | **%** | **MW** | **%** | **MW** | **%** | **MW** | **%** | **MW** | **%** | **MW** | **%** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Renewable Energy** | **Hydro** | 816 | **46** | 821 | **38** | 900 | **27** | 1500 | **25** | 2500 | **23** | 3000 | **20** |
| | **Geothermal** | 250 | **15** | 594 | **38** | 800 | **24** | 2000 | **33** | 4000 | **37** | 5450 | **37** |
| | **Wind** | 6 | **0** | 25 | **1** | 500 | **15** | 900 | **15** | 1200 | **11** | 1500 | **10** |
| | **Cogeneration/ Gassification** | 26 | **1** | 38 | **2** | 50 | **2** | 100 | **2** | 300 | **3** | 600 | **4** |
| | **Biogas** | 0 | **0.00** | 0.2 | **0.01** | 2 | **0.06** | 5 | **0.06** | 6 | **0.06** | 10 | **0.1** |
| | **Solar PV** | 1 | **0.03** | 1.7 | **0.78** | 40 | **1.22** | 300 | **4.96** | 700 | **6.54** | 1200 | **8.2** |
| | **Total** | 1099 | **62** | 1478 | **68** | 2292 | **70** | 4805 | **79** | 8706 | **81** | 11760 | **80** |
| **Non-Renewable Energy** | | 667 | **38** | 695 | **32** | 1000 | **30** | 1243 | **21** | 2000 | **19** | 2916 | **20** |
| **Grand Total** | | 1767 | **100** | 2173 | **100** | 3292 | **100** | 6048 | **100** | 10706 | **100** | 14676 | **100** |

*Note.* Adapted from "Sustainable energy for all Kenya action agenda; Pathways for concerted action toward sustainable energy for all by 2030" by Kenya's Ministry of Energy and Petroleum, & Sustainable Energy for All, 2015.

To be able to contextualize the status quo and the potential of Kenya in terms of electricity generation and its impacts on water resources, we take a case study of Africa in the following subchapter.

## 3.2 Africa

Africa is the continent with the highest amount of people without electricity access (Energy Agency - IEA, 2016). It is expected to show a trend of massive population increase, a potential development in energy and increased urbanization in the coming decades (BP, 2017). This pattern has already been witnessed in the start of this millennium in Africa. From the year 2000 to the year 2012 for instance, Sub-Saharan Africa had a population growth of 270 million people with a consequential energy demand rise by 45% making Africa the fastest worldwide in terms of population growth (Sanchez et al., 2020). Therefore, with growth expected in the energy sector in Africa, water consumption is also expected to rise leading to increased competition with other water demands of the continent especially agriculture which is currently the backbone and the mainstay of the African economy. 80% of water consumption in Africa in 2014 were for agricultural purposes (Energy Agency - IEA, 2016). There is therefore need to study the situation of the various sources of energy in Africa to be able to decipher the ones that play a major role and what needs to be done going forward and to get good understanding about what is happening in the larger context of the African energy ecosystem before diving into Kenya which is the main country of interest for this research.

### 3.2.1 Relevance of hydroelectricity in Africa

Electricity consumption from hydroelectricity sources currently dominates the African Energy scene. According to Sanchez et al. (2020), eight countries in the continent have their energy mixes dominated by hydroelectricity by over 70% of the total energy generated. A further fourteen countries have their energy mixes dominated by hydroelectricity by over 50% of the total energy generated. In terms of the dominance of hydroelectricity in the three major regions of sub-Saharan Africa, Central Africa leads the pack with hydroelectricity taking a share of 58% of the total energy generated in the region, Eastern Africa follows closely with hydroelectricity taking a share of 54% of the total energy generated in the region and the Western African region excluding Nigeria which mainly depends on natural gas has hydroelectricity taking a share of 30% of the total energy generated in the region (Sanchez et al., 2020)

This dominance of hydroelectricity in the continent of Africa is alarming considering the huge water intensity of hydroelectricity mainly caused by water evaporation from the reservoirs used for hydroelectricity generation. Losses of water through evaporation signifies a real loss because this water is lost from the water basin where the reservoir is located to another water basin in a different location. Other factors affecting hydroelectricity generation are droughts which is becoming a norm in Africa just like the rest of the world due to climate change, seepage losses which does not signify a real loss because the water remains in the same water basin (Gleick, 1994) and floods that reduce the storage capacity of dams because of massive siltation (Loisulie, 2010). The total amount of water lost in the form of water evaporated from reservoirs used for hydroelectricity generation in Africa was estimated to be 42 billion cubic meters in the year 2016 (Sanchez et al., 2020).

### 3.2.2 The potential of renewable energies in Africa

Africa is estimated to have a potential of realizing 310 Gigawatts of renewable energy by 2030 with an estimation capacity of 350 GW for hydro, 110 GW for wind, 15 GW for geothermal and 10 GW for solar power (Renewable Energy Agency, 2014). Due to recent advancement in technology, non-hydro renewable sources of electricity are less capital intensive than in the past. This means that African countries can now go full-throttle in the quest to invest in this kind of energy. According to a recent study by Sanchez et al. (2020), non-hydro renewable sources of energy in Africa takes up an equivalent of 1% of all water withdrawn or consumed for energy generation purposes. This illustrates the immense need for advancement of the energy mix of the entire continent towards non-hydro renewable sources in order to ensure that the overall WF of electricity consumption is brought down considerably hence reducing pressure on water resources.

### 3.2.3 Power grid infrastructure in Africa

One of the main challenges of exploitation of the potential of renewable energy that Africa is bestowed with is the inadequate power grid infrastructure within countries and between countries and regions of Africa. This is an additional cost that African countries have to bear in order to accelerate rapid growth of renewable energy which is green and less water intensive (Sanchez et al., 2020).

### 3.2.4 The electricity mix of Uganda, Tanzania and Ethiopia

One of the parameters used in this study to calculate the WF of electricity consumption in Kenya is the electricity imports to Kenya from three of its neighbors namely Uganda, Tanzania and Kenya. The problem is there is no data about the energy mixes of this imports in order to properly allocate the imports among different components of the energy mixes. In order to find a basis for making assumptions in this regard, information about the electricity mixes of the three countries in terms of percentages from 2015 to 2019 as shown in **Table 2**, **Table 3** and **Table 4** below, which were adapted from Ritchie (2020).

**Table 2.** *Uganda's electricity mix changing from 2015 to 2020*

| Year / Electricity Type (TWh). | 2015 | % | 2016 | % | 2017 | % | 2018 | % | 2019 | % | 2020 | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Coal | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** |
| Gas | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** |
| Hydro | 2.41 | **76** | 3.27 | **81** | 3.41 | **81** | 3.60 | **81** | 4.00 | **82** | 4.00 | **82** |
| Other renewables | 0.49 | **16** | 0.50 | **12** | 0.50 | **12** | 0.50 | **11** | 0.51 | **10** | 0.51 | **10** |
| Solar | 0.03 | **1** | 0.04 | **1** | 0.06 | **1.4** | 0.07 | **1.6** | 0.07 | **1.5** | 0.07 | **1** |
| Oil | 0.23 | **7.3** | 0.23 | **5.7** | 0.26 | **6.1** | 0.27 | **6.2** | 0.29 | **5.9** | 0.29 | **6** |
| Wind | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** |
| Nuclear | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** |
| Total | 3.16 | **100** | 4.05 | **100** | 4.23 | **100** | 4.45 | **100** | 4.87 | **100** | 4.87 | **100** |

*Note.* Adapted from "Energy" by Hannah Ritchie, Max Roser and Pablo Rosado (2020). Published online at OurWorldInData.org. Retrieved from: https://ourworldindata.org/energy [Online Resource]

**Table 3.** *Ethiopia's electricity mix changing from 2015 to 2020*

| Year / Electricity Type (TWh). | 2015 | % | 2016 | % | 2017 | % | 2018 | % | 2019 | % | 2020 | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Coal | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** |
| Gas | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** |
| Hydro | 9.58 | **92** | 11.64 | **93** | 12.55 | **96** | 12.89 | **96** | 13.99 | **96** | 13.99 | **96** |
| Other renewables | 0.03 | **0.3** | 0.03 | **0.2** | 0.03 | **0.2** | 0.03 | **0.2** | 0.03 | **0.2** | 0.03 | **0** |
| Solar | 0.02 | **0.2** | 0.02 | **0.2** | 0.02 | **0.2** | 0.02 | **0.1** | 0.02 | **0.1** | 0.02 | **0** |
| Oil | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.01 | **0** | 0.01 | **0** | 0.01 | **0** |
| Wind | 0.76 | **7.3** | 0.78 | **6.3** | 0.53 | **4.1** | 0.53 | **4** | 0.53 | **3.7** | 0.53 | **4** |
| Nuclear | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** |
| Total | 10.39 | **100** | 12.47 | **100** | 13.14 | **100** | 13.48 | **100** | 14.58 | **100** | 14.58 | **100** |

*Note.* Adapted from "Energy" by Hannah Ritchie, Max Roser and Pablo Rosado (2020). Published online at OurWorldInData.org. Retrieved from: https://ourworldindata.org/energy [Online Resource]

**Table 4.** *Tanzania's electricity mix changing from 2015 to 2020*

| Year / Electricity Type (TWh). | 2015 | % | 2016 | % | 2017 | % | 2018 | % | 2019 | % | 2020 | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Coal | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** |
| Gas | 3.32 | **51** | 3.43 | **50** | 3.46 | **50** | 3.50 | **51** | 3.56 | **51** | 3.56 | **51** |
| Hydro | 2.09 | **32** | 2.34 | **34** | 2.33 | **34** | 2.21 | **32** | 2.25 | **32** | 2.25 | **32** |
| Other renewables | 0.06 | **1** | 0.07 | **1** | 0.07 | **1** | 0.07 | **1** | 0.07 | **1.1** | 0.07 | **1** |
| Solar | 0.02 | **0.2** | 0.03 | **0.5** | 0.04 | **0.6** | 0.09 | **1.3** | 0.09 | **1.2** | 0.09 | **1** |
| Oil | 0.99 | **15** | 1.03 | **15** | 1.04 | **15** | 1.05 | **15** | 1.07 | **15** | 1.07 | **15** |
| Wind | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** |
| Nuclear | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** | 0.00 | **0** |
| Total | 6.48 | **100** | 6.91 | **100** | 6.94 | **100** | 6.92 | **100** | 7.04 | **100** | 7.04 | **100** |

*Note.* Adapted from "Energy" by Hannah Ritchie, Max Roser and Pablo Rosado (2020). Published online at OurWorldInData.org. Retrieved from: https://ourworldindata.org/energy [Online Resource]

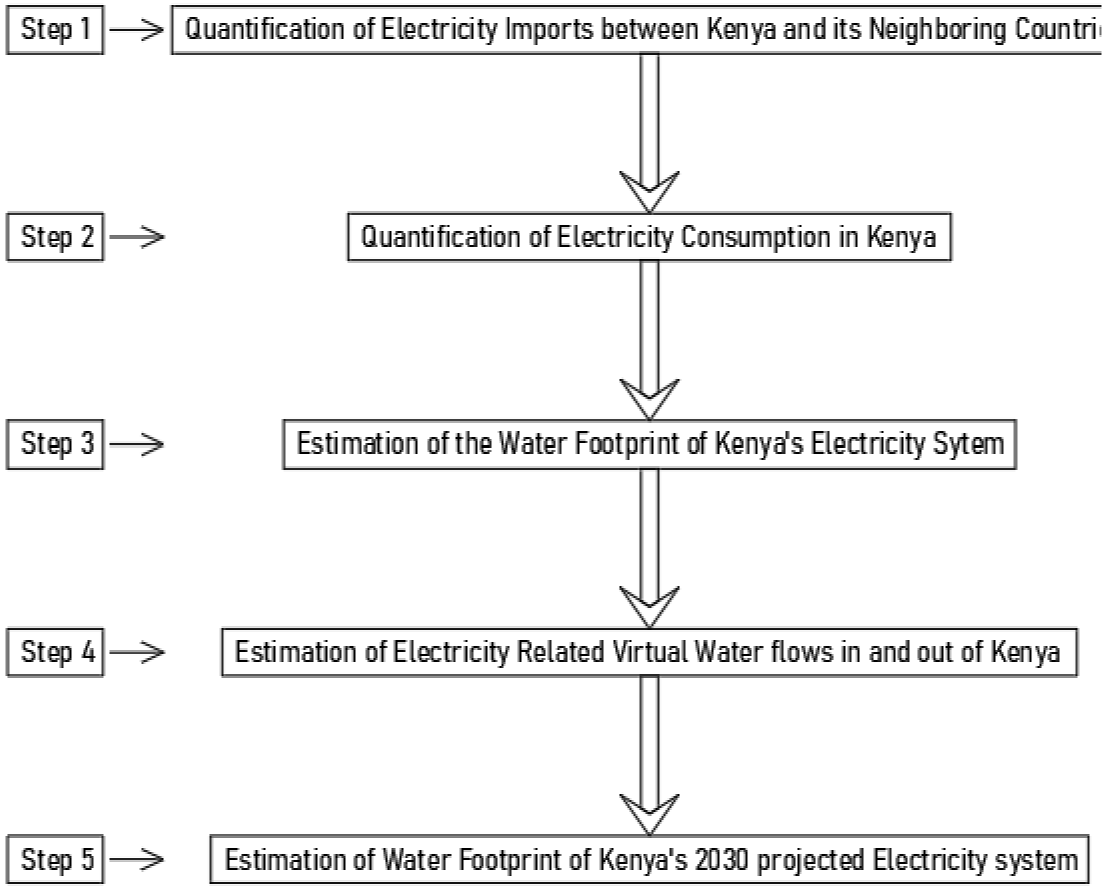
# Chapter 4: Methodology

The first step of this study is the analysis of the status quo of Kenya's electricity system yearly from 2016 to 2020. This is in terms of establishing how much electricity is generated in the country, how much of the generated electricity is exported abroad, how much electricity is imported into the country and what is the net flow of electricity into the country. With the knowledge of all these, the quantity of electricity consumed within the borders of Kenya is estimated in the second step.

The third step which forms the basis of the main objective of this research is the estimation of the water footprint electricity consumed within the borders of Kenya. This is accomplished with the application of the water footprint concept (Hoekstra et al., 2011) which is an indicator of the volume of freshwater that a product or service consumes and pollutes during the entirety of its life, that is, from cradle to grave. According to Hoekstra and his co-authors, the total water footprint of a product or service is equivalent to the amount of freshwater consumed by a unit amount of that product or service. Electricity in Kenya is the product of focus in this study and its water footprint estimated in units of cubic meters of water consumed for every megawatt or gigawatt of electricity consumed ($m^3$/MWh or $m^3$/GWh) in a specified amount of time say year. Only the blue water footprint of Kenya's electricity system is studied in this research based on the fact that data required to study the green and grey water footprints of Kenya's electricity system needs longer time frames of data collection in the study area which is beyond the scope of this research.

The third step of this study is the estimation of the amount of electricity related virtual water flow between Kenya and its neighboring countries. The water footprint concept comes in handy again in this step as it is applied to determine the quantities of virtual water flow having established the electricity exchanges in the first step. The aim of this step is to identify the main protagonists in terms of electricity exchanges among the neighboring countries of Kenya and to try and get an idea of how much environmental impact Kenya is having on its neighbors and vice versa. The individual steps of the methodology chapter are indicated in ***Figure 2*** below and described in depth in the subsequent sections.

**Figure 2**. *Flowchart with the methodological steps adopted in the analysis of Kenya's electricity system.*




## 4.1 Quantification of electricity exports and imports for Kenya to and from Uganda, Tanzania and Ethiopia (2016 to 2020).

In this subsection, the flows of electricity to and from all the countries that Kenya shares borders with are estimated and presented in chord diagrams. This is done through the estimation of the quantities of the various individual types of electricity exchanged ranging from hydro, thermal, geothermal, solar, biomass and wind sources. The Knowledge of quantities of imports and exports by electricity source is important in the estimation of electricity related virtual water exchanges between Kenya and its neighbors. This is because different electricity sources have different water intensities.

The Kenyan imports and exports for individual electricity types to and from Uganda, Tanzania and Ethiopia are calculated by applying a product to the total electricity exported or imported to or from Kenya during a specific time frame within the study period and the percentage proportion of the electricity type in the source country during the same period. Equations *(1)* and *(2)* below explain this step further.

$$E_{xy} = E_y * P_{xk} \qquad (1)$$

Where:

$E_{xy}$ = Exports of electricity type x to country y from Kenya during a specific period within the study period (MWh/[Time]).

$E_y$ = Total electricity exports to country y from Kenya during a specific period within the study period (MWh/[Time]).

$P_{xk}$ = Proportion of electricity type x in Kenya's electricity mix during a specific period within the study period (%).

$$I_{xy} = I_y * P_{xy} \qquad (2)$$

Where:

$I_{xy}$ = Imports of electricity type x from country y to Kenya for a specific period within the study period (MWh/[Time]).

$I_y$ = Total electricity imports from country y to Kenya for a specific period within the study period (MWh/[Time]).

$P_{xy}$ = The proportion of electricity type x in the electricity mix of country y during a specific period within the study period (%).

## 4.2 Quantification of electricity consumption in Kenya (2016 to 2020).

In this step, we use the Knowledge of the electricity imports and exports between Kenya and the three countries namely Uganda, Tanzania and Ethiopia to calculate the net Imports of the various types of electricity to Kenya. The addition of the net Imports to the electricity that is generated in Kenya for a specific period within the study period gives us the total quantities of the various electricity types consumed in Kenya for a specific period within the study period. Equations *(3)* and *(4)* below give a visual perspective of this step.

$$NI_x = [(I_{xu} - E_{xu}) + (I_{xt} - E_{xt}) + (I_{xe} - E_{xe})] \qquad (3)$$

$$C_x = G_x + NI_x \qquad (4)$$

Where:

$NI_x$ = Net imports of electricity type x to Kenya during a specific period within the study period (MWh/[Time]).

$I_{xu}$ = Imports of electricity type x from Uganda to Kenya during a specific period within the study period (MWh/[Time]).

$E_{xu}$ = Exports of electricity type x from Kenya to Uganda during a specific period within the study period (MWh/[Time]).

$I_{xt}$ = Imports of electricity type x from Tanzania to Kenya during a specific period within the study period (MWh/[Time]).

$E_{xt}$ = Exports of electricity type x from Kenya to Tanzania during a specific period within the study period (MWh/[Time]).

$I_{xe}$ = Imports of electricity type x from Ethiopia to Kenya during a specific period within the study period (MWh/[Time]).

$E_{xt}$ = Exports of electricity type x from Kenya to Ethiopia during a specific period within the study period (MWh/[Time]).

$C_x$ = Amount of electricity type x consumed in Kenya during a specific period within the study period (MWh/[Time]).

$G_x$ = Amount of electricity type x generated in Kenya during a specific period within the study period (MWh/[Time]).

With the quantities of various electricity types consumed within the Kenyan boundaries calculated, a simple summation of the individual values gives the total amount of electricity consumed during a specific period within the study period in Kenya. Equation *(5)* below shows this step.

$$C_k = \sum_{1}^{n}(C_x) \qquad (5)$$

Where:

$C_k$ = Total amount of electricity consumption in Kenya during a specific period within the study period (MWh/[Time]).

$C_x$ = Amount of electricity type x consumed during a specific period within the study period (MWh/[Time]).

n = the number electricity types consumed in Kenya.

## 4.3 Estimation of the water footprint trend for electricity consumption in Kenya (2016 to 2020).

### 4.3.1 Estimation of the water intensity factors for the various electricity sources in Kenya.

In order to make reliable estimates of the WF of any product or service which in the case of this research is the consumption of electricity in Kenya, availability of a reliable WIF for that commodity is crucial. From the literature review of this research, there have been attempts globally to estimate the WIFs of various electricity types with varied successes and difficulties in almost equal measure. Therefore, in this subsection, methods and sources of information for the, assumptions, estimation or retrieval of the WIFs for each electricity source type available in Kenya are described and delved into.

**a) Non-hydro sources**

The WIFs for non-hydro sources (Thermal, geothermal, wind, solar and biomass) will be adopted from the studies by Macknick et al. (2012) and Roidt et al. (2020). The WIFs adopted in these studies have been extensively applied by reliable, published and peer reviewed scientific researches. They are therefore deemed reliable enough for use in this research for the estimation of the WF of respective electricity sources in Kenya.

**b) Hydro sources**

The analysis of WF of hydroelectric consumption is a complex affair. For instance, allocating all the WF of a multipurpose dam to hydroelectricity generation is logically incorrect. A conundrum arises in this situation because how does one determine the correct share of WF to allocate to hydroelectricity where energy generation is one among many uses. According to a study by Bakken et al. (2013), to find the correct WF of hydroelectricity generation, the correct way is to use the economic weight or value of each function as a factor to allocate the WF of the reservoir system to the various uses.

Another simplification usually made is neglecting the background evapotranspiration of the reservoir. This simply means double counting. Background Evapotranspiration is the amount of water which would have been lost if the reservoir did not exist or the evapotranspiration which occurred on the dam site before the dam construction commenced (Bakken et al., 2013).

The units used for WIFs of electricity consumption are as follows; $m^3$/kWh or L/kWh or $m^3$/MWh or L/MWh or $m^3$/GJ. As shown in ***Table 5*** below, there exists a huge variation of data findings of previous research done on WIFs of hydroelectricity consumption by many individuals and organization all over the world for the past three decades. In 2003, the National Renewable Energy Laboratory did a research on the average hydroelectricity WIF of the entire United States and found it to be 68.9 L/kWh (Torcellini et al., 2003). In 2011 based on information extracted from five sources, the Intergovernmental Panel on Climate Change argued that the WIF for hydroelectricity is in the range of 0 L/kWh and 209 L/kWh (Edenhofer et al., 2012).

**Table 5.** *WIFs for hydroelectric consumption estimated around the globe over time.*

| Study | Estimate [$m^3$/GJ] | Geographical Region | Calculation Method |
|---|---|---|---|
| | 0.01 (min) | | |
| | 1.5 (median) | | |
| Gleick (1992,1993) | 58 (max) | California, USA (a diverse set of 100 plants) | WF-1 (gross) |
| Gleick (1994) | 4.7 (average) | US average | WF-1 (gross) |
| Torcellini et al. (2003) | 19 (average) | US average e 120 largest plants, providing ~ 65% of total electricity produced by hydroelectric facilities in 1999 | WF-1 (gross) |

| | | | |
|---|---|---|---|
| Pasqualetti and Kelley (2008) | 31.6 | Arizona, USA | WF-1 (gross) |
| Gerbens-Leenes et al. (2009) | 22 | Global average | WF-1 (gross) |
| Herath et al. (2011) | 5.8 (gross average) | "All plants" Northern and Southern New Zealand | WF-1 (gross), WF-2 (net) and WF-3 (water balance) |
| | 2.7 (net average) | | |
| | 1.5 (water balance) | | |
| Mekonnen and Hoekstra (2012) | 0.3 (min) | Worldwide, 35 plants, including 7 in Brazil and 12 in Latin America ~ 8% of global installed hydroelectric capacity. | WF-1 (gross) |
| | 68 (average) | | |
| | 846 (max) | | |
| Amøy (2012) | 1.05 to 1.22 (range gross E) | Norway | WF-1 (gross) and WF-3 (water balance) |
| | -24.4 to -0.86(range WB) | | |
| Yesuf (2012) | 9.5 (gross min) | Ethiopia (OmoeGhibe River) | WF-1 (gross) and WF-2 (net) |
| | 22.8 (gross max) | | |
| | 2.8 (net min) | | |
| | 7 (net max) | | |
| Tefferi (2012) | 3.05 (min) | Ethiopia (Blue Nile) | WF-1 (gross) |
| | 38 (max) | | |
| | 27.5 (w. Average) | | |
| | 380.8 (min) | Sudan (Blue Nile) | |
| | 978 (max) | oseires and Sennar Irrigation reservoirs | |
| | 411.1 (w.average) | | |
| Demeke et al. (2013) | 0 (min) | Austria, Ethiopia, Turkey, Ghana, Egypt and Lao PDR | WF-1 (gross) and WF-2 (net) |
| | 1736 (max) | | |
| Zhao and Liu (2015) | 1.5 (average) | China (Three Gorges reservoir) | WF-1 (gross) |
| Liu et al. (2015) | 3.6 (average) | China - 209 hydroelectricity generation plants. ~53% of China's total hydroelectricity prod. | WF-1 (gross) |
| Bakken et al. (2015) | 0.05 (net average) | Norway - Trolleim HPP | WF-1 (gross) and WF-2 (net) |
| | 1.25 (gross average) | | |

| | | | |
|---|---|---|---|
| | 0.04 (net average) | Norway - Embretsfoss 4 | WF-1 (gross) and WF-2 (net) |
| | 19.75 (gross average) | | |
| Scherer and Pfister (2016) | 65.1 (gross average) | Worldwide, 1473 plants, ~43% of global hydroelectric energy | WF-1 (gross) and WF-2 (net) |
| | 38.1 (net average) | | |

*Note*. Adapted from "Special report on renewable energy sources and climate change mitigation: summary for policymakers: a report of working group III of the IPCC and technical summary" by Edenhofer, Ottmar., Pichs Madruga, R., Sokona, Youba., United Nations Environment Programme., & World Meteorological Organization, 2012.

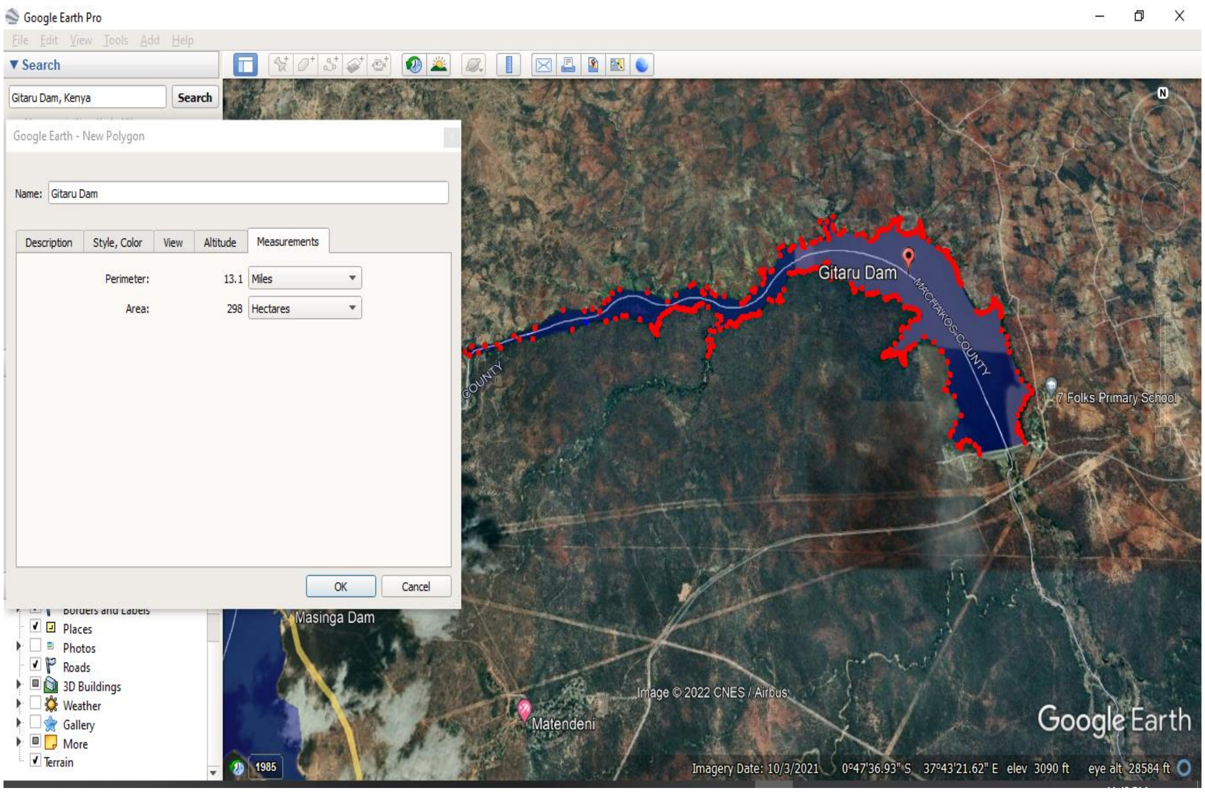
Unlike non-hydro sources of electricity whose WIFs are relatively uniform, hydro sources of electricity prove to have the most varied WIFs. This is apparent in the massive range of WIFs for hydro sources of electricity estimated by different researchers worldwide over time as displayed in ***Table 5*** above. It is therefore difficult to quantify and estimate the WIFs of hydroelectricity for regions or countries around the world. Kenya which is the context of this research is no exception to this reality. With the application of some background principles and data from reliable scientific resources, this research went about to estimate the water intensity value for hydro electricity consumption in Kenya.

According to the research by (Mekonnen & Hoekstra, 2011) from which the basis of the estimation of WIF for hydroelectricity in Kenya is anchored on in this research, water loss through evaporation from reservoirs of hydroelectric generating plants is the main contributor to the WF of hydroelectric energy. The two main determinants of the quantity of evaporation from water surfaces are the geographical location and the surface area of the water body. Geographical location of a reservoir based hydroelectric generating plant influences its evaporation rate because reservoirs located near the earth's tropical regions experience more evaporation than reservoirs in temperate regions due to the climatic variations which foster a difference in evaporation rates. In addition to this, the amount of evaporation from any reservoir or any water body for that matter, with all factors kept constant, is directly proportional to its surface area.

According to the same research, the ratio of the surface area of the reservoir of a hydroelectric generating plant to the installed capacity of that plant is directly proportional to how much water is lost per unit electricity generated by the plant (WIF). Therefore, a plant with a small surface area reservoir and a large Installed capacity will have a low WIF while a plant with a large surface area reservoir and a small installed capacity will have a high-WIF. One of the objectives that research was the estimation of WIFs of hydroelectricity plants all over the world and one plant in Kenya known as Kiambere hydroelectricity generation plant was part of the project. The WIF, the installed capacity and the reservoir surface area of Kiambere are therefore adopted for this research. Through direct proportionality, this information is applied to estimate the WIFs of other reservoir hydroelectric generation plants in Kenya.

To achieve this, first, an exercise to estimate the surface area of all reservoirs engaged in hydroelectricity generation in Kenya is conducted. The areas are estimated using Google Earth polygon measurement tool. To illustrate further, ***Figure 3*** below shows a picture of Google Earth Polygon Measurement of the area of Gitaru reservoir.

**Figure 3.** *Google Earth estimation of the surface area of Gitaru hydroelectricity generation plant's reservoir.*




*Note.* Image source: Google [Google Earth Pro screenshot]. Retrieved April 4, 2022, from https://earth.google.com/web/search/Gitaru+Dam,+Kenya

This exercise is followed by the retrieval of their respective installed capacities. The installed capacities are obtained from the website of KENGEN which is one of the Kenya government's parastatals under the Ministry of Energy. Thereafter, the water intensity factors for all reservoir based hydroelectric generating plants in Kenya are approximated using equation *(6)* below.

$$\mathrm{if_p} = \frac{\mathrm{if_k} * (\mathrm{A_p}/\mathrm{I_p})}{(\frac{\mathrm{A_k}}{\mathrm{I_k}})} \qquad (6)$$

Where:

$\mathrm{if_p}$ = WIF of hydroelectricity generation plant p [$m^3$/GJ].

$\mathrm{if_k}$ = WIF of Kiambere hydroelectricity generation plant [$m^3$/GJ].

$A_p$ = surface area of the reservoir for hydroelectricity generation p [hectares].

$A_k$ = surface area of Kiambere hydroelectricity generation plant's reservoir [hectares].

$I_p$ = installed capacity of hydroelectricity generation plant p [MW]

$I_k$ = installed capacity of Kiambere hydroelectricity generation plant [MW]

Once the WIFs for all the hydroelectricity generation plants in Kenya have been estimated, all the values are aggregated to obtain one weighted value to be used as the WIF for hydroelectricity related WF calculations in Kenya. The weighting factors for each hydroelectricity generation plant are calculated using equation *(7)* below while the final hydroelectricity WIF for Kenya are calculated as in equation *(8)* below.

$$W_p = \frac{I_p}{I_t} \qquad (7)$$

$$IF_H = \sum_{p=1}^{6} (W_p * if_p) \qquad (8)$$

Where:

$IF_H$ = weighted value for WIF of hydroelectricity WF calculations in Kenya [$m^3$/GJ]

$if_p$ = WIF hydroelectricity generation plant p [$m^3$/GJ]

$W_p$ = Weighting factor that determines the contribution of hydroelectricity generation plant p to the final hydroelectricity WIF in Kenya [-]

$I_p$ = Installed capacity of hydroelectricity generation plant p in Kenya [MW]

$I_t$ = Total installed capacity of hydroelectricity in Kenya [MW]

#### 4.3.2 Sensitivity Analysis due to a wide range of water intensity factors expected among different hydroelectricity generation plants in the study area.

Due to the variation of WIFs seen in the multiple results of research conducted world over during different times as seen in ***Table 5***, substantial variation of WIFs is expected for hydroelectricity estimated by this research for the various reservoir hydroelectricity generation plants in Kenya. For this reason, a sensitivity analysis is performed in this research for all possible values in the WIF ranges estimated for various hydroelectric power plants in Kenya together with the WIFs for Ethiopia and Sudan adopted from literature. This is in order to get a glimpse of how the WF of electricity consumption is affected by a huge range of possible WIFs for hydroelectricity generation plants in Eastern Africa. Different scenarios are created based on the various WIF values estimated for various hydroelectric generation plants. The scenarios are applied to the entire system to understand the sensitivity of the system to the variation of WIFs from plant to plant. This sensitivity is judged based on the results of water footprints obtained from the various scenarios created.

### 4.3.3 Quantification of the estimate electricity water footprint in Kenya (2016 to 2020).

After the prior quantification of estimate electricity consumption in Kenya at specific periods within the temporal study scope of this research and the determination of the estimate WIFs of the various electricity sources in Kenya, the WF of the various sources of electricity and indeed for the entire Kenyan system is estimated in this subsection. This is achieved through a simple product of two values. That is the estimate consumption amount of each electricity type in Kenya for a specific period of time say a month and the corresponding WIF for the said electricity type. This produces the estimated WF for various electricity types in monthly or annual periods. Equation *(9)* below illustrates this step.

$$\mathrm{WF}_x = \mathrm{C}_x * \mathrm{if}_x \qquad (9)$$

Where:

$WF_x$ = WF of electricity type x consumed in Kenya during a specific period within the study period ($m^3$/[Time]).

$C_x$ = Amount of electricity type x consumed in Kenya during a specific period within the study period (MWh/[Time]).

$if_x$ = WIF of electricity type x in Kenya [$m^3$/GJ]

Finally, the WF of electricity consumption for the whole system in Kenya for a particular period of time within the study period is calculated by summing up the WFs of the individual electricity types during that period. Here next is equation *(10)* showing this step.

$$\mathrm{WF} = \sum_{x=1}^{n} (\mathrm{WF}_x) \qquad (10)$$

Where:

WF = Total WF of electricity consumption in Kenya during a specific period within the study period ($m^3$/[Time]).

$WF_x$ = WF of electricity type x consumed in Kenya during a specific period within the study period ($m^3$/[Time]).

n = the number electricity types consumed in Kenya during a specific period within the study period [-].

## 4.4 Estimation of virtual water exchange trend between Kenya and its neighboring countries 2016 to 2020.

With possession of Kenya's estimate electricity imports and export trends over the entire period of study, this research uses this information to estimate the virtual water flows into Kenya. This estimate flows are displayed again in a chord diagram to give the reader a quick overview these exchanges.

Having outlined all the methods and steps undertaken in order to meet the objectives of this research, the results of the undertakings of this chapter are displayed and discussed in the next chapter.

## 4.5 Estimation of water footprint of the projected electricity system in Kenya for 2030.

A look into the projected electricity development plans by the government of Kenya and an estimation of the related water footprints is important. This will provide a clear picture of where the country is headed in terms of water resource utilization in this sector and will help give guidance to efforts by relevant stakeholders to optimize this aspect. Electricity consumption forecasts, are mainly obtained from the ministry of energy in Kenya. Water use calculation are based once more on the water footprint concept.

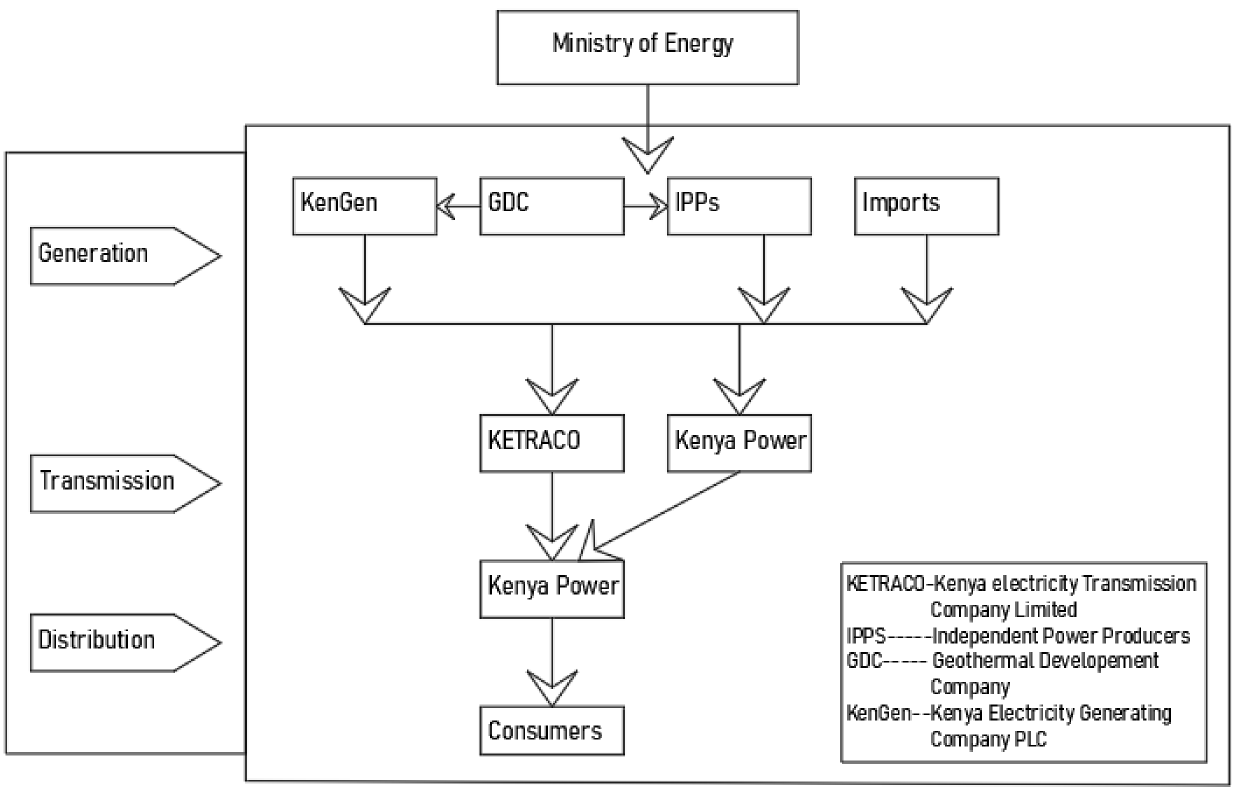
# Chapter 5: Data

Chapter four of this study introduces the reader to data collected essential in meeting the objective of this research.

## 5.1 Structure of Kenya's electricity System.

Kenya's energy sector is spearheaded by the Ministry of Energy which has several government-owned and Semi-Autonomous Agencies (SAGAs) under it. These agencies have different mandates within Kenya's energy sector. Kenya Power and Lighting Company PLC (Kenya) which is the source of the primary data forming the basis of analysis for this research is one of the companies under the under the ministry of energy of the semi-autonomous kind. The government of Kenya is the main shareholder of Kenya Power taking up 50.1% of the company shares while the private sector owns 49.9% of the company. The key mandate of Kenya Power is the transmission and distribution of electricity fed into the national Grid by government owned producers, SAGAs, Independent Power Producers (IPPs) and Imports from Neighboring Countries. ***Figure 4*** below shows the structure of Kenya's energy sector indicating the position of Kenya Power in the entire energy equation.

**Figure 4.** *Structure of Kenya's Energy System*




*Note.* Adapted from "Least Cost Power Development Plan; Study Period (2020-2030)" by the Republic of Kenya, 2020.

## 5.2 Data description

### 5.2.1 Base data

The base data used in this study is exclusively owned and was donated by Kenya Power. This data is mainly composed of the monthly amount of electricity fed into the national grid by electricity generation power plants owned by the Kenya Electricity Generating Company PLC (KenGen), Independent Power Producers (IPPs) and net electricity imports from Uganda, Tanzania and Ethiopia which are neighboring countries with electricity exchange agreements with Kenya. The data collected covers the entirety of the study period of this research which is from 2016 to 2020. For purposes of illustration, ***Table 6*** and ***Table 7*** display electricity amounts only for the year 2016 from different producers cumulated together and grouped according to electricity types like wind, solar etc.

**2016 electricity amounts fed into the national grid**

***Table 6.*** *Monthly amount of electricity fed into Kenya's national grid for 2016*

| Month<br>Sources (MWh) | Jan-16 | Feb-16 | Mar-16 | Apr-16 | May-16 | Jun-16 | Jul-16 | Aug-16 | Sep-16 | Oct-16 | Nov-16 | Dec-16 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Hydro** | 326,711 | 299,848 | 338,093 | 306,563 | 337,692 | 351,748 | 340,837 | 368,167 | 353,206 | 360,887 | 322,226 | 308,497 | **4,014,476** |
| **Geothermal** | 393,372 | 392,395 | 384,128 | 395,361 | 404,447 | 343,003 | 394,267 | 346,565 | 336,933 | 364,992 | 372,471 | 375,805 | **4,503,740** |
| **Thermal** | 96,995 | 98,352 | 117,770 | 106,795 | 96,365 | 116,906 | 110,305 | 137,543 | 136,468 | 134,854 | 158,096 | 158,026 | **1,468,475** |
| **Wind** | 5,000 | 6,710 | 6,694 | 4,213 | 2,419 | 2,072 | 1,850 | 3,715 | 3,750 | 5,763 | 6,182 | 8,019 | **56,388** |
| **Solar** | 141 | 115 | 123 | 110 | 113 | 116 | 111 | 133 | 138 | 130 | 135 | 155 | **1,519** |
| **Biomass** | 21 | 63 | 35 | 28 | 89 | 75 | 66 | 57 | 77 | 44 | 152 | 110 | **817** |
| **Total Energy Consumed** | **822,241** | **797,484** | **846,843** | **813,071** | **841,125** | **813,920** | **847,437** | **856,179** | **830,571** | **866,670** | **859,263** | **850,611** | **10,045,416** |

*Note.* Adapted from electricity consumption data collected from Kenya power which is the company mandated to manage transmission and distribution of electricity fed into the national electricity grid.

**Imports and exports of electricity between Kenya and its neighbors for 2016**

***Table 7.*** *Electricity imports and exports between Kenya Uganda, Tanzania and Ethiopia*

| Month<br>Im & Ex (MWh) | Jan-16 | Feb-16 | Mar-16 | Apr-16 | May-16 | Jun-16 | Jul-16 | Aug-16 | Sep-16 | Oct-16 | Nov-16 | Dec-16 | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Imports from Uganda** | 6,402,550 | 5,264,300 | 5,939,300 | 5,221,050 | 5,678,100 | 6,069,750 | 6,221,000 | 6,955,350 | 7,001,100 | 6,829,100 | 9,448,365 | 12,184,335 | **83,214,300** |
| **Exports to Uganda** | 3,380,200 | 3,564,350 | 3,501,050 | 3,218,900 | 3,436,000 | 3,326,350 | 3,331,300 | 2,961,600 | 3,005,180 | 4,106,795 | 1,408,445 | 1,715,650 | **36,955,820** |
| **Imports from Tanzania** | 155 | 153 | 103 | 191 | 272 | 131 | 168 | 168 | 168 | 168 | 402 | 324 | **2,403** |
| **Exports to Tanzania** | 172,200 | 187,080 | 195,240 | 199,680 | 180,360 | 193,860 | 163,380 | 132,360 | 149,100 | 201,120 | 186,420 | 193,860 | **2,154,660** |
| **Imports from Ethiopia** | 221,700 | 261,060 | 260,700 | 170,340 | 190,300 | 281,600 | 301,080 | 275,520 | 265,320 | 280,500 | 266,520 | 260,220 | **3,034,860** |
| **Exports to Ethiopia** | - | - | - | - | - | - | - | - | - | - | - | - | - |

*Note.* Adapted from electricity consumption data collected from Kenya power which is the company mandated to manage transmission and distribution of electricity fed into the national electricity grid.

### 5.2.2 The Electricity mix of immediate neighboring countries of Kenya: Uganda, Tanzania and Ethiopia

One of the parameters used in this study to calculate the WF of electricity consumption in Kenya is the electricity imports to Kenya from three of its neighbors namely Uganda, Tanzania and Kenya. The problem is there is no data about the energy mixes of this imports in order to properly allocate the imports among different components of the energy mixes. The electricity mixes for the three countries in terms of percentages from 2015 to 2019 as shown in ***Table 2***, ***Table 3*** and ***Table 4*** in the case study chapter were adapted from Ritchie (2020).

### 5.2.3 The Target numbers of electricity mix in Kenya from 2012 to 2030

One of the objectives of this study is to estimate and compare WF for both the period of study (2016-2020) and for 2030 which is the year the Kenyan government has anchored most of its development agenda coined as "Vision 2030". Kenya has an ambitious plan to increase its electricity production in terms quantity and to shift its energy mix from high dependency on hydroelectricity to a more dependency on geothermal, wind and solar sources. The target numbers can be seen in ***Table 1*** in the case study chapter. In a nutshell, the government is aiming to have approximately 80% of its electricity coming from renewables.

### 5.2.4 Water intensity factors for non-hydro sources of electricity in Kenya.

For the estimation of the WF of the various electricity sources and for the entire system, knowledge of the WIFs for the various electricity sources is key. The WIFs used in this research for the estimation of the WF of thermal, geothermal, wind, solar and biomass sources of electricity in Kenya, have been adopted from the researches by (Macknick et al., 2012; Roidt et al., 2020). The WIF for each electricity source is calculated by averaging water consumption factors for different electricity generation approaches used to generate that type of electricity. According to the same studies, wind and solar electricity sources have negligible WIFs compared to other non-hydro sources which explains the null values under the corresponding sources in ***Table 8*** in the results and discussion section. The adopted WIFs in this study for all non-hydro sources are displayed in the same table. WIFs for hydro sources of electricity sources in Kenya are estimated in this research. All the steps taken to estimate the WIF for hydro sources are explained in the methodology section and results displayed in the results and discussion chapter.

# Chapter 6: Results and discussion

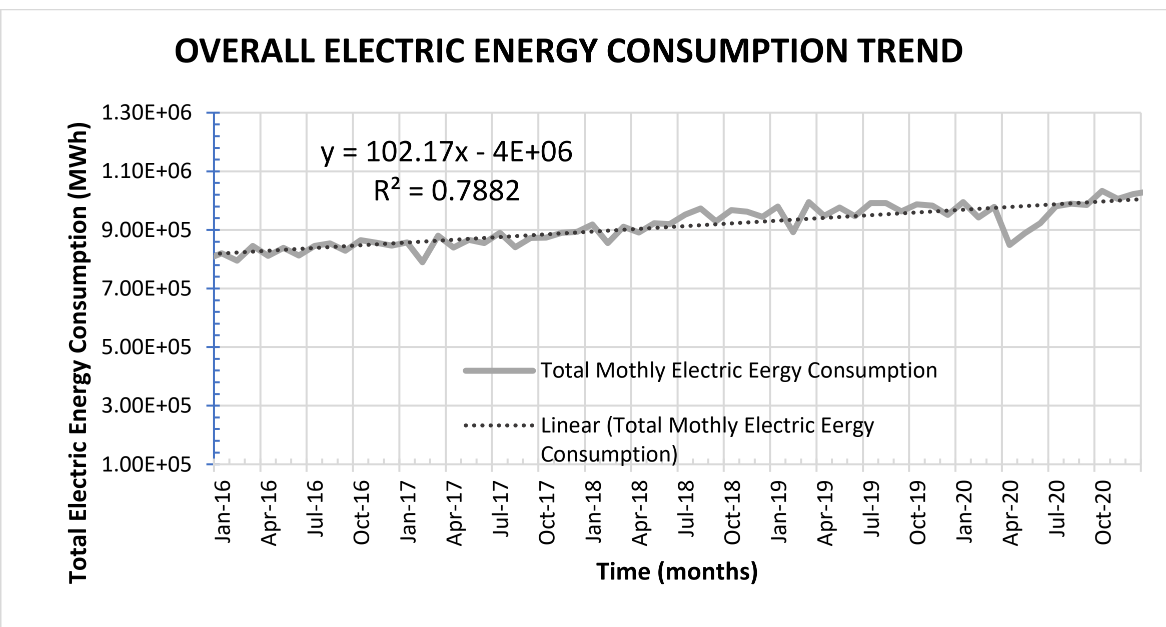
In this chapter, the results obtained in the entirety of this research are presented, intersected and viewed deeply to give them meaning and to provide answers to questions that this research poses. In essence, it seeks to expound and dissect the entire electricity system in Kenya up to the individual sources of electricity in terms of their consumption and the implication of the consumption on water resource availability in Kenya.

## 6.1 Electricity consumption trend in Kenya (2016 to 2020).

### 6.1.1 Overall electricity consumption trend

This subsection takes a look at the trend of electricity consumption in Kenya for the study period of this research on a monthly basis from January 2016 to December 2020. As seen in ***Figure 5*** below, a steady growth is seen with minor oscillations from time to time. Dips are seen at the end of every year stretching to the beginning of another year which signifies a general low productivity in Kenya during this time of the year. This coincides with a period every year when most Kenyan citizens are winding up the festive season and embarking into work which happens in December of every year plus a bit of the beginning of the following year. During this period electricity intensive activities are at the lowest. Other than this normal phenomenon, the overall growth trend of the electricity curve is relatively low and steady with an average linear annual growth of 0.0378%.

**Figure 5.** *Monthly energy consumption from January 2016 to December 2020*




### 6.1.2 Trend of Kenya's electricity mix and cumulative quantities (2016-2020)

**Kenya's electricity mix and cumulative numbers for 2016**

As seen in ***Figure 6*** below, in 2016, geothermal sources took the bigger share of Kenya's annual electricity with 44.83% (4,503,740 MWh) followed closely by hydro sources with 39.96% (4,014,476 MWh). The remaining 15% was taken majorly by thermal sources with 14.62% (1,468,475 MWh) while wind, solar and biomass sources had relatively almost negligible portions of 0.56% (56,388 MWh), 0.02% (1,519 MWh) and 0.01% (817 MWh) respectively. The cumulative total electricity consumed in Kenya in 2016 as seen in ***Figure 7*** was 10,045,416 MWh.

**Kenya's electricity mix and cumulative numbers for 2017**

In 2017, represented in ***Figure 6*** below, there is a drop in the share of hydroelectric sources from about 40% (4,014,476 MWh) in 2016 to approximately 28% (2,958,816 MWh). This drop is seen to be majorly compensated by thermal sources which rise from 15% (1,468,475 MWh) in 2016 to 24% (2,544,951 MWh) in 2017. The share of geothermal sources increased slightly from about 45% (4,503,740 MWh) the previous year to 47% (4,856,029 MWh) in 2017. wind, solar and biomass sources had almost negligible portions once more of 0.59% (61,064 MWh), 0.03% (3,566 MWh) and 0.02% (1,902 MWh) respectively. The cumulative total electricity consumed in Kenya in 2017 as seen in ***Figure 7*** was 10,426,329 MWh a 3.79% increase from the previous year.

**Kenya's electricity mix and cumulative numbers for 2018**

***Figure 6*** below again shows the electricity proportions for 2018. A slight development different from the previous 2 years is seen. This is the emergence of wind sources increasing from 0.59% (61,064 MWh) in 2017 to 3.34% (374,268 MWh) in 2018. hydro sources also regained their territory almost like in 2016 with a 28% (4,078,809 MWh) share in 2018. Consequently, thermal sources which looks like the substitute to hydro sources went down from 24% (2,544,951 MWh) in 2017 to 14% (1,549,438 MWh) in 2018. Geothermal sources maintained their lead share with 46% (5,171,551 MWh) in 2018. A slight increase in solar sources is seen as well standing at 0.14% (15,745 MWh) from 0.03% (3,566 MWh) in the previous year while biomass sources remained almost static with 0.02% (2,506 MWh) in 2018. The cumulative total electricity consumed in Kenya in 2018 as seen in ***Figure 7*** was 11,192,322 MWh a 7.35% increase from the previous year.

**Kenya's electricity mix and cumulative numbers for 2019**

In 2019, there was a continued rapid growth of wind sources and a slight growth of solar sources. As seen in ***Figure 6***, wind sources rose from 3.34% (374,268 MWh) to approximately 13% (1,560,788 MWh) while solar sources rose from 0.14% (15,745 MWh) to 0.82% (95,297 MWh). The growth in wind and solar sources dealt a blow to the thermal portion. thermal sources went down from 14% (1,549,438 MWh) in 2018 to 11% (1,323,987 MWh) in 2019. hydro sources on the other hand had a slight drop in the amount registered. That is from about 4,078,809 MWh (28%) in 2018 to approximately 3,375,281 MWh (29%) in 2019. Geothermal sources remained in the lead almost as in previous years taking 46% (5,321,856 MWh). Biomass sources remained relatively low at 0.03% (316 MWh) in 2019. The cumulative total electricity consumed in Kenya in 2019 as seen in ***Figure 7*** was 11,677,525 MWh a 4.34% increase from the previous year.

**Kenya's electricity mix and cumulative numbers for 2020**

As seen again in ***Figure 6***, there was not much change of the electricity mix in Kenya in 2020 which is the last year of the study period of this research. The exception was the usual fluctuation of hydro sources with the detriment of thermal sources. hydro rose from about 29% (3,375,281 MWh) in 2019 to approximately 37% (4,346,547 MWh) in 2020 while thermal sources dropped from 11% (1,323,987 MWh) in 2019 to about 7% (761,322 MWh) in 2020. The rest of the sources remained quite stagnant as compared to 2019 with a bit of drop in proportion due to the growth of hydro sources. Geothermal, wind, solar and biomass took approximately, 44% (5,110,545 MWh), 11% (1,329,642 MWh), 0.78% (90,276 MWh) and 0.02% (316 MWh) respectively. The cumulative total electricity consumed in Kenya in 2017 as seen in ***Figure 7*** was 11,638,516 MWh a slight decrease from the previous year (-0.33%).

**Figure 6.** *Kenya's electricity mix changes (2016-2020)*

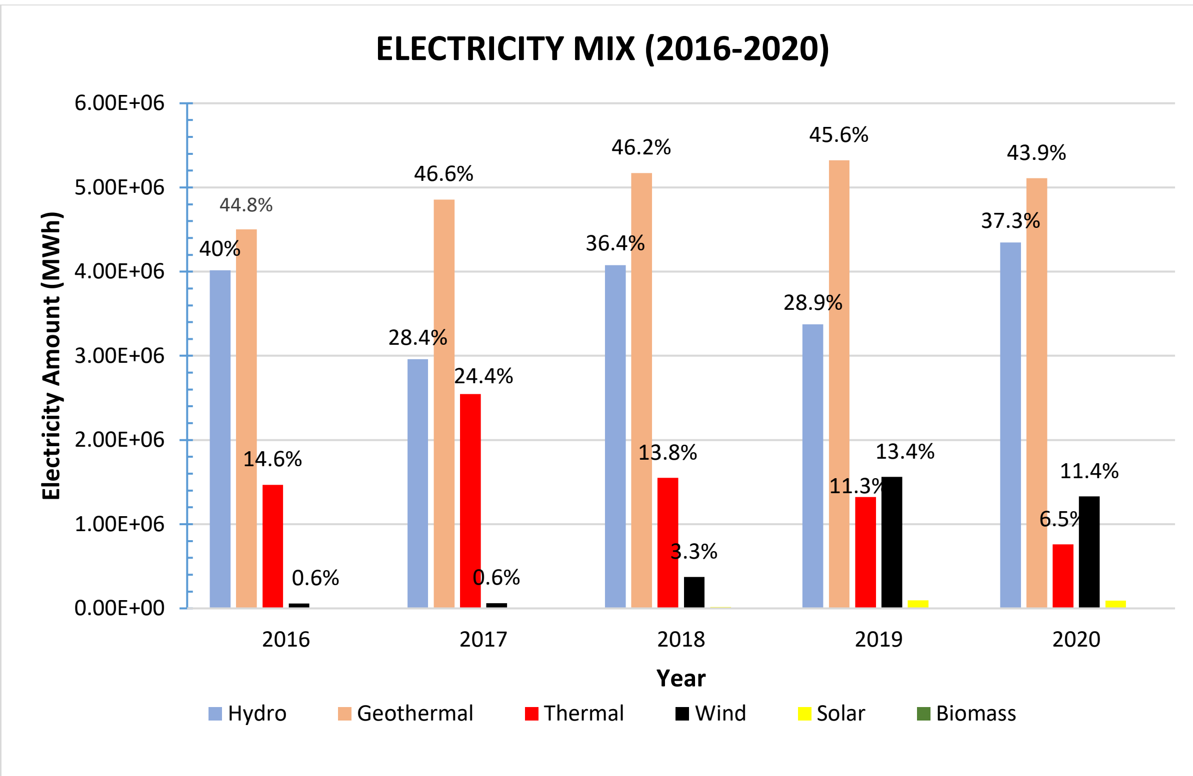
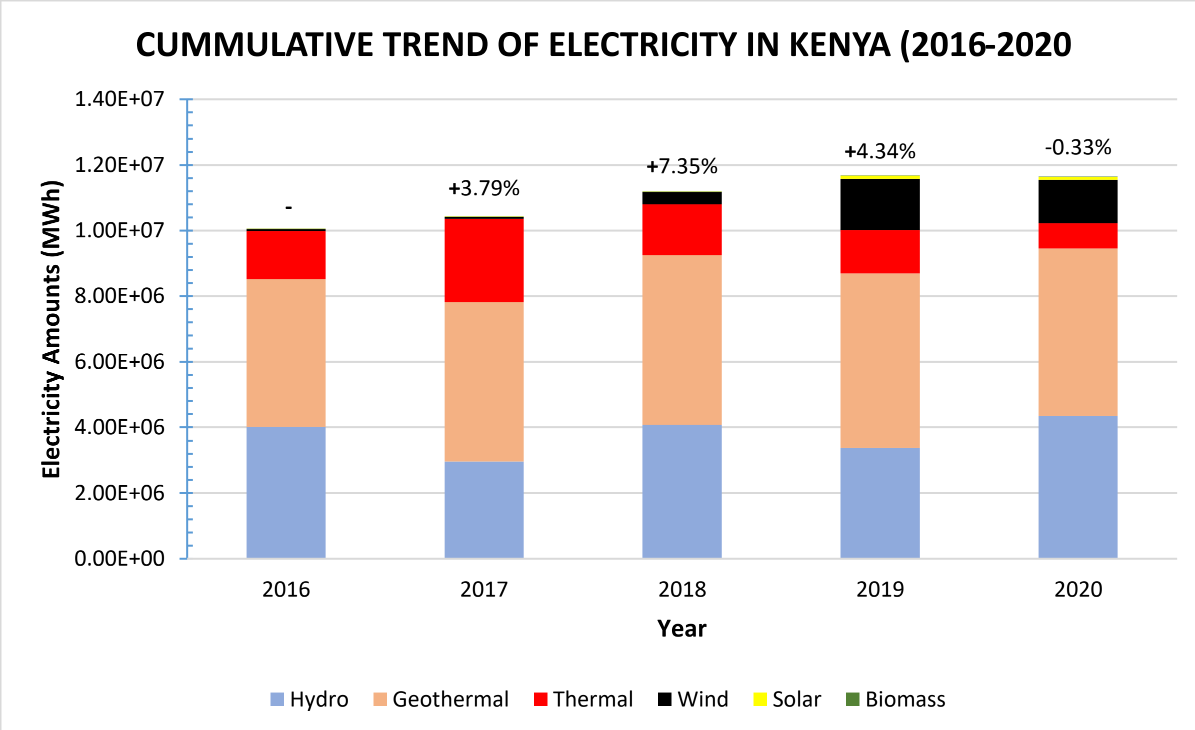
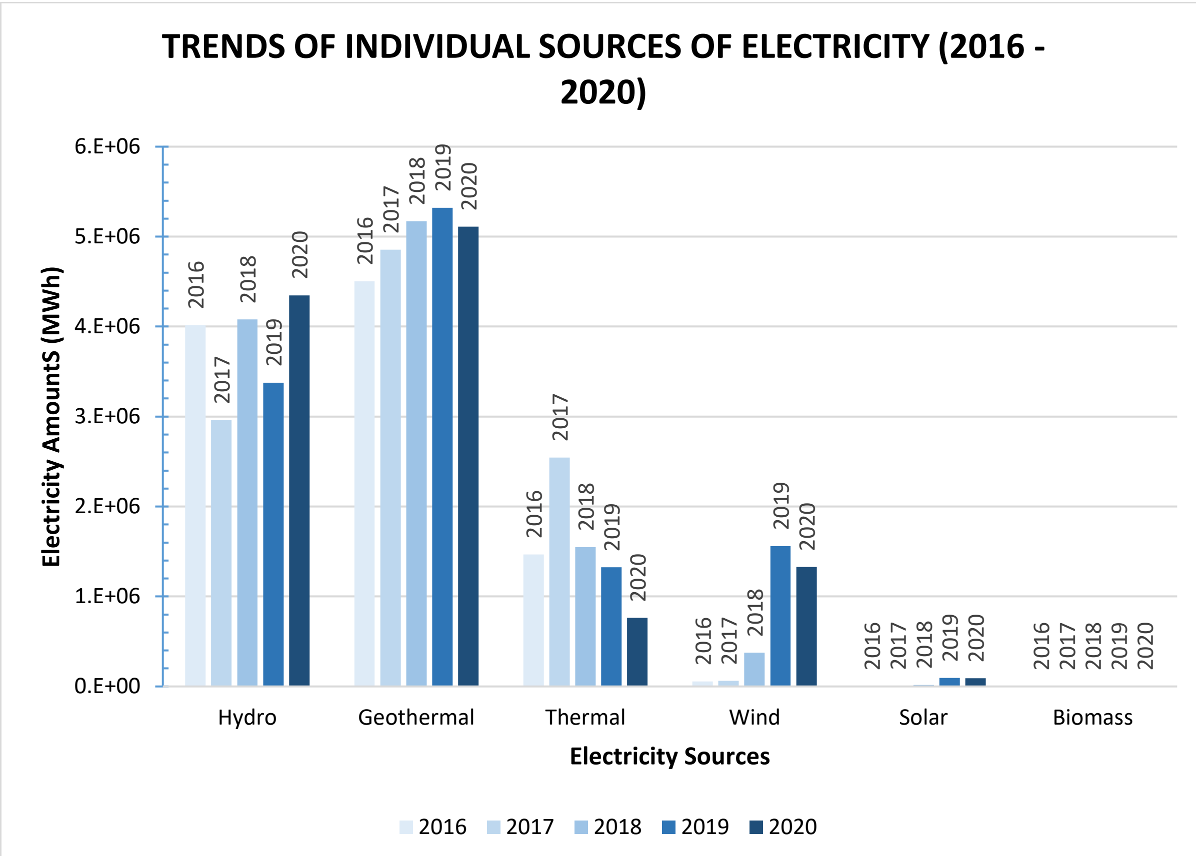


**Figure 7.** *Kenya's cumulative trend of electricity consumption (2016-2020)*




To understand and to really appreciate the trends for all the sources of electricity in Kenya, ***Figure 8*** provides a closer look into the individual sources. Bars of the same electricity source but of different years within the study period are clustered together. This also provides a chance to visualize the comparison in terms of influence of the various sources of electricity to the entire electricity system in Kenya over the entire study period.

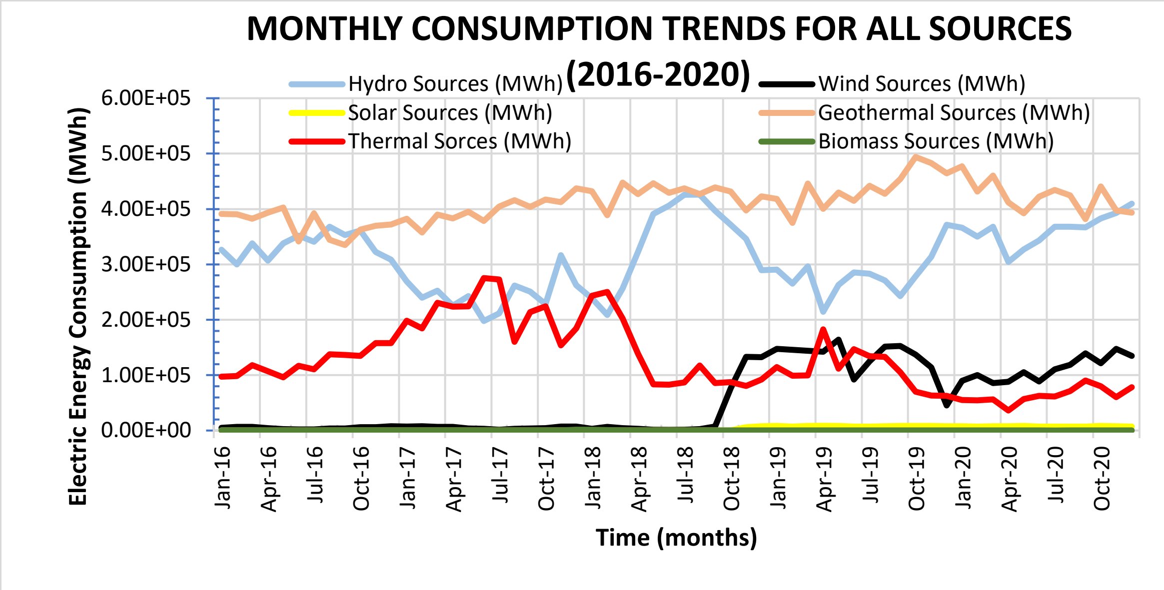
**Figure 8.** *A closer look at the trends and comparison between individual sources of electricity in Kenya (2016-2020).*




*Note.* Bars of the same electricity source but of different years within the study period are clustered together with increasing weights of the blue color starting from 2016 with the lightest blue and finishing with 2020 with the deepest blue.

In summary, Kenya's electricity trend over the study period (2016-2020) shows a steady transition from traditional non-renewable sources (thermal sources) towards renewable sources with geothermal electricity leading the pack followed closely by hydroelectricity with wind and solar sources picking up momentum from the year 2018 onwards. Looking at the trends of each of all the electricity sources in Kenya plotted together from January 2016 to December 2020 in ***Figure 9*** below, there is an apparent dominance of two electricity sources namely, geothermal and hydro sources throughout the period. Geothermal sources show a steady growth while hydro sources show a bit of fluctuation from year to year with thermal sources acting as a substitute to times when hydro sources are on a dip. It is only after July 2018 when wind and solar sources emerged to take up some piece of the energy mix cake to the detriment of thermal sources.

**Figure 9.** *Overall Monthly Consumption Trends (all Sources) 2016-2020*




## 6.2 Water footprint trend for electricity consumption in Kenya (2016 to 2020).

### 6.2.1 Water intensity factors (WIF) and sensitivity analysis.

#### a) Water intensity factors for non-hydro sources of electricity in Kenya.

The WIFs used in this research for the estimation of the WF of thermal, geothermal, wind, solar and biomass sources of electricity in Kenya, have been adopted from the studies by Macknick et al. (2012) and Roidt et al. (2020). The WIF for each electricity source is calculated by averaging water consumption factors for different electricity generation approaches used to generate that type of electricity. According to the same studies, wind and solar electricity sources have negligible WIFs compared to other non-hydro sources. The adopted WIFs in this study for all non-hydro sources are displayed in ***Table 8*** below.

**Table 8.** *Water Intensity Factors for non-hydro sources of electricity*

| **Energy Mix** | **Water Intensity Factor (m3/MWh)** |
|---|---|
| **Geothermal** | 0.05 |
| **Thermal** | 1.82 |
| **Wind** | 0 |
| **Solar** | 0 |
| **Biomass** | 1.36 |

#### b) Water intensity factors estimated for hydro sources of electricity in Kenya.

Surface areas of all reservoirs involved in hydroelectricity generation in Kenya estimated using Google Earth polygon measurement tool are displayed in hectares in the fourth column read from left in ***Table 9*** below.

**Table 9.** *All reservoir-based hydroelectricity generation plants with related characteristic factors of interest to this research.*

| **Hydro Plant Station** | Type | **Installed Capacity (MW)** | **Reservoir Area (Ha)** | **Flooded Area per unit of Plant Capacity (ha/MW)** | **Water Intensity Factor ($m^3$/GJ)** | **Water Intensity Factor ($m^3$/MWh)** | **Weighting Factor** | **Contribution to the Weighted Average ($m^3$/GJ)** |
|---|---|---|---|---|---|---|---|---|
| **Kiambere** | **Reservoir** | **168.00** | **2,500.00** | **14.88** | **18.00** | **64.80** | **0.205379** | **3.70** |
| Masinga | Reservoir | 40.00 | 12,000.00 | 300.00 | 362.88 | **1,306.37** | 0.0488998 | 17.74 |
| Kindaruma | Reservoir | 72.00 | 245.00 | 3.40 | 4.12 | **14.82** | 0.0880196 | 0.36 |
| Kamburu | Reservoir | 94.00 | 1,128.00 | 12.00 | 14.52 | **52.25** | 0.1149144 | 1.67 |
| Gitaru | Reservoir | 225.00 | 298.00 | 1.32 | 1.60 | **5.77** | 0.2750611 | 0.44 |
| Turkwel | Reservoir | 106.00 | 2,187.00 | 20.63 | 24.96 | **89.84** | 0.1295844 | 3.23 |
| Tana | River | 20.00 | - | - | - | **-** | 0.0244499 | - |
| Sondu | River | 60.00 | - | - | - | **-** | 0.0733496 | - |
| Sangoro | River | 21.00 | - | - | - | **-** | 0.0256724 | - |
| Mini hydros | Mixed | 12.00 | - | - | - | **-** | 0.0146699 | - |
| **Total (MW)** | | | | | | | | **27.15** |

The installed capacities shown in megawatts in column three read from the left in **Table 9** above are obtained from the website of KENGEN which is one of the Kenya government's parastatals under the ministry of energy. The WIFs of each reservoir-based hydroelectricity generation plant which is a result of direct proportionality calculations are also listed in $m^3$/GJ and in $m^3$/MWh in the sixth and seventh column from left. Displayed as well in the second last column from left and listed without units are the weighting factors. The weighting factors are used to obtain the contribution amount of the WIF of each plant to the national weighted average which are displayed in the last column from left in $m^3$/GJ. Lastly, the final national weighted hydroelectricity WIF for Kenya is listed as 27.15 $m^3$/GJ in the last column from left and in the last cell of this column at the bottom end of **Table 9** above. This value is used afterwards in this research in hydroelectricity WF calculations and as one of the values in a range of overall hydroelectric WIFs put to test in a sensitivity analysis of the system.

### c) Sensitivity analysis

As is evident in ***Table 9*** above, the results of the estimated WIFs for the various hydroelectricity generation plants in Kenya shows a wide range of values. Gitaru plant with an estimate of 6 $m^3$/MWh has the lowest WIF while Masinga plant has the highest WIF standing at an estimate of 1,305 $m^3$/MWh. This is owing to the simple fact that Gitaru and Masinga have the smallest and the highest Surface Area to Installed Capacity Ratio respectively which is the factor dictating the WF of each hydroelectric generation plant. This massive variability among the various hydroelectricity generation plants in Kenya and within neighboring regions of Sudan and Ethiopia fosters uncertainty in the results of WF calculations in Kenya. Therefore, a sensitivity analysis is conducted with all the possible hydroelectricity WIFs factored into calculations to give a clear understanding of the implication of this variability on the WF of the entire electricity system in Kenya.

In consequence, scenarios one through five as seen in ***Table 10*** below are established to give this research a robust sensitivity analysis. The description of the five scenarios are given herein as follows; Scenario 1 is where the WIF used to estimate WF of hydroelectricity consumption in Kenya is the average of the WIFs of hydroelectricity scientifically estimated for Sudanese and Ethiopian regions. Scenario 2 is where the WIF used to estimate of hydroelectricity consumption in Kenya is a simple average of all the WIFs estimated for all reservoir hydroelectricity generation plants in Kenya. Scenario 3 is where the WIF of hydroelectricity consumption in Kenya is the weighted average of WIFs estimated for all reservoir hydroelectricity generation plants in Kenya. Scenario 4 is where the WIF used to estimate WF of hydroelectricity consumption in Kenya is the maximum WIF estimated among all reservoir hydroelectricity generation plants in Kenya. And finally, scenario 5 is where the WIF used to estimate WF of hydroelectricity consumption in Kenya is the minimum WIF estimated among all reservoir hydroelectricity generation plants in Kenya.

**Table 10.** *WIFs for all the scenarios of the sensitivity analysis performed in this research*

| **WIF** | **Water Intensity Factor ($m^3$/GJ)** | **Water Intensity Factor ($m^3$/MWh)** | **Scenario** |
|---|---|---|---|
| **Average WIF Sudan and Ethiopia** | 280.73 | 1,009.80 | **= WIF Scenario One** |
| **Normal Average WIF Kenya** | 42.61 | 153.26 | **= WIF Scenario Two** |
| **Weighted Average WIF Kenya** | 27.15 | 97.65 | **= WIF Scenario Three** |
| **Maximum WIF Kenya** | 362.88 | 1,305.32 | **= WIF Scenario Four** |
| **Minimum WIF Kenya** | 1.60 | 5.76 | **= WIF Scenario Five** |

Looking at the results of the sensitivity analysis as displayed in the ***Table 11*** below which shows the annual WF of electricity consumption in Kenya for different sensitivity analysis scenarios from 2016 to 2020, an existence of a huge range of hydroelectric WIFs changes the overall WF of electricity massively. The value 445 $m^3$/MWh listed in larger font in the last cell of the last column counted from left in ***Table 11*** shows the average of the differences between the maximum and the minimum WF values among all the scenarios considered in the sensitivity analysis of this research.

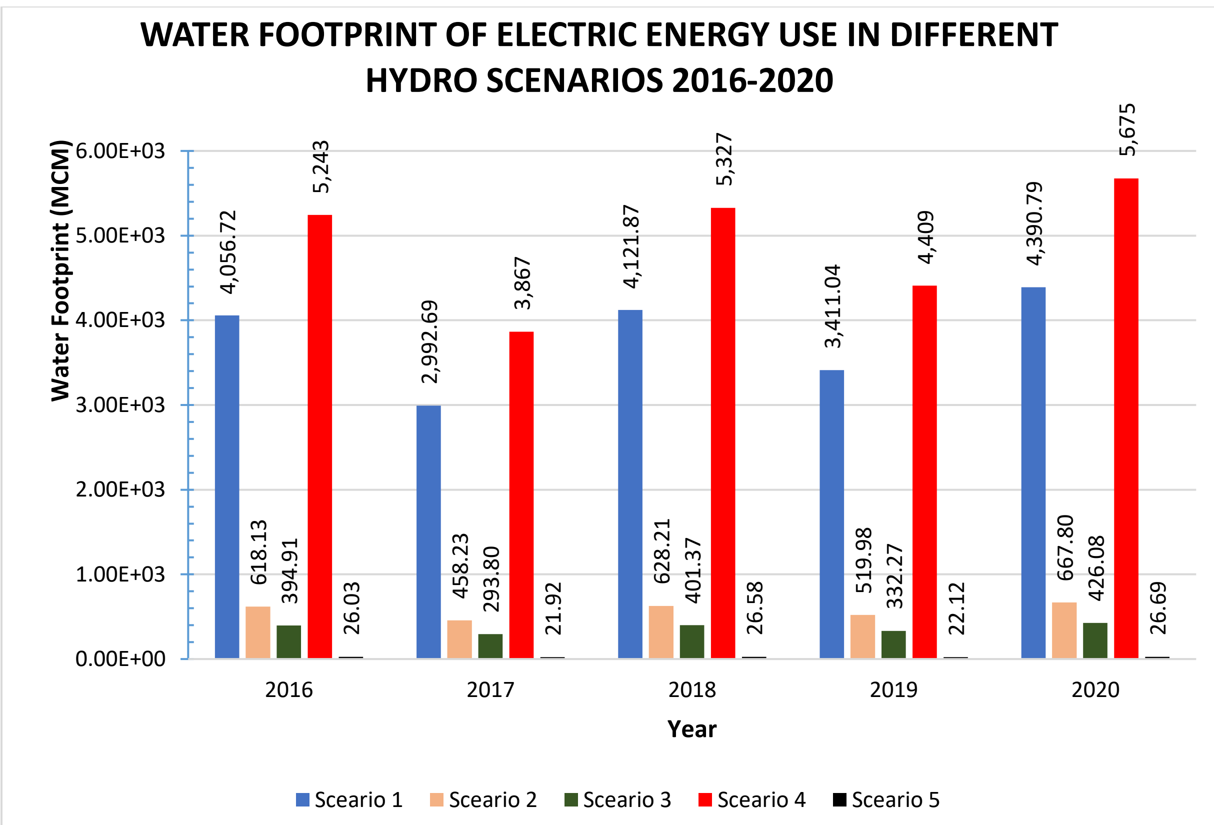
**Table 11.** *Annual WF of electricity consumption in Kenya for different sensitivity analysis scenarios 2016-2020*

| **Scenario / Year** | **Water Footprint Scenario 1 ($m^3$/MWh)** | **Water Footprint Scenario 2 ($m^3$/MWh)** | **Water Footprint Scenario 3 ($m^3$/MWh)** | **Water Footprint Scenario 4 ($m^3$/MWh)** | **Water Footprint Scenario 5 ($m^3$/MWh)** | **Difference between Maximum and Minimum ($m^3$/MWh)** |
|---|---|---|---|---|---|---|

| | | | | | | |
|---|---|---|---|---|---|---|
| **2016** | 404 | 62 | 39 | 522 | 2.6 | **519** |
| **2017** | 287 | 44 | 28 | 371 | 2.1 | **369** |
| **2018** | 368 | 56 | 36 | 476 | 2.4 | **474** |
| **2019** | 292 | 45 | 28 | 378 | 1.9 | **376** |
| **2020** | 377 | 57 | 37 | 488 | 2.3 | **486** |
| **Average** | 346 | 53 | 34 | 447 | 2 | **445** |

This difference is relatively high and outlines the great sensitivity of quantification of WF of the overall electricity system in Kenya to the tinkering by a huge margin of the WIFs for hydroelectricity consumption in Kenya. The total annual amount of water consumed by the whole electricity system in Kenya for all the years within the study periods of this research (2016-2020) are displayed in MCM (Million Cubic Meters) in ***Figure 10*** below.

**Figure 10.** *WF of electricity use in different hydro scenarios 2016-2020*




*Note.* The results of the different scenarios are displayed with different colors as follows; Scenario 1 with blue, Scenario 2 with pink, Scenario 3 with green, Scenario 4 with red and Scenario 5 with black.

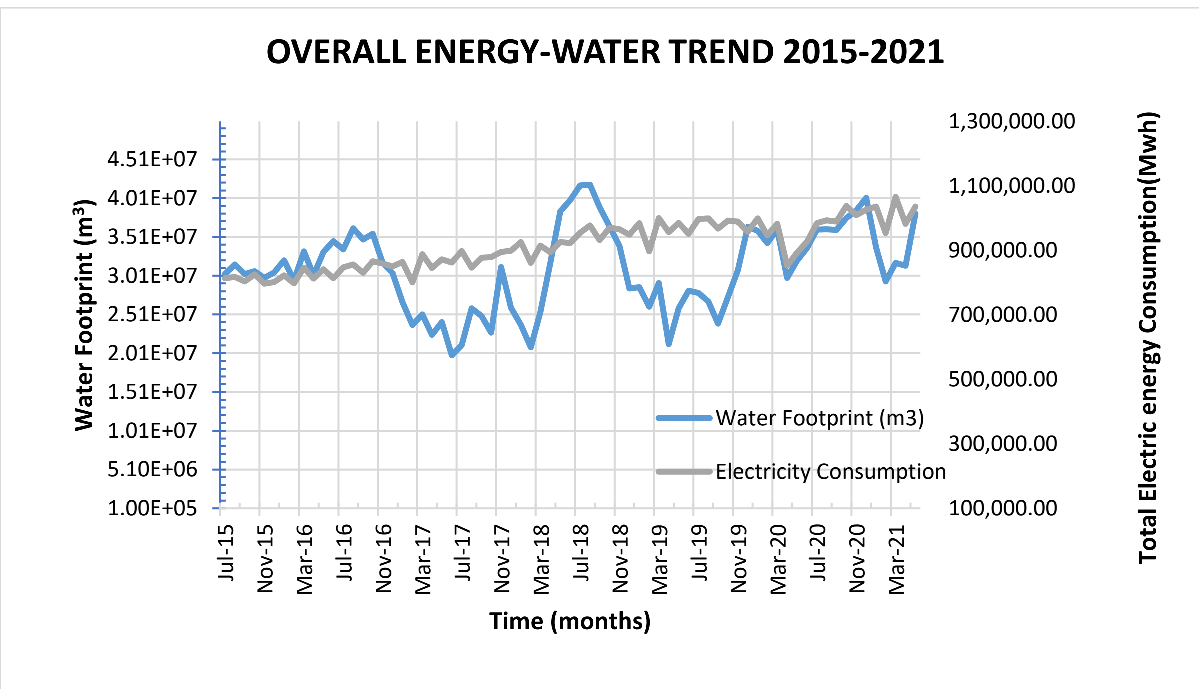
This chart once more, displays the huge range of WF of electricity consumption in Kenya when a huge range of hydroelectric energy's WIFs are used in WF calculation of the entire system as already explained above.

Due to the huge variability of results obtained from having a huge range of WIFs from one hydroelectric generation plant to another, this research looks to recommend Scenario 3 highlighted in green above as the safest scenario. This is because the mode of estimation of the hydroelectricity WIF applied in this scenario puts into account the weighted contribution of the various hydroelectricity generation plants to the national electricity grid. This is done by incorporating the installed capacities of hydroelectricity generation plants in the estimation of the weighting factors of each plant which directly translates to how much electricity is generated and fed into the national electricity grid from each hydroelectric generation plant in Kenya. In other words, putting into account the individual contribution of the various hydroelectricity generation plants in terms of quantity of hydroelectricity fed into the nation electricity grid also means that the right amount of water consumed by each plant is factored in.

Henceforth, in the subsequent subsections of the results and discussion chapter of this research, the WIF used in scenario 3 is used as the sole WIF for hydroelectricity sources in Kenya.

### 6.2.2 The role of hydroelectricity in driving the entire water footprint of the electricity system.

**Figure 11.** *WF trend plotted together with the electricity consumption trend in Kenya 2015-2021*




As seen in ***Figure 11*** above, there has been a steady increase of the annual electricity consumption in Kenya for the five years under study in this research i.e. 2016 to 2020. The steady increase has meant that the annual electricity consumption in Kenya rose from 10,045,416 MWh in 2016 to 11,638,516 MWh in 2020 which means an increase of 1,593,100 MWh which is approximately +16% change. The steady increase in electricity consumption is attributed to the continued development in this sector in terms of increasing production of already influential electricity sources such as geothermal which showed a steady increase, solar and wind whose generation rose significantly from the year 2018 onwards having been present subtly before 2018 as seen in ***Figure 9***. But looking at the WF of the overall electricity consumption, it has been very unstable and displays substantial oscillation with an overall slight decline when the value of 2016 is compared to the value of 2020 which are 39 $m^3$/MWh and 37 $m^3$/MWh respectively. This is a -7% change.

Zooming closer into the temporal electricity mixes in Kenya from 2015 to 2021 as seen in ***Figure 12*** below ,viewed together with ***Figure 13*** below showing the WF trend of electricity consumption in Kenya 2015-2021 , it can be seen that the hydroelectricity is at its highest percentage of the energy mix during the months when there is a high value of the WF of the overall system. The three peaks of the WF curve appear in 2016, 2018 and 2020. This coincides with when there are the highest percentages of the hydro portion of the mix. That is, in 2016 when we have 39.96% which is the highest within the study period, in 2018 with 36.44% and in 2020 with 32.92%. The opposite is also true as high percentages are preceded and succeeded by low percentages of hydroelectricity which also match with the dips in the curve. It is also evident that the emergence of wind and solar energy in the year 2018 to 2020 there is a relative stability of the WF curve despite continued oscillation of the portion of hydroelectric power. This gives an indication of the benefit of less water intensive electricity sources going into the future.

**Figure 12.** *Electricity mix in Kenya 2015 to 2021*.

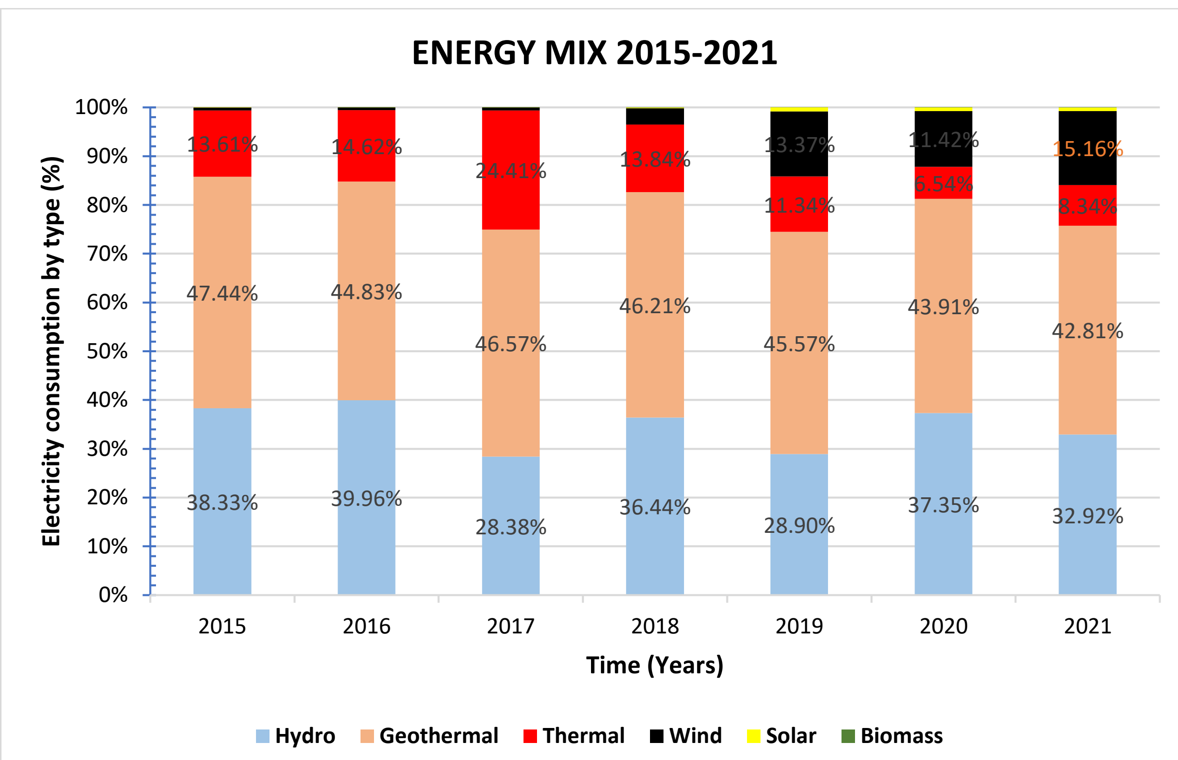
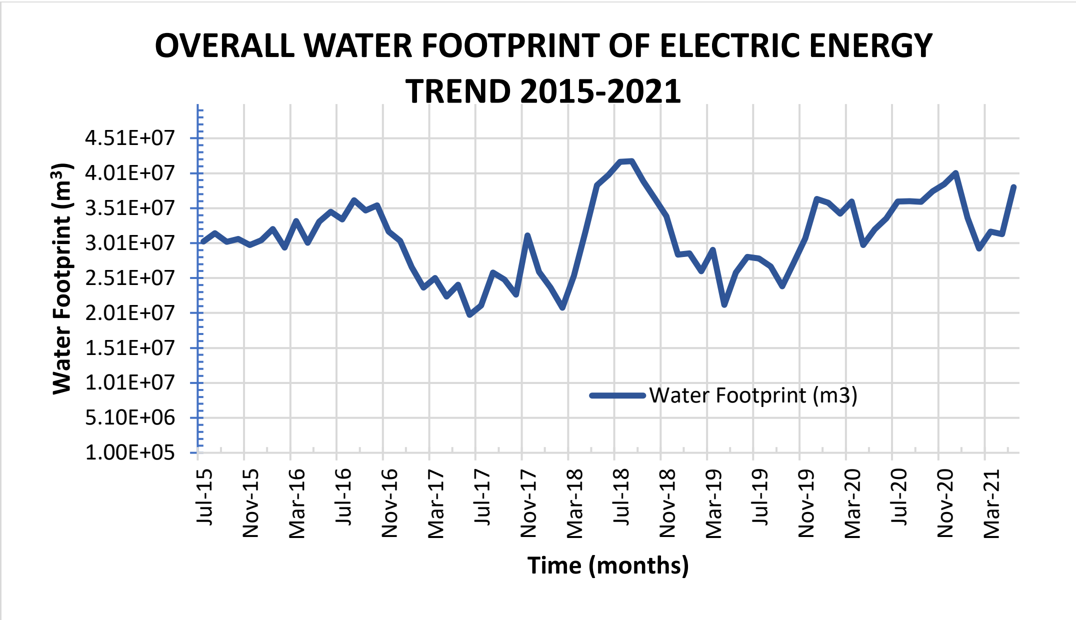
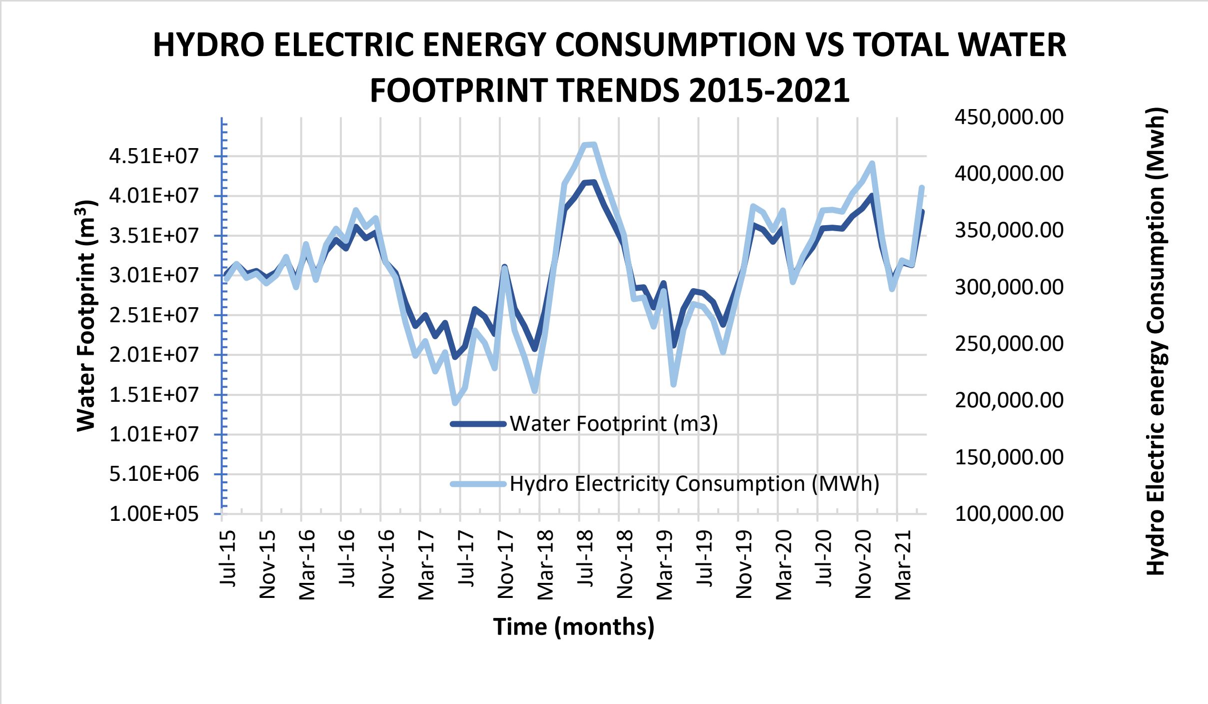


**Figure 13.** *WF trend of electricity consumption in Kenya 2015-2021*




The correlation between overall water consumption by the electricity system to hydroelectricity sources in Kenya is further demonstrated when the trend of total WF of the system is plotted together with the trend of hydro electricity consumption. The two curves show a very similar and almost overlapping pattern as seen in ***Figure 14*** below.

**Figure 14.** *WF trend plotted together with the hydro electricity consumption 2015-2021*

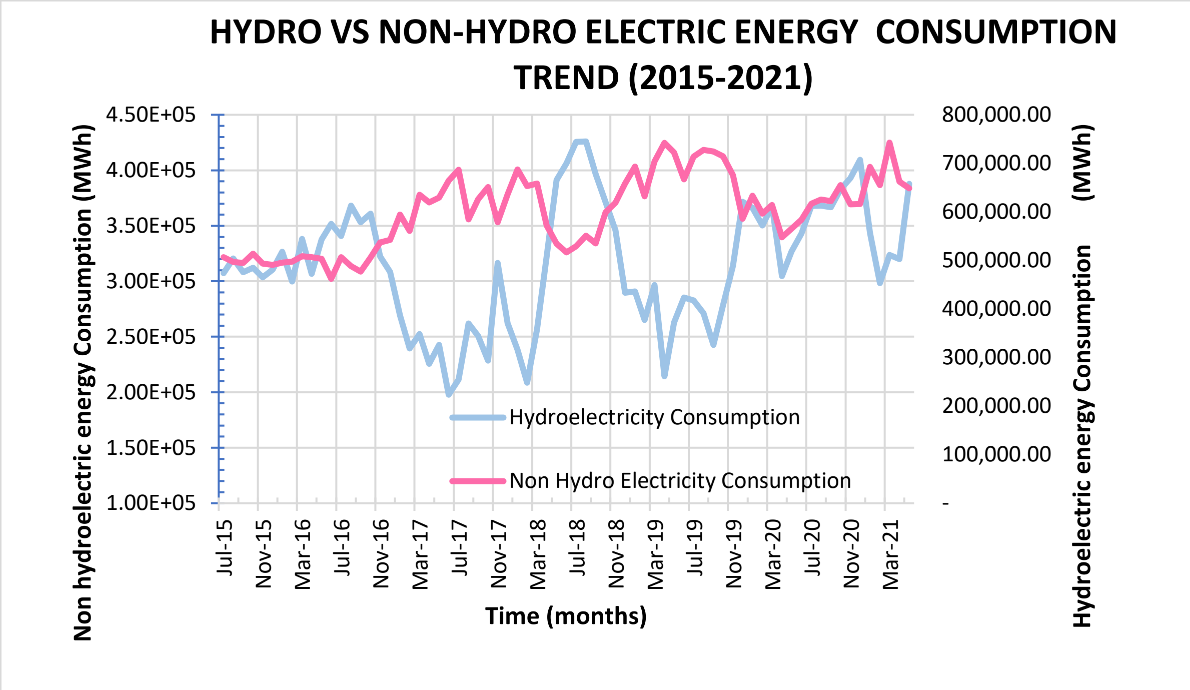



This explains the conjoined relationship between hydroelectricity consumption and high-water consumption by the entire system.

### 6.2.3 Illustration of the positive impact of utilizing non-hydroelectricity sources on the overall water footprint of the electricity system.

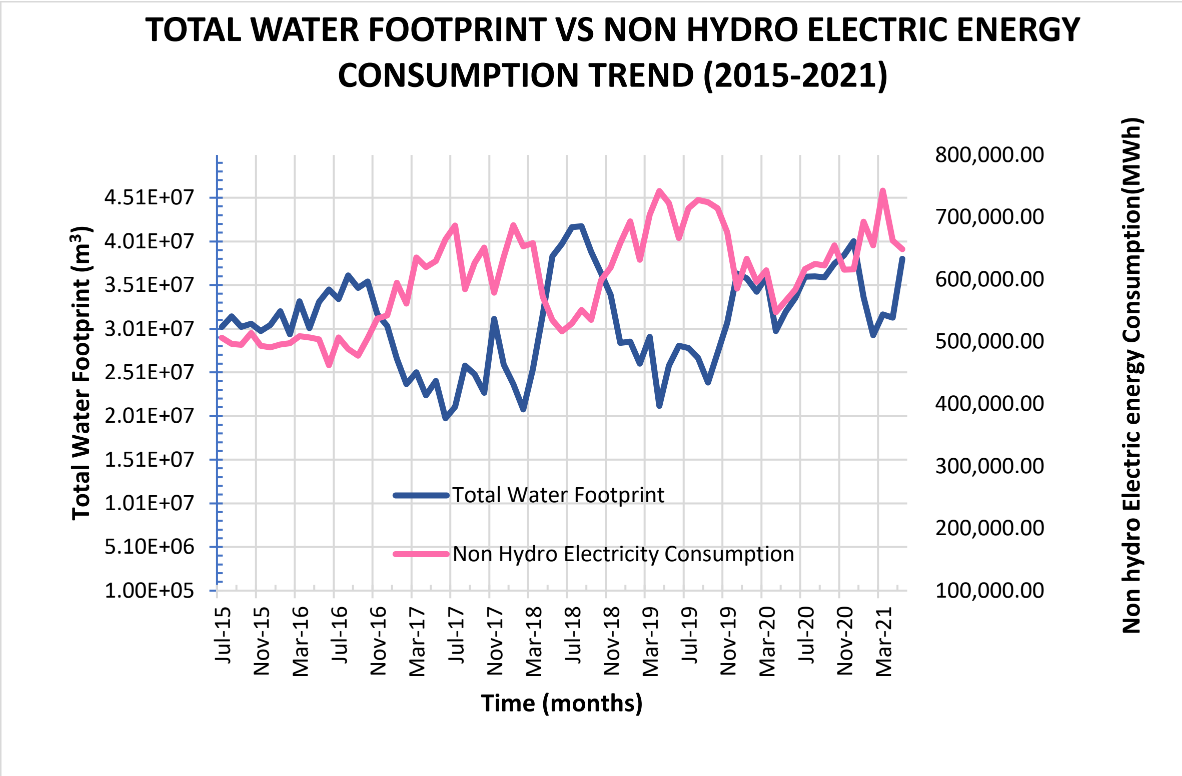
A plot of hydro electricity consumption vs non-hydroelectric sources of electricity in Kenya in ***Figure 15*** below shows their counter fluctuation over time. The fluctuation of hydroelectricity over time is due to perennial changes in seasonal weather patterns that lead to seasonal water abundance and sometimes droughts which causes fluctuation in the levels of hydroelectric reservoirs. This renders a high fluctuation in the amount of hydroelectricity generated. To maintain a steady supply of electric energy, the relevant stakeholders of the Kenyan energy system counter the fluctuation of hydroelectricity by increasing or decreasing non-hydro sources to compensate for the change.

**Figure 15.** *Hydro electricity consumption vs non-hydroelectric sources of electricity in Kenya.*




Unlike the direct relationship of hydroelectricity sources to the overall WF of electricity systems, non-hydro sources are indirectly proportional to the overall WF of the electricity system. This is illustrated by ***Figure 16*** below. This means that the combined effect of reduction of hydro sources of electricity and the increase of non-hydro sources will substantially contribute to the reduction of WF of electricity in the current and future developments in Kenya's electricity system.

**Figure 16.** *Total WF vs non-hydro electricity consumption trend (2015-2021).*

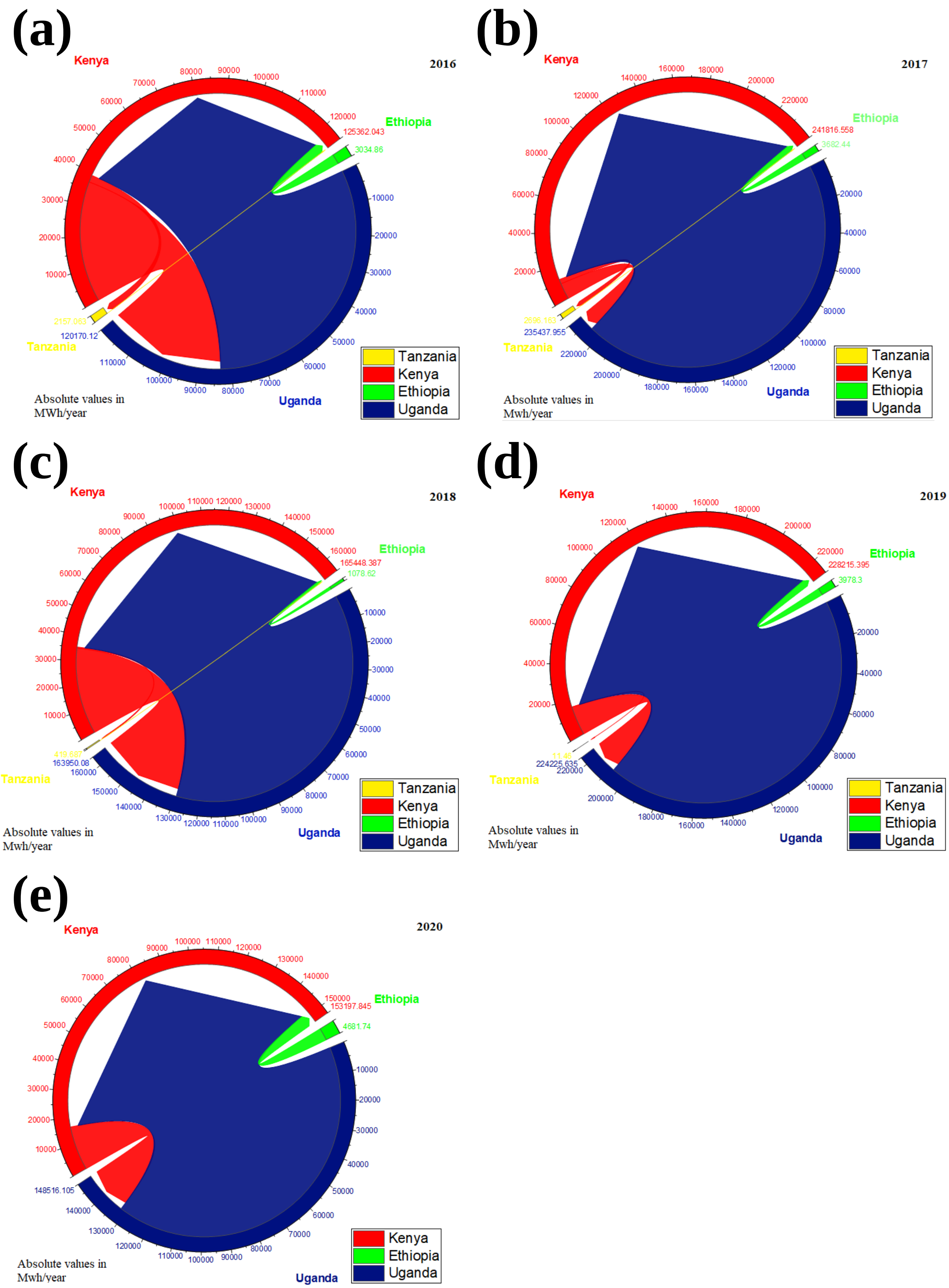



## 6.3 Electricity imports and exports trend in Kenya (2016 to 2020).

In this subsection, annual electricity exchanges between Kenya and its neighbors are mapped in chord diagrams from 2016 to 2020. The aim is to visualize the electricity flows and to estimate electricity related virtual water trade between Kenya and its neighboring countries. In all the years considered, countries are represented by different colored portions of the circular ring of the chord diagrams. The electricity flow from one country to another is represented by an arrow colored similar to the exporting country's color with the arrow pointing to the importing country. The thickness of the arrow represents the quantity of the electricity flow whose units are MWh/yr. This quantity is read on a scale marked in a clockwise pattern on the outside of the circular ring of each chord diagram. In all instances in the study period, Kenya is represented by the red portion of the ring and the red arrows, Uganda by the blue ones, Ethiopia by the green ones and Tanzania by the yellow ones.

The description of the flow pattern results for electricity exchanges between Kenya and its neighboring countries in this subsection starts by dissecting the imports to Kenya and thereafter looking at the exports out of Kenya for each of the years under consideration in this research. In the entire study period from 2016 to 2020, Kenya exchanged electricity between almost all countries it shares borders with namely Uganda, Ethiopia and Tanzania. There was no exchange in this period between two of its direct neighbors namely; South Sudan and Somalia.

**Figure 17.** *Electricity Flows to and from Kenya in the years from 2016 to 2020*



*Note.* Figures a, b, c, d, e represents flows for 2016, 2017, 2018, 2019 and 2020 respectively. The arrows point to the importing country and originates from the exporting country with colors of the segments and the arrows representing different countries. Kenya with red, Uganda with blue Tanzania with yellow and Ethiopia with green.

### 6.3.1 Electricity imports and exports patterns for 2016.

In 2016, Kenya exchanged electricity with three of its five countries it shares borders with namely; Uganda, Tanzania and Ethiopia. The energy imports to Kenya in the chord diagram in ***Figure 17*** **(a)** above are shown by arrows pointing to the red segment of the ring. The blue arrow, which is the largest among all the arrows, shows the quantity of electricity in relative terms that Kenya imported from Uganda. This made up 96% (83,214 MWh) of its total annual electricity imports that year. The remaining 4% of Kenya's electricity imports in 2016 were split between Ethiopia (about 4%) shown by the green arrow and Tanzania (with a mere 0.003%) shown by the almost invisible yellow arrow. Regarding the electricity exports from Kenya to its neighbors, exports to Uganda led the way by a huge gap summing up to approximately 94% (36,956 MWh) of its total electricity exports in 2016 as displayed by the large red arrow pointing to the blue segment of the ring. Tanzania received the whole of the remaining 6% of Kenya's 2016 electricity exports shown by the smaller red arrow pointing at the yellow segment of the rings. Kenya did not export electricity to Ethiopia in 2016.

### 6.3.2 Electricity imports and exports patterns for 2017

2017 showed a similarity of electricity flow with 2016 in the sense that there were flows between Kenya and three of the five countries it shares borders with namely; Uganda, Tanzania and Ethiopia just like in 2016. The pattern and the magnitude of flow as seen in ***Figure 17*** **(b)** above remained the same with the only difference being an increase in the dominance of the Uganda imports to Kenya and reduction to the exported electricity to Uganda from Kenya. The increase in the imports by Kenya from Uganda seen by the big blue arrow was both in percentage and in the quantity compared to the previous year. The percentage of electricity imports by Kenya from Uganda rose from 96% to 98% of its total annual electricity imports that year while the quantity rose from 83,214 MWh in the previous year to 225,876 in 2017 which is a 171% increase. The remaining 2% of the imports that year came majorly from Ethiopia with an increase quantity wise from the previous year by 25%. Just like in 2016, Kenya exported electricity in 2017 to Uganda and Tanzania shown by the large and small red arrows respectively. Exports to Uganda in 2017 diminished significantly from 36,955,820 MWh (94% of total electricity exports) in 2016 to 9562 MWh (78% of total electricity exports) in 2017 which is a 74% drop. Kenya increased its exports to Tanzania by 25% from 2155 MWh (0.03% of total electricity exports) in 2016 to 2693 MWh (22% of total electricity exports) in 2017.

### 6.3.3 Electricity imports and exports patterns for 2018

The countries involved with electricity exchanges in 2018 remained the same as in 2017 and 2016. These countries are; Uganda, Tanzania and Ethiopia. Although the quantity of imports from Uganda dropped by 43% and the quantity of exports to Uganda shot by 264% dropped compared to 2017, the most noticeable aspect about flows in 2018 is the increased dominance of electricity flows between Kenya and Uganda. This is shown in ***Figure 17*** **(c)** above by the almost diminishing yellow and green arrows and the occupancy of almost the entire circle by the two red and blue arrows signifying exchanges between Kenya and Uganda. Looking at the electricity imports, Kenya imported 129,167 MWh (99% of total electricity imports) from Uganda and only 1,078 MWh (1% of total electricity imports) from Ethiopia. Imports from Tanzania were only 0.006% (7.43 MWh) of total electricity imports in 2018. Regarding the electricity exports in 2018, exports to Uganda dominated by 99% (34,783 MWh) and only 412 MWh (1% of total electricity exports) were exported to Tanzania. Kenya did not export electricity to Ethiopia in 2018 just like in 2016 and 2017.

### 6.3.4 Electricity imports and exports patterns for 2019

In 2019, flows were again between Kenya and three of its five countries that it shares borders with namely; Uganda, Tanzania and Ethiopia. The dominance of exchanges between Kenya and Uganda continued to take center stage. In ***Figure 17*** **(d)** above, the imports from Uganda shown by the blue arrow shows a continued dominance with the figures reading at 208,059 MWh (98% of total electricity imports in 2019) which is a 61% increase from the previous year. The rest of the imports 3978 MWh (2% of total electricity imports in 2019) shown by the green arrow were from Ethiopia as Kenya did not import electricity from Tanzania in 2019 (no yellow arrow). Regarding Kenya's electricity exports, Uganda was almost the sole recipient with 16,167 MWh (99.93% of total electricity exports in 2019) shown by the red arrow pointing the blue segment of the ring in ***Figure 17*** **(d)** above. Tanzania with the almost invisible red arrow received 11.46 MWh (0.07% of total electricity exports in 2019).

### 6.3.5 Electricity imports and exports patterns for 2020

Despite the continued dominance of the red and blue arrows in 2020 and a bit of growth of the green arrow signifying the continued prominence of flows between Uganda and Tanzania and a bit of growth of the Ethiopian imports to Kenya, of note is the disappearance of Tanzania completely from the picture leaving exchanges between Kenya with only Uganda and Ethiopia. Electricity imports from Uganda shown by the prominent blue arrow in ***Figure 17*** **(e)** above, were 131,997 MWh (97% of total electricity imports in 2020) while imports from Ethiopia shown by the green arrow were 4,681 MWh (3% of total electricity imports in 2020). Regarding Kenya's 2020 electricity exports, Uganda was the sole receiver with 16,518 MWh displayed by the large red arrow pointing to the blue segment of the ring.

### 6.3.6 Discussion; Imports and exports of electricity between Kenya and its neighbors (2016 to 2020).

As a summary, ***Table 12*** below shows the net electricity imports by Kenya from the countries it shares its borders with for the period between 2015 and 2020. The difference in magnitude between the net imports from Uganda from those from Ethiopia and Tanzania highlights the most outstanding fact about the electricity imports and exports trend results. That is, Uganda is a significant player in Kenya's energy story as it dominates the net imports to Kenya consistently for all the years under consideration. There are minor oscillations between the amounts of net imports to Kenya for all the countries but the order of magnitude of change of the flows are small and similar.

The study therefore focuses hereafter in establishing the net virtual water flows to the countries where electricity exchanges exist and within the period of study.

**Table 12.** *Net Electricity Imports for Kenya from 2016 to 2020*

| NET IMPORTS TO KENYA FROM; | 2016 (MWh/yr) | 2017 (MWh/yr) | 2018 (MWh/yr) | 2019 (MWh/yr) | 2020 (MWh/yr) |
|---|---|---|---|---|---|
| **Uganda** | 46,259 | 216,313 | 94,384 | 191,892 | 115,480 |
| **Ethiopia** | 3,035 | 3,682 | 1,079 | 3,978 | 4,682 |
| **Tanzania** | (2,152,) | (2,690) | (405) | (12) | - |

*Note.* Values in brackets show a negative net imports by Kenya from Tanzania meaning there were net electricity exports to Tanzania from Kenya rather than net imports to Kenya as seen in the case of Ethiopia and Uganda.

## 6.4 Virtual water exchange trend between Kenya and its neighboring countries (2016-2020).

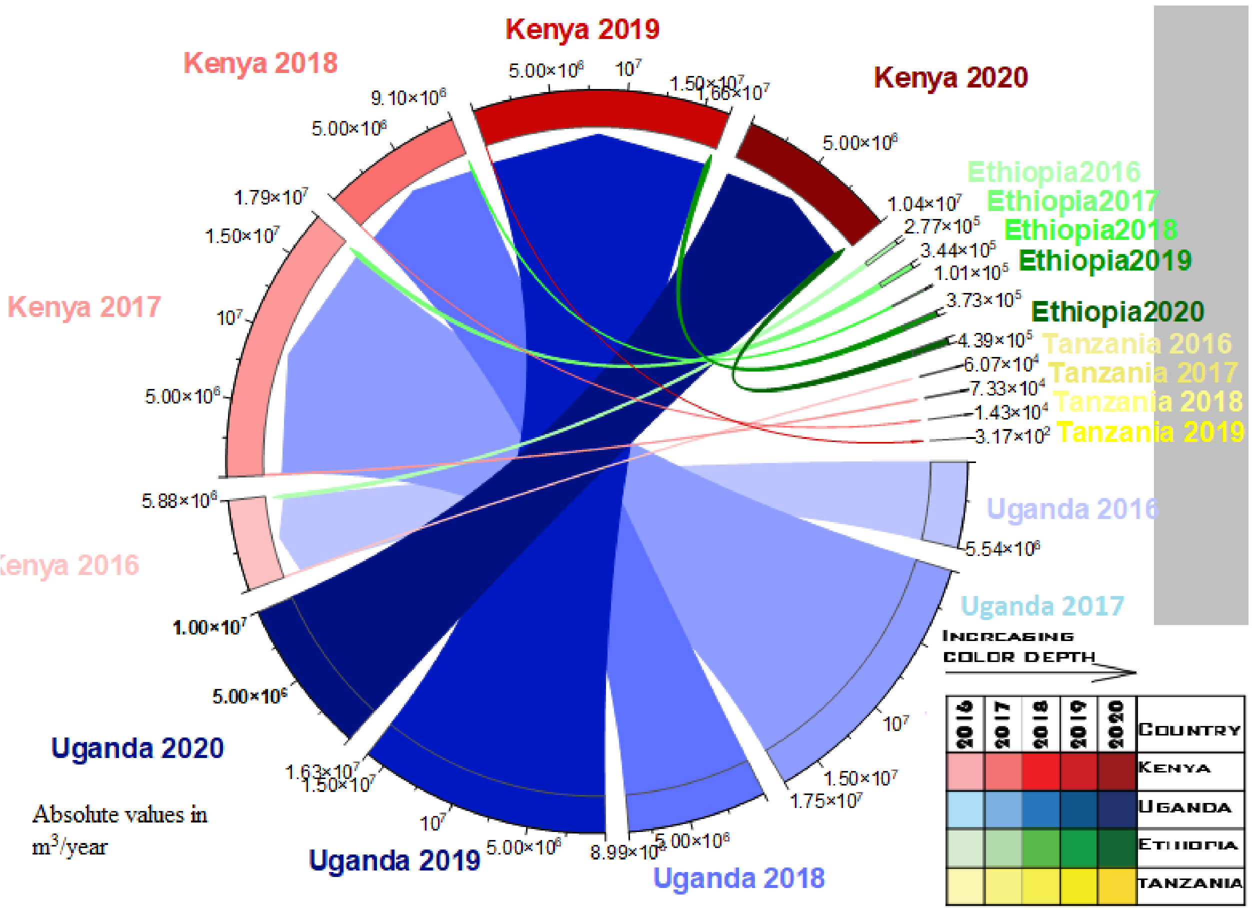
Having determined the electricity flows between Kenya and its neighbors in the subsection prior to this, it is of great importance to be able to estimate exactly how much water is imported and exported in and out of Kenya. The purpose of this undertaking is to estimate the WF of Kenya's electricity consumption on water resources of other countries and as well the estimation of the WF of electricity consumed outside of Kenya's borders on water resources within Kenya for proper planning going into the uncertain future in terms of environmental sustainability.

The chord diagram in IRENA-International Renewable Energy Agency, Renewable Energy Statistics. (2021). *Data and statistics – Capacity* [Data file]. Retrieved from below shows the net virtual water flows between Kenya and and its neighboring countries namely, Uganda, Ethiopia and Tanzania for the year 2016 to 2020. The colors of the components (segments of the ring and arrows emanating from the same segment) of each country under study in this subsection are similar to the colors used for the same countries in the previous subsection and are as follows: Kenya with red, Uganda with blue, Ethiopia with green and Tanzania with yellow. Like before, one specific color used for a ring segment and arrows emanating from that segment signify components of a specific country. However, to differentiate components of the same country but of different years within the period of study, the colors of the components of a country in different years are represented by increasing weight of color from light to heavy. For example, Uganda's 2016 segment of the ring together with the net flows out of the country in the same year have the lightest blue while Uganda's 2020 segment of the ring together with the net flows out of the country in that year have the heaviest blue.

The quantities of flows from one country to another are read in a clockwise manner with the values indicated on the outside of the circular ring. Units of the virtual water exchanges studied in this subsection are $m^3$/ day.

The resulting patterns of the flow as seen in ***Figure 18*** below underpin once again the dominance of exchanges between Kenya and Uganda as compared to other countries which is consistent with results of the electricity exchange patterns seen in the previous subsection. With the established awareness of the existing exchanges between the two countries, it is therefore upon the different stakeholders of both Kenya and Uganda to develop an electricity exchange framework that will give a better-informed direction towards better and informed future exchanges with water needs of both countries at the center of considerations.

**Figure 18.** *Electric Energy related Net Virtual Water Flows to and from Kenya in 2020*




*Note.* The colors of the arrows and the segments represent one country but the change of the depth of the same color represents different years. 2016 has the lightest color while 2020 has the deepest color. The arrows point to the net importing country and originates from the net exporting country with colors of the segments and the arrows representing different countries. Kenya with red, Uganda with blue Tanzania with yellow and Ethiopia with green.

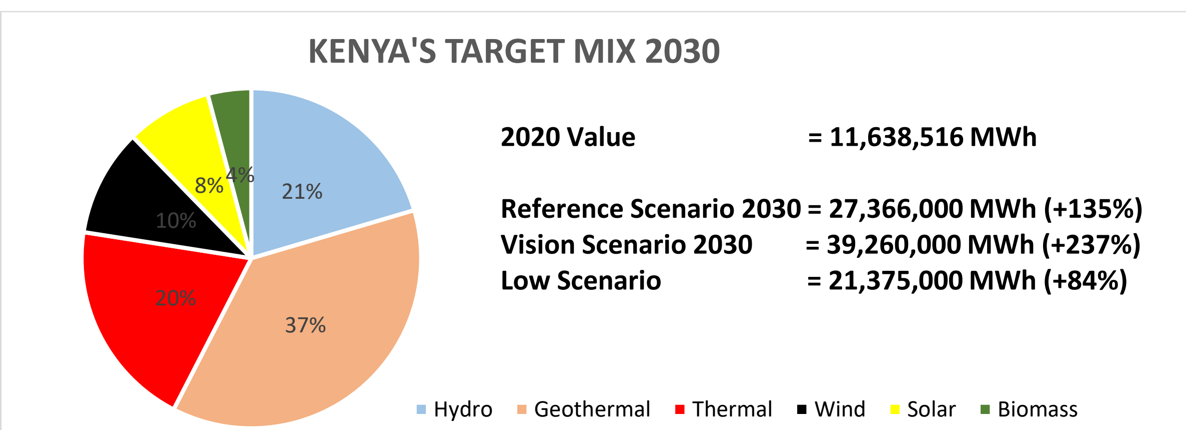
## 6.5 Future electricity consumption and water footprint estimation forecasting for Kenya.

### 6.5.1 Kenya's electricity consumption forecasting for 2030

With the knowledge of Kenya's electricity consumption trends from 2016 to 2020, it is worth looking into the future to understand what will happen in terms of electricity demand/generation and related use of water resources in the sector. Kenya's Ministry of Energy and Petroleum through the German company Lahmeyer International GmbH (2016) have developed electricity demand and generation forecasts in three scenarios namely: reference scenario, vision scenario and low scenario. The reference scenario is whereby projected values are arrived at based on past trends and real plans by the government for the future in terms of economic, population and infrastructural plans. The vision scenario is based on more ambitious and optimistic development plans by the government while the low scenario is based on pessimistic and conservative plans by the government.

***Figure 19*** below, 2030 forecasts show that Kenya's electricity generation/ consumption is projected to grow by approximately 135% (27,366,000 MWh), 237% (39,260,000 MWh) and 84% (21,375,000 MWh) for reference scenario, vision scenario and low scenario respectively. This is from the 2020 value of 11,638,516 MWh. The government of Kenya in 2012 through the Ministry of energy and petroleum in collaboration with many other stakeholders under the umbrella of United Nation's Sustainable Energy for All Program, teamed up together to come up with a road map of Kenya's Energy system through a document named 'the Kenyan Action Agenda and Investment Prospectus'. The major aim of the government was to shift the energy mix towards majorly renewable sources of electricity. The projected mix as shown in ***Figure 19*** will consist of 20% non-renewable sources and 80% renewable sources with geothermal taking up the largest share (37%) followed by hydro, wind, solar and biomass sources with 21%, 10%, 8% and 4% respectively in 2030.

***Figure 19.*** Energy Targets for Kenya by the year 2030




*Note.* Data source: Ministry of Energy and Petroleum & Sustainable Energy for All, 2015.

### 6.5.2 Water footprint projections for 2030

Water footprint of projected electricity consumption is estimated to illustrate changes in the use of water resources by this sector in the near future and particularly 2030 which is a target year by most of government development projects in Kenya. As seen in ***Table 13*** above, the results of the analysis show a slight improvement in terms of water footprint of the electricity system in 2030 compared to values for 2020.

With the application of the 2030 projected energy mix for Kenya, the overall water use of electricity consumption in 2030 is estimated to increase by +28% (547 MCM) for the reference scenario, +84% (784 MCM) for the vision scenario and +0.2% (427 MCM) for the low scenario. This is from the 2020 value of 426 MCM. The increase in overall amount of water used is lesser in comparison to the increase in electricity generated/ consumed in 2030. This is due to the shift of the electricity mix to less water intensive renewable electricity sources. The estimated WF of Kenya's electricity system is estimated reduce by 46% from the 2020 value of 37 $m^3$/MWh to the 2030 values of 20 m3/MWh for all the scenarios considered. The reduction of the WF of the electricity system further illustrates the benefit of the ambitious plan by the government of Kenya to shift the energy mix to 80% renewable energy by 2030. There is therefore need to analyze the system together with all related sectors in an holistic manner with all relevant factors considered and if possible invest on less water intensive sources in the country, This will ensure that optimization of water use in the sector is realized irrespective of the inevitable growth of electricity demand and generation due to population growth and development.

**Table 13.** *Projected electricity consumption and related water footprint for 2030*

| **Reference Scenario** | **Mix portions** | **Electricity Consumption 2030 (MWh)** | **Water Use 2030 ($m^3$)** | **Water Footprint 2030 ($m^3$/MWh)** |
|---|---|---|---|---|
| Hydro | 20.44% | 5,473,200 | 534,454,037.63 | |
| Geothermal | 37.13% | 10,125,420 | 506,271.00 | |
| Thermal | 20.00% | 5,473,200 | 9,961,224.00 | |
| Wind | 10.22% | 2,736,600 | - | |
| Solar | 8.20% | 2,244,012 | - | |
| Bio | 4.10% | 1,122,006 | 1,525,928.16 | |
| **Total** | **100.00%** | **27,174,438** | **546,447,461** | **20** |
| **Vision Scenario** | **Mix Portions** | **Electricity Consumption 2030** | **Water Use 2030** | **Water Footprint 2030** |
| Hydro | 20.44% | 7,852,000 | 766,742,144.17 | |
| Geothermal | 37.13% | 14,526,200 | 726,310.00 | |
| Thermal | 20.00% | 7,852,000 | 14,290,640.00 | |
| Wind | 10.22% | 3,926,000 | - | |
| Solar | 8.20% | 3,219,320 | - | |
| Bio | 4.10% | 1,609,660 | 2,189,137.60 | |
| **Total** | **100.00%** | **38,985,180** | **783,948,232** | **20** |
| **Low Scenario** | **Mix Portions** | **Electricity Consumption 2030** | **Water Use 2030** | **Water Footprint 2030** |
| Hydro | 20.44% | 4,275,000 | 417,450,670.70 | |
| Geothermal | 37.13% | 7,908,750 | 395,437.50 | |

| | | | | |
|---|---|---|---|---|
| Thermal | 20.00% | 4,275,000 | 7,780,500.00 | |
| Wind | 10.22% | 2,137,500 | - | |
| Solar | 8.20% | 1,752,750 | - | |
| Bio | 4.10% | 876,375 | 1,191,870.00 | |
| **Total** | **100.00%** | **21,225,375** | **426,818,478** | **20** |

*Note.* The projection values for the electricity mix and the total electricity consumption is adapted from "Development of a Power Generation and Transmission Master Plan, Kenya, Volume II—Annexes" by the Ministry of Energy and Petroleum through the German company known as Lahmeyer International GmbH (2016) and "sustainable energy for all Kenya action agenda; Pathways for Concerted Action toward Sustainable Energy for All by 2030" by the Ministry of Energy and Petroleum, & Sustainable Energy for All. (2015) respectively.

# Chapter 7: Conclusion and future developments

In this section of this study, a wrap up of the findings of the research and clear actions and recommendations that the relevant stakeholders of the entire electricity ecosystem in Kenya need to undertake and implement for sustainable water use in the sector are provided. Future possible undertakings to improve this research are also mentioned at the end.

## 7.1 Conclusion

This research was conducted in two main parts. First, it sought to study the electricity consumption and exchanges between Kenya and its neighboring countries from the 2016 to 2020 coupled with a comparison between the 2020 situation to the 2030 projections in the same sector. Secondly, the existing WF trend of Kenya's electricity system in the same period was estimated and compared to the projected WF of consumption in 2030.

The findings for this thesis show that there has been a slight but steady increase of the annual electricity consumption in Kenya for the five years under study in this research i.e. 2016 to 2020. The steady increase has meant that the annual electricity consumption in Kenya rose from 10,045,416 MWh in 2016 to 11,638,516 MWh in 2020, i.e., an increase of 1,593,100 MWh, +16% change approximately. The increase in electricity consumption is attributed to the continued development in this sector in terms of increasing production of already influential electricity sources such as geothermal sources and the introduction into the fold of others which were present in insignificant amounts like wind and solar sources whose numbers started rising from the year 2018 onwards to satisfy the country's existing electricity demand. Comparing the individual electricity consumption change in Kenya, there is an apparent shift from non-renewable electricity sources to renewable sources. There was a particularly visible growth of non-hydro renewable sources. The following are the 2016 to 2020 change numbers of the individual electricity source starting from the gaining sources to the losing ones in order of percentage change. +5843% for solar, +2259% for wind, +13% for geothermal, +8% for hydro, -48% for thermal and -78% for biomass.

With the electricity trends highlighted the corresponding trend of WF of electricity consumption in Kenya is calculated. The WF displays substantial oscillations but with a slight decline in its overall value which is from 39 $m^3$/MWh (392 MCM) in 2016 to 37 $m^3$/MWh (426 MCM) in 2020. This is a -7% change in the water footprint and a +9% change in overall annual water use.

Looking at the 2030 energy projections, Kenya's Ministry of Energy and Petroleum through the German company Lahmeyer International GmbH (2016) developed electricity demand and generation forecasts in three scenarios. The reference scenario, the vision scenario and the low scenario. The reference scenario is whereby projected values are arrived at based on past trends and real plans by the government for the future in terms of economic, population and infrastructural plans. The vision scenario is based on more ambitious and optimistic development plans by the government while the low scenario is based on pessimistic and conservative plans by the government. The 2030 forecasts show that Kenya's electricity generation/consumption is projected to grow from the 2020 value by approximately 135%, 237% and 84% for the reference scenario, the vision scenario and the low scenario respectively. The government also plans to revolutionize the electricity sector to achieve 80% renewable energy by 2030.

The overall water use of electricity consumption in 2030 is estimated to increase from the 2020 value by +28% for the reference scenario, +84% for the vision scenario and +0.2% for the low scenario. The increase in overall amount of water used is lesser in comparison to the increase in electricity generated/ consumed in 2030 due to the shift of the electricity mix to less water intensive renewable electricity sources. The estimated WF of Kenya's electricity system shows a reduction by 46% from 2020 to 2030 for all the scenarios considered. The reduction of the WF of the electricity system further illustrates the benefit of the plan by the government to shift the energy mix to 80% renewable energy by 2030. There is therefore need to analyze the system holistically with all factors considered and if possible invest on less water intensive sources in the country. This will ensure that optimization of water use in the sector is realized irrespective of the inevitable growth of electricity demand and generation due to population growth and development.

Although seen as a progressive source of electricity in terms of its low carbon footprint, this study emphasizes on the need to carb the dominance of hydroelectricity in Kenya. This is due to the direct proportional relationship between hydroelectric energy trend with the patterns of WF of the entire electricity system in Kenya over the entire study period as seen in this research. Instead, other non-hydro renewables such as geothermal, wind and solar sources of electricity should be progressively fostered going into the future due to their apparent benefit of minimal pressure on water resources. This will drastically reduce the burden exerted by the electricity consumption on scarce and limited environmental resources in Kenya and thereby contributing to sustainable development in this sector.

The patterns of electricity flow between Kenya and its neighboring countries underpins the dominance of exchanges between Kenya and Uganda as compared to other countries. At the same time, the patterns of virtual water flow estimated marries together with the electricity flows as Uganda is prominent once more in this regard. With the established awareness of the existing exchanges between the two countries, this research therefore recommends that the different stakeholders of both Kenya and Uganda should develop an electricity exchange framework that will give a better-informed direction towards better and informed future exchanges with water needs of both countries at the center of considerations. Finally, the projections and planning done onwards in the electricity sector by the relevant institutions in Kenya whether governmental or private should incorporate WF as one of the guiding factors with the help of the findings of this research.

## 7.2 Future developments

- There is need for further studies on the impact of hydroelectric generation plants on water resources in Kenya to allow for establishment of more accurate and precise WIFs to be used in the calculation of the WF of the hydroelectric energy.
- Although neglected due to the assumption of its negligibility in terms of their relative comparison with reservoir hydroelectricity generation plants, the WF of river based hydroelectric plants need to be incorporated in future research to leave no stone unturned in the calculation of the WF of the electricity system in Kenya.
- The WF calculations in this research ignores energy losses in the transmission phase of the energy from generation to consumption. Future research should therefore improve the quality of the result by factoring in the energy losses in between.
- This research only studies the blue WF of the electricity system in Kenya. Future research should include the green and grey WF so as to be able to exhaustively and comprehensively estimate how much impact the electricity sector has on water resources.
- Some of the hydroelectric reservoirs in Kenya have other functions such irrigation and domestic water use. Future research should consider spreading the water footprint burden to all the existing reservoir uses.
- There is need to undertake an optimization problem exercise to establish an optimal mix that will guarantee minimum WF of the electricity system in Kenya without excluding other possibly conflicting objectives and constraints factors such as carbon footprint, financial capacity of the country to exploit proposed electricity sources and the physical existence of the potential to exploit these sources.

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