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The Economics of Off-Grid Generation Versus connection to the National Grid: Case Study for Wajir County

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Declaration

I **Daisy Karimi Muthamia** declare that this report is my original work, and except where acknowledgements and references are made to previous work, the work has not been submitted for examination in any other University.

Signature.........................Date...................

Approval by supervisors

I confirm that the study was carried out under my supervision and has been submitted for examination with my approval as University supervisor.

Prof. J. M. Mbuthia Signature..............Date................

Dr. C. Wekesa Signature..............Date................

Dedication

Dedicated to my sisters, brothers and parents.

Acknowledgement

I hereby acknowledge the support, direction and ideas accorded me by my supervisors Prof. Mwangi Mbuthia and Dr. Cyrus Wekesa, Lecturers - University of Nairobi. I would also like to acknowledge the support I received from the KPLC Off-Grid office and the Rural Electrification office during data collection, my boss, Eng. J. Githinji for his patience, my classmates especially Nazarene Kirimi, Tony Nyagah and my colleague Harrison Sungu.

Abstract

It is a well-known fact that electricity is essential for national development and many third world developing economies, have prioritized adequate energy provision to its populace as a key economic pillar. Despite this, many regions in these countries remain unconnected to electric power grids. Today, only about 35% of Kenyans have access to the country's electricity grid. Principal alternatives to connecting the remaining users include grid extensions and off-grid generation. It is important to assess these alternatives from an economic viewpoint.

This study has primarily focused on an economic appraisal for electricity planning, looking at the extension of the grid to Wajir town which is currently supplied by off-grid diesel power plants. The main objective was to carry out an economic study comparing the cost of off grid generation to the cost of investing in transmission infrastructure focusing on regions supplied off the national grid.

The study was conducted via a detailed data gathering exercise at the Kenya Power and Lighting Company (KPLC) off-grid office, the KPLC's rural electrification office and the Kenya Electricity Transmission Company (KETRACO). The data included cost of operation and maintenance, installation cost, historical fuel costs, historical data on power and energy generated from the plant. A load flow study was carried – using PSS/E^{TM} software – to model the transmission line and its effect on the existing transmission grid. The power flows from the model were used to assess the need for reactive compensation hence the inclusion of the reactors as part of the installation. It was also useful in sizing of the electrical switchgear and transmission line conductor to be used.

From the results obtained, it was observed that the cost per kilowatt-hour of building the transmission infrastructure **USD 0.2125 /kWh per annum** while that of remaining off grid and putting up a diesel plant to sufficiently supply the load until 2030 was **USD 0.42 /kWh per annum.** It was concluded that the option to extend the transmission line from Garissa County to Wajir County would be recommended for this as the most economical option in the area under study. The grid connected supply would have other environmental benefits of utilization of the hydro-electric renewable energy source over the diesel generator powered off-grid alternative.

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List of Nomenclature

SSM – Supply Side Management

CG - Centralized Generation

DG - Distributed Generation

RER- Renewable Energy Resources

LCPDP- Least Cost Power Development Plan

KPLC – Kenya Power and Lighting Company

KETRACO – Kenya Electricity Transmission Company

KENGEN – Kenya Electricity Generating Company Limited

GDC – Geothermal Power Development Company

REA – Rural Electrification Authority

MOE- Ministry of Energy

ERC – Energy Regulatory Commission

PSS/E™ – Power System Simulation / Energy Software

Technical Abbreviations

kW/MW/GW – kilo/Mega/Giga-Watt

kWh – kiloWatt-hour

Other Terms

(FIT) - Feed-in tariff:

1. Introduction

1.1 Background

In an electricity supply system, effective Supply Side Management (SSM) can increase the efficiency of provision of power. Improved efficiency would allow utility companies to defer major capital expenditures which might otherwise be required to capacity in growing markets. SSM enables the installed generation capacity to provide electricity at a lower cost and reduce environmental emissions per unit end use of electricity provided. SSM can also contribute to improving the reliability of the supply system [1].

Power generation and energy conversion is where most energy losses occur. Power plants can be improved by either improving operations in existing plants or replacement of old technologies and equipment with new and best modern practice designs.

Another area of SSM concerns transmission and distribution of electricity to consumers. A reliable system depends on the reliability of the lines taking power from the generator to the end user. One of the major issues in electrical power systems is the losses incurred during the transmission of electrical power. As daily power demand increases, increased power generation leads to increased corresponding power losses primarily in transmission and distribution

The table below shows the international network losses for various countries according to the US Energy Information Administration, EIA [2].

Table 1.1: International Network Losses

Country	**2007**	**2008**	**2009**	**2010**
Algeria	17.87%	18.11%	20.58%	19.95%
India	22.79%	21.98%	22.01%	21.97%
China	6.27%	6.14%	6.03%	6.10%
Iran	18.98%	17.54%	15.61%	14.19%
Jordan	14.38%	14.08%	14.18%	21.00%
Kenya	**15.94%**	**15.61%**	**15.55%**	**15.73%**
Germany	4.69%	4.77%	4.28%	3.85%
Finland	3.75%	4.31%	3.85%	3.43%
Australia	5.97%	6.08%	6.12%	6.06%
Brazil	16.14%	16.65%	17.17%	16.63%
USA	6.03%	6.05%	6.13%	6.11%

Source: U.S Energy Information Administration, EIA

The percentage power loss during transmission and distribution is approximated at an average of *6.07%* for North America, *4.46%* for Pacific and *5.97%* for Europe [2].

The main challenges in transmission are power losses due to the inherent thermal limitation of the line, voltage fluctuations that occur due to variations in electricity demand and to failures of transmission lines and the system operation constraints resulting from other connected networks. The main cause for these power losses is the resistance of wires used in electricity grid caused by the inherent thermal limitation.

The efficiency of power transmission can be improved to a certain level by using high strength composite overhead conductors and underground cables that use high temperature super conductors. Despite this, the transmission can still be inefficient due to technical losses, grid's inefficiencies and theft.

According to data collected from the Kenya Power off grid office, KPLC currently has 11 off grid generation stations which include: *500KW* Mpeketoni power plant in Lamu district, *800kW* Hola in Tana River district, *360kW* El wak in Mandera South, *120kW* Baragoi in Samburu North District, *180kW* Mfangano Island in Suba district, *138kW* Merti in Isiolo, *300kW* Habaswein in Wajir South district and several more in Marsabit, Lodwar and Moyale.

The ministry of energy though the Kenya Electricity Transmission company is in the process of constructing Transmission infrastructure to connect these areas to the grid. These transmission lines to be used include the *220kV* Rabai – Malindi –Garsen – lamu line which will supply the Lamu Port, *220kV* Kindaruma – Mwingi – Garissa and Lamu – Hola –Garissa which will supply Garissa town, *400kV* Loiyangalani – Suswa which will supply the Turkana region among others.

There are several small to medium sized renewable energy generation plants already established around the country by either KENGEN or Independent Power Producers. This study will look at the economics of power generation from one of these plants and compare it to that of building a transmission infrastructure.

1.2 Problem Statement

It is well known that electricity is essential for national development. However, many areas in third world countries are not connected to the grid. In fact only 30% of the population in Kenya has access to grid connection. Principal alternatives for connecting the rest of the users include grid extension and off-grid generation. It is therefore important to assess these alternatives from an economic viewpoint.

The main focus of this study will be the economics of the KPLC off grid generation stations with the Wajir diesel station as case study. The cost of generating a unit of electricity will be derived for power from this diesel plant and compared to supplying the region by extension of the national grid from Garissa to Wajir. It seeks to study the economics of off-grid generation versus the connection to the national Grid.

1.3 Justification

According to a study published in the economist, with nearly 1 billion people, Africa accounts for over a sixth of the world's population, but generates only 4% of global electricity. [3]

Today, approximately 35% of Kenyans have access to electricity form the national grid. The situation is no better in rural areas where the electrification rate stands at only 5%. Few Africans in rural areas have access to electricity and connecting them to the national grid is slow and expensive. According to a study carried out by the World Bank [4], ‘the cost of lighting a shack takes 10% of income in the poorest households and the kerosene lamps are highly polluting.’

The above reasons justified the carrying out of the study.

1.4 Study Objective

The main objective of this study was to identify an indicative economic comparison between off grid generation and investing in transmission infrastructure. A case study was carried out on the off grid generation Plant in Wajir to compare the cost per Kilowatt**(KW)** of power generated from this plant to the cost per KW for power supplied to Wajir by the extension of the National grid from Garissa.

The specific objectives of the study were:

a) Carry out an economic study to compare the cost of off grid generation to the cost of investing in transmission infrastructure and in particular Wajir town which is currently supplied off the national grid;

b) Undertake a power system transmission simulation to see the effect of investment of the Kenyan transmission system parameters; and

c) Determine the optimal tariff by drawing a comparison between an off grid diesel generation plant and electricity generation connected to the grid with a view to find out the cost per kilowatt;

1.5 Scope

The study covered the existing Wajir diesel power generation plant that is currently owned and operated by Kenya Power and the existing transmission infrastructure. Data collection was done from the Kenya Power rural electrification office (including the off grid office) and from the Kenya Electricity Transmission Company Planning and Development department.

1.6 Hypothesis

Use of clean energy supplied from the national grid will reduce the cost of power per kWh.

2. Literature review

2.1 Background

The prevailing condition in Kenya's power sector is characterized by rampant fraud and electricity theft, low electrification levels, high electricity prices, high system losses, persistent power interruptions and power shortages. The unstable power prices are mainly as a result of volatile oil prices.

There is need to ensure that there is enough energy available to meet current demands and ensure future security of supply. The high energy cost in Kenya is unfavorable to domestic power consumers and for energy companies to be able to stay in business there is need for development of both environmentally compatible and publicly acceptable energy sources. Power is a key enabler for the vision 2030 economic, social and political pillars [5].

2.2.1 Centralized energy generation, transmission and distribution

Central Generation (CG) is the electric power production by central station power plants that provide bulk power [6]. Under the current centralized generation paradigm, electricity is mainly produced at large generation facilities and shipped through the transmission and distribution grids to the end consumers. Most of them use large dams for hydro generation, burn fossil fuels like gas or coal or use nuclear reactors to heat boilers to produce steam that drives turbine generators. In Kenya for example these include the following mixes as shown in the table below:

Table 2.1: Energy Sources in Kenya by April 2015

Sources (MW)	Installed Capacity (MW)	Capacity % Share
Hydro	827.02	36%
Fossil fuels (including gas, diesel and emergency power)	811.3	35%
Geothermal	593	26%
Bagasse Cogeneration	38	2%
Wind	25.5	1%
Total	**2,294.82**	**100%**

Source: Global Village Energy Partnership (GVEP) International, Kenya

These large plants require costly management of large infrastructures. CG plants are susceptible to unreliability and instability under unforeseeable events like natural disasters, and may be vulnerable to attacks. Vandalism of transmission line infrastructure which is rampant in Kenya leads to collapsing of towers causing supply interruptions over large areas. Faults in the large substations also cause widespread outages across the country. Power from isolated grid currently stands at *14.6MW*.

Centralized generation has other limitations, that relate to the efficiency, environmental and social impact, and resources required to sustain them. For example construction of large dams for hydroelectric power require large scale relocation of people. Constriction of transmission lines also requires way leaves. This may cause public acceptance issues and other undesirable environmental impacts such as deforestation.

Centralized generation is normally located where there is either a natural head of water, easy access to fossil fuels, available land and least environmental disruption or access to natural hot springs among other factors. The energy produced using Centralized generation is transmitted over long distances using High Voltage transmission lines and delivered to the consumer using a complex and expensive distribution network. These limitations have led to renewable energy resource options for researchers and policy-makers.

The growth of a system usually starts with the installation of a new centralized generation whose projects may be implemented continuously followed by new transmission and distribution networks to go with the plants. Transmission and distribution network implementation though continuous may have reduced frequency.

One of the main elements in this development path is that the taking of decisions comes from ~~a~~ centralized generation plant~~s~~ expansion within vertically integrated industry.

The electric market growth, the financial market's development and the accelerated technical progress have led to a decrease in the optimum size ~~in~~ of new investments in generation in relation to the market size and to the private financial capacity. As a result, new conditions have appeared in the generation sector making it able to respond to the market. Furthermore, deregulation processes have made this possible by promoting competence in generation.

There has been a radical change in the generation costs behavior in the last decades owing to technological changes. Currently, the MW minimal cost for thermal plants is no longer obtained by increasing the generating plant size. Moreover, today's different generation technologies efficiencies for some fuels like gas plants do not change significantly when the generator power varies. It is important to note that in the past the situation was to the contrary. The differences in efficiency became significant with the variation of the plant size. Today there are technologies that allow generation using relatively small sized plants with respect to conventional generation, and with smaller costs per MW generated. This is a technological change that has altered the strategic importance of CG because the efficiency relation was what, in the past, dictated the CG economies of scale [1].

Considering this new situation, one of the main factors that economically justified the construction of large plants in the past, has been lost. On the other hand, these new (smaller) sizes of generators do not need a transmission system because they may be connected directly to the distribution networks, meaning the energy produced by them can be consumed directly at the place where it is produced. The elimination of the necessity of the transmission network, means that the investment costs that the CG system requires and the power transmission losses in the transport network, can be avoided.

In the Kenyan Electric system, one part of the demanded energy is supplied by the conventional central generators, while another is or will be produced by distributed generation.

The demand growth can be satisfied in two ways:

- Setting up conventional CG generation and enlarging the transport networks.

- Setting up DGs.

A big modern plant connected to the transmission network will always be more efficient than a small one. Moreover, if the wish is to power an old generating plant, the associated costs may end up becoming more than if a new distributed generating plant is set up. This is due to the fact that one of the features of the DGs is that they are factory produced in a standard way and subsequently easily set up on site as a ‘plug and play solution. This notably reduces their cost.

The transmission in the centralized system has mostly been to the present time what has been described as a natural monopoly [7]. In the processes of regulatory change, in which the electric markets are inserted, the regulators are confronted with the complex task of regulating a natural monopoly. This complexity is magnified by the fact that technological revolution may develop forces that produce the disappearance or impairment of the “natural” factors that determine the existence of a monopoly. Regulations must allow the appearance of those forces with the intensity that corresponds to them and not mitigate them with rigid policies that keep the fictitious existence of a monopoly. It is therefore very important to detect and define with precision the main factor that makes a company to be listed as a natural monopoly.

In the transmission sector, the answers to the monopoly questions have not generated much debate. The fixed transmission network costs have a high impact in front of the variables and the rigidity of those variables for a wide production range (kW transmitted) is what makes that average costs to decrease. Furthermore, the majority of these fixed costs are irreversible, meaning, they are sunk costs, that impose restrictions to the arrival of competition from DG. On the demand side, the entire generation built up by big generators, was based on the transmission system therefore, any user that has the intention of buying or selling electric energy needs to be a user of the transmission, in other words, the DG proposition is a captive of the transmission network.

2.2.2 Decentralized energy generation and distribution.

DG is power generation built near consumers. The recent quest for energy efficiency, reliability and reduction of greenhouse emissions has led us to explore possibilities that will alter the current generation paradigm and increase its overall performances.

DG sources include small-scale, environmentally friendly technologies (e.g., Photovoltaic and wind) installed on and designed primarily to serve a single end user’s site. But when reliability and power quality issues are critical, DG most often includes more traditional fossil fuels like fired reciprocating engines or gas turbines.

The limited generation in the power sector has continually been exacerbated by load growth, power demand, limitations in the ability to site new transmission lines, limitations in the ability to construct large scale generation due to increased environmental regulation, and lack of technology development to meet the new requirements. Man power is required to achieve the development of a sustainable, secured, and economically-viable society and infrastructure.

The disparity in energy consumption in developed and developing countries has created a divide in terms of economic wealth. The major energy consumption disparities are reflected in the low income per capita in developing countries. The universal electrification challenge to meet the world's population per capita energy consumption equivalent to the current developed economies per capita electricity consumption will require massive increases in electricity generation capacities.

In some cases, properly planned and operated DG can provide consumers, as well as society, with a wide variety of benefits. Many electricity supply systems utilities have installed DG on their systems and they benefit from government research funds to develop new technologies.

The interconnection of DG with the electric grid continues to pose genuine safety and reliability risks for the utility. DG could reduce the demand for traditional utility services. DG also poses an economic risk to incumbent utilities and their consumers unless appropriate rate structures or cost recovery mechanisms are put into place. DG is environmentally friendly due to its "friendly" technologies. These "friendly" technologies include: photovoltaic (PV) systems, fuel cells, small wind turbines, or more conventional technologies such as: micro turbines and reciprocating engines that are fueled by renewable fuels, for instance, landfill gas.

DG encompasses generation built within close proximity to a consumer's load despite size or energy source. The latter definition could include diesel-fired generators with significant emissions.

The main characteristic of the DG is that it offers an alternative for any user who wishes to consume electric energy without being necessarily connected to the national transmission system.

Other definitions of DG include some or all of the following:

a) Any generation interconnected with distribution facilities;

b) Commercial emergency and standby diesel generators installations, (i.e., hospitals and hotels);

c) Residential standby generators sold at hardware stores;

d) Generators installed by utility at a substation for voltage support or other reliability purposes;

e) Any on-site generation with less than “X” kW or MW of capacity. “X” ranges everywhere from 10 kW to 50 MW;

f) Any generation facilities located at or near a load center;

When DG is used, the “natural” transmission tends to lose its captive demand. Therefore, the transmission loses one of the “natural” factors which make it a monopoly. In these conditions, the regulated and isolated determination of the transmission prices tend to lose validity. Furthermore, if the regulator wishes to fix a price when the DG is connected to the natural transmission system, the electricity supply industry monopoly must net the quantity of energy demanded from the transmission against any excess energy supplied by the DG (feed in tariff) and the electricity supply industry monopoly must pay for any surplus energy from the DG. Supposing, for instance, that the regulator fixes a high feed in tariff. This would cause the energy price at the grid supply points (i.e. boundaries between the natural transmission and the distribution systems) to rise.

As a result, an increase in the DG offer would occur, which would eventually lead to a decrease in the amount of energy demanded from the natural transmission system. This mechanism would then adjust the amount of energy demanded from the natural transmission system to the new price. Evidently, to make these results effective and encourage further investment in DG it is vital that the regulator fixes a competitive feed-in tariff by respecting the DG key competitive natural factor and not charging transport costs for an activity that does not use that service.

2.2.3 Decentralized generation versus centralized generation and transmission

The location of DG's near consumers reduces transmission and distribution losses significantly based upon the very large numbers of individual generators and statistical robustness of such a collection compared to centralized generation. DG is a simple manufacturing and installation technology when compared to CG. By using DG the amount of energy lost in transmitting electricity is reduced because the electricity is generated near to where it is eventually consumed. This also reduces the size and number of power lines that need be constructed.

Typical distributed power sources in a Feed-in Tariff (FIT) scheme [8] have low maintenance, low pollution and high efficiencies, but because most FIT tariffs require use of intermittent renewable resources, reliability and power quality issues become important. In the past, DG as described required dedicated operating engineers and large complex plants to reduce pollution.

Today, modern embedded systems can provide these traits with automated operation and renewable resources, such as sunlight, wind and geothermal. This reduces the size of power plants that can yield profit. However, the renewable energy resources (RER) still have limitations which include:

a) The cost of electricity in some cases is higher than the one from CG (i.e., “hidden costs”.

b) CG's monopolistic nature may require restructuring of the electricity supply infrastructure. Evolution of the electricity networks will be found in future distribution networks where there will be automatic network reconfiguration schemes aimed at facilitating high penetration of DG while reducing systems down time due to faults. This can be found in transmission and sub-transmission active networks with high voltages. In a situation where a DG system is embedded in the system, there will still be a number of technical implications.

c) Since fault level increase with increasing number of DG installations, they will end up dictating the size of the DG. In network security, the size will be limited in light of the fact that that a DG has to comply with set standards rather than to simply meeti~~ng~~ supply security at the pre-reconnection point. More control options will therefore be required for better security though at higher than budgeted cost.

d) Voltage level of radial type system supply a number of distributed consumers with DG at different locations will increase local voltage level and cost implications.

e) Network stability issues under fault condition leads to system dynamics which may cause instability depending on the characteristics of the DG. If this occurs, appropriate control systems have to be included at a cost to overcome the instabilities.

Additional benefits of DG interconnection to the future grid include:

a) Electric system reliability increases

b) Supplies urgent power demands

c) Peak power reduction

d) Power quality improvements

e) Infrastructure resilience improvement

f) Land use effects reduction

g) Vulnerability reduction.

The vast majority of electric power generated by DG is provided directly to consumers without being transmitted or distributed by means of the power grid. Such DGs supplying consumers' power are termed "stand-alone", while those that are connected to the power grids are referred to as "grid connected".

This clearly shows that energy reliability could be enhanced with DG. Even though DG has the enumerated benefits, a proper interconnection to the power grid is necessary to forestall any undesirable consequences to local electric system operations. Proper interconnection and use of control devices would ensure a seamless transition when the DG is not operating.

In a Centralized Generation power system network, power is transmitted over long distances from the centralized system before it is availed to consumers through distribution networks. At the generating end, power is generated with different sources such as: hydropower, nuclear power, thermal power, geothermal etc.

2.3 Related Studies

The Energy Regulatory Commission – (ERC) carried out the Least Cost Power Development Plan – LCPDP (2009 – 2029) and has been carrying out an update to this study annually since then. (Energy Regulatory Commisssion-2009) [9].

The purpose of the LCPDP is to guide stakeholders with respect to how the sub-sector plans to meet the energy needs of the nation for subsistence and development at least cost to the economy and the environment. The least cost evaluation criteria and modeling approaches were used to prioritize the projects. The LCPDP as indicated in the Vision 2030 medium term plan aims [9].

The latest Distribution master plan was carried out in 2013 by Parsons Brinkerhoff consultants appointed by The Kenya Power & Lighting Company Limited (KPLC) to conduct a Distribution Master Plan Study to address the country's distribution requirements up to 2030.

The main objectives of the study were (1.) To conduct a detailed assessment of KPLC's distribution system requirements over the 2012-2030 planning period and develop a Distribution Master Plan and (2.) To undertake an environmental scoping study for the investments recommended in the short-medium term (3-5 years) [10].

From the Distribution study, the urban electrification level of households in Wajir County is approximately 20% and that of the rural areas is less than 1%. This shows a need for the county to either get connection to the grid or have the capacity of the off grid plant increased.

According to the Scaling-up Renewable Energy Program (SREP) study carried out by the ERC in 2011, there is a need to formulate strategies whose objectives are to rapidly expand installed electricity capacity, expand and upgrade the transmission and distribution networks and develop renewable sources of energy [11].

The Rural Electrification Master Plan refers to the strategy of rural electrification as either grid extension or off grid supply through the use of renewable energy sources such as solar, wind, biomass and small hydropower [12].

This project's objective is to provide a comparative analysis between the cost of grid extension and off grid generation in a remote area in Kenya, with Wajir County chosen as the subject of study.

3. Methodology

3.1 Introduction

This section covers the general approach and the methods used to determine the cost of a unit of energy generated either from an off grid plant or from the extension of the transmission infrastructure. It also covers the data collection and selection of the power system simulation software.

3.2 Structure of Costs

The study seeks to compare the cost of a unit kWh produced by an off grid diesel plant to that supplied from the national grid. The method is based on the comparison of the overall discounted cost of a kWh (investment, fuel, operating, repair and maintenance costs) for an off grid generation plant to that of extending the national grid (investment, losses, operating, repair and maintenance costs)

One of the characteristics of fossil fuel based electricity production is that the expenditures for fuel and operating-maintenance are considerably high

Thus, the structure of the cost of a kWh delivered by a fossil fuel based system will include a large part of the initial investment cost, the fuel expenditure, and the operating, repair and maintenance expenditures.

The costs of electricity vary widely according to the ways of its production and distribution. There is a great difference between the price of electricity delivered by large, grid-connected power stations and the price of peak stand-alone power plants.

The overall discounted cost includes the amortization of investment, functioning over the period of exploitation (fuel, operational, repair and maintenance). The amortization by constant installments "A" of an initial investment "I" over a period of "n" years at a constant annual discount rate "t%" is given by the equation (3.2), where,

$$r = \frac{t}{100} \tag{3.1}$$

$$A = \frac{I(r)(1+r)^n}{(1+r)^n - 1} = \frac{I\left(\frac{t}{100}\right)\left(1+\frac{t}{100}\right)^n}{(1+\frac{t}{100})^n - 1}\,[\$] \tag{3.2}$$

Introducing the average annual load factor, F_c, defined as the average load divided by the peak load in a specified time period and expressed as a percentage, as well as investment ratio I_{up} that indicates the relationship between the amount of money invested and the profit made from it, K_A and K_{EM} defined respectively:

- I_{up} = initial investment (I)/rated power, in kW, of the production equipment (P);
- K_A = A/I
- K_{EM} = Annual operating-maintenance expenditures/I

The overall discounted cost, *C*, of a delivered electric kWh, excluding fuel cost, is then given by the equation:

$$C = \frac{I_{up}(K_A + K_{EM})}{8760.F_c} \qquad F_c = \frac{(\text{annual energy produced, in kWhrs})}{(P,\text{ in } kW)(\text{annual time, in } hrs)} \tag{3.3}$$

The calculations are based on the reference methodology adopted in previous studies, i.e., the levelized lifetime cost approach. The calculations use generic assumptions for the main technical and economic parameters as agreed upon in the ad hoc group of experts, e.g., economic lifetime (40 years), average load factor for base-load plants (85%) and discount rates (5% and 10%) [13].

$$I_{up} = \frac{Initial\ Investment\ (I)}{rated\ power\ in\ kW\ of\ production\ equipment(P)} [\$\ per\ kW] \tag{3.4}$$

$$K_A = \frac{A}{I} \tag{3.5}$$

$$K_{EM} = \frac{(Annual\ operating - maintenance\ expenditures)}{I} \tag{3.6}$$

$$C = \frac{I_{up}(K_A + K_{EM)}}{8760 \times F_c} [\$] \tag{3.7}$$

$$F_c = \frac{(Annual\ energy\ producedin\ kWh)}{(P, inkW)(annual\ time\ , in\ hrs)} \tag{3.8}$$

3.1.1 Determination of Cost for Off-Grid Generation

The cost of a kWh delivered by a fossil fuel based system includes the initial investment cost, the fuel expenditure, and the operating, repair and the maintenance expenditures. The chart below shows how this cost was derived.

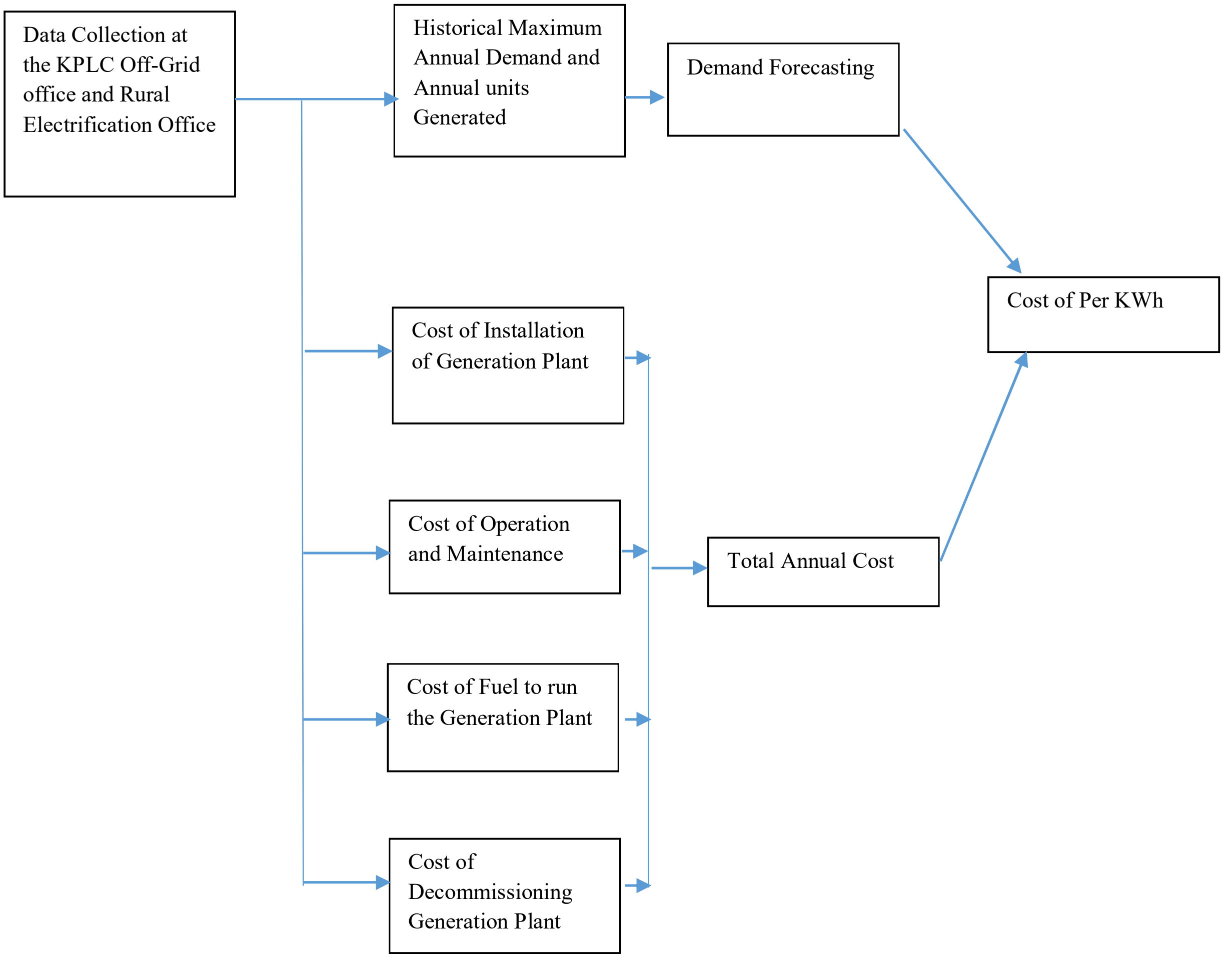

Fig 3.1 Determination of Cost for Off-Grid Generation

3.1.2 Determination of Cost for Transmission and Distribution

In determining the cost of a kWh of electricity delivered by large, grid-connected power stations through the construction of the transmission infrastructure, the cost includes the initial investment cost, and the operating, repair and maintenance expenditures. The figure below shows how this cost was derived.

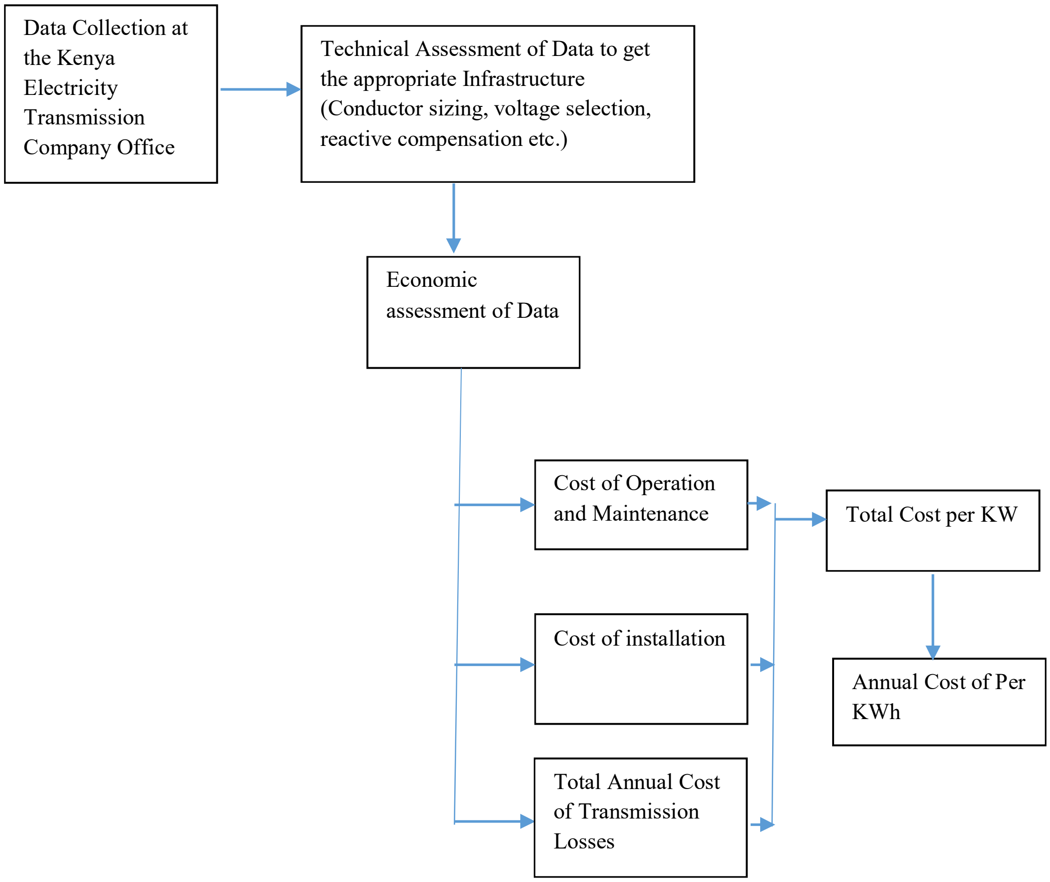

Fig 3.2 Determination of Cost Transmission Infrastructure

3.1.4 Software Selection

PSS/E software was used to model the transmission line and its effect on the existing transmission grid. The power flows from the model were used to assess the need for reactive compensation hence the inclusion of the reactors as part of the installation. It was also useful in sizing of the electrical switchgear and transmission line conductor to be used.

3.1.5 Demand Forecasting

The demand forecast was carried out from data gathered from the off-grid and the Rural Electrification offices in KPLC and on site at the Kenya power office at the generation site. A comparison was also done with the data collected from the Least Cost Expansion Plan.

Since there are no documented vision 2030 flagship projects in Wajir, the maximum percentage annual increase from historical data was used to forecast the annual increase in the maximum power demand from 2014 to 2030.

4. Research Results and Analysis

4.1 Off-Grid Plants in Kenya

The total energy generated by the off-grid power plants is relatively low and for the year 2010/11 represented just 0.8 % of the total electricity sales in the country. The combined peak demand of the off-grid power plants was around 9 MW for 2010/11 [14].

There are 11 off grid generation stations which are Mpeketoni power plant in Lamu district, Hola in Tana River district, Elwak in Mandera South, Baragoi in Samburu North District, Mfangano Island in Suba district, Merti in Isiolo, Habaswein in Wajir South district and several more in Marsabit, Lodwar and Moyale.

For this particular study the focus was the Wajir area which is currently supplied off grid from a diesel power plant. The load forecast involved data collection from the KPLC control centers and the off grid office.

Table 4.1: Off-Grid Plants in Kenya for the year 2014

County	Location	Status	Capacity (KW)	Annual Generated energy – 2013/2014 (MWh)	Peak demand (KW)	Load factor
Turkana	Lodwar	Existing		3556	650	62%
Marsabit	Marsabit	Existing	2489	2799	600	53%
Marsabit	Moyale	Existing	1341	1969	540	42%
Samburu	Baragoi	Existing		153	41	43%
Mandera	Mandera	Existing	1,600	4,167	858	55%
Mandera	El wak	Existing	360	416	95	50%
Mandera	Takaba		184			
Mandera	Rhamu		184			
Wajir	Wajir	Existing	1,700	5,234	1,020	59%
Wajir	Habaswein	Existing	300	603	108	64%
Isiolo	Mertl	Existing	138	170	44	44%
Garissa	Garissa	Existing	6,100	17,129	3,435	57%
Tana River	Hola	Existing	800	1,494	309	46%
Lamu	Lamu	Existing	2,378	4,871	942	59%
Lamu	Mpeketoni	Existing		1,109	312	41%
Homa Bay	Mfangano	Existing		90	26	40%
TOTAL			17,634	43,760	9,040	55%

Source: KPLC Off-Grid Office

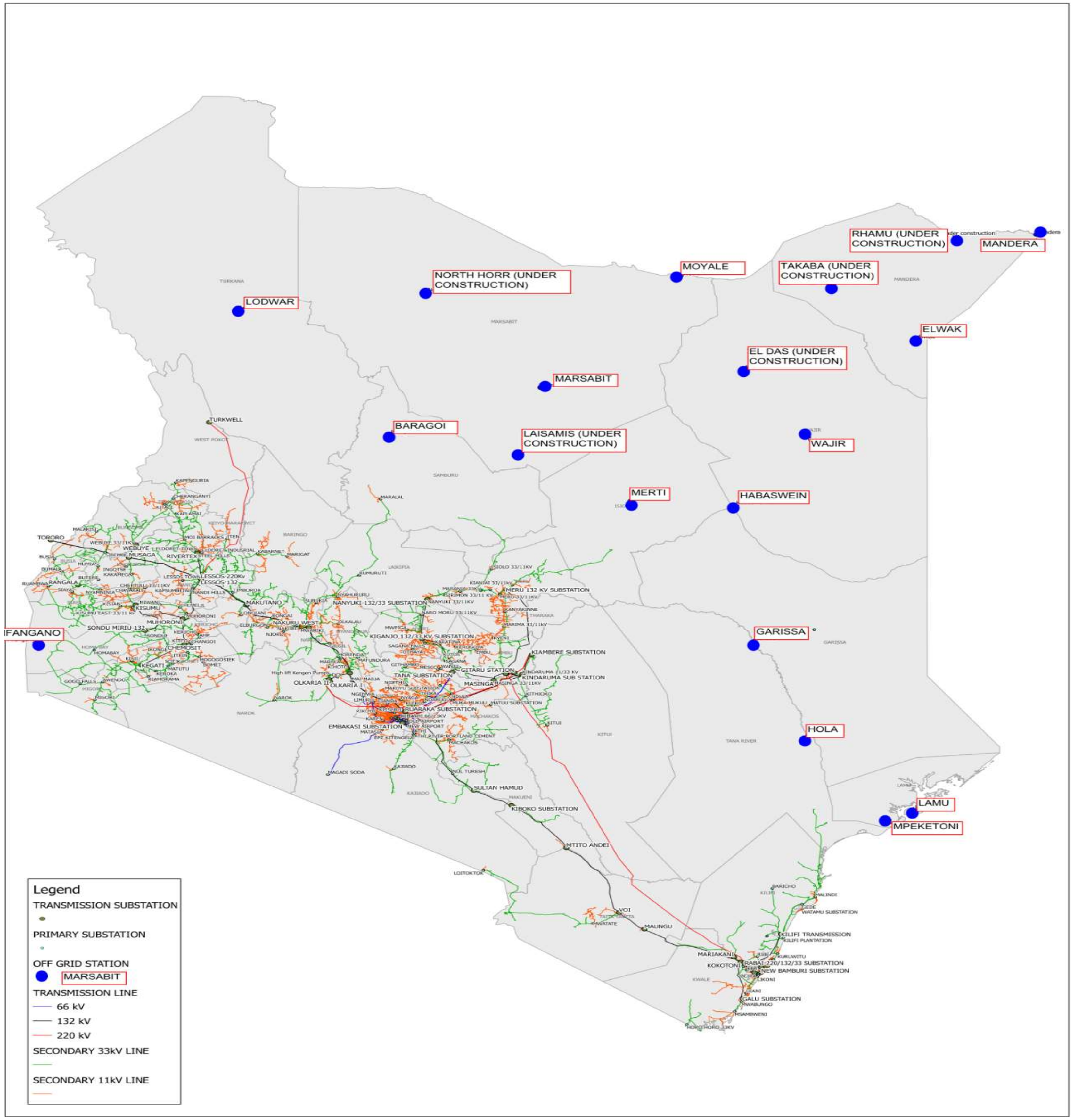

Fig 4.1: **Off-grid power plants in Kenya**

Source: KPLC off-grid office

Related Transmission developments

There are a number of transmission grid expansion projects at various stages of development to which some off-grid stations are earmarked for connection: The figure below shows some of the transmission line projects at various stages of implementation

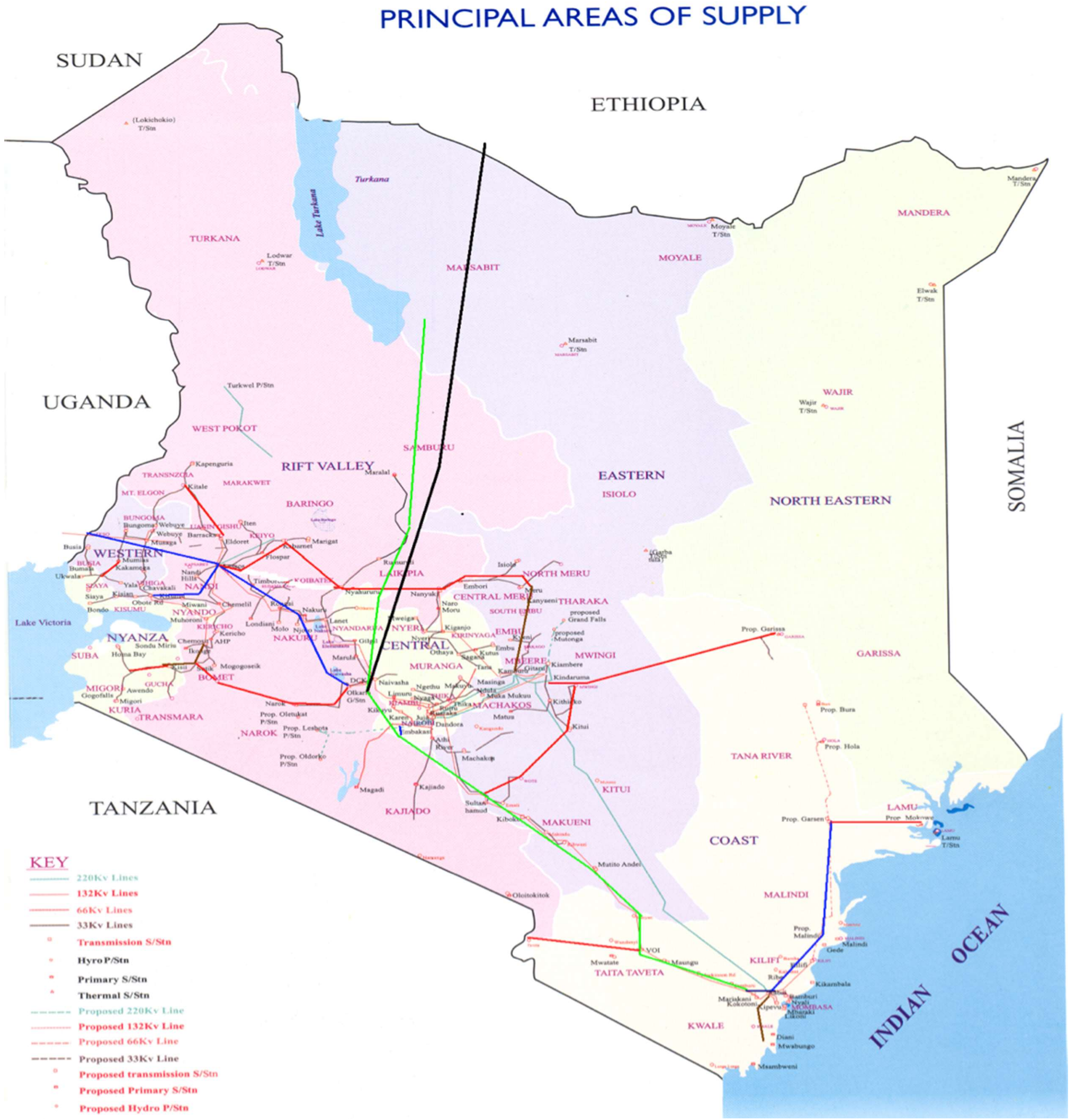

Fig 4.2: Power Transmission Network in Kenya.

Source: KETRACO office

Table 4.2: Transmission Projects to Off-Grid Regions

Transmission Project	Voltage (kV)	Capacity (MVA)	Status	Expected completion	Affected off-grid power plant
Rabai-Malindi-Garsen-Lamu	220	150	Completed	2014	Lamu
Kindaruma-Mwingi-Garissa	132	80	On-going	2016	Garissa
Garsen-Hola-Garissa	220	150	Feasibility stage	2017	Hola

Source: KPLC Off-Grid office

4.2 Wajir off grid plants

The example case has considered the viability of extending the grid from Garissa to Wajir town, which is the county headquarters for Wajir County. Wajir County is currently supplied off grid through three existing (Diesel) generator stations namely Wajir 1700KW, Habaswein 300KW and El Das 300KW.

The gaps in this distributed generation include:

a) The cost of electricity is higher than the one from CG because of the cost of diesel used. The plant(s) is/ (are) far from the port hence the cost of transportation also increases the cost of the electricity produced.

b) A fault in the plant means that the entire area is not supplied. This is because there is no security as was seen in a situation where a fire at the plant interrupted supply to the area for over two weeks.

c) Security of supply would mean investing in a redundant plant which is costly. In network security, the size will be limited seeing that a DG has to comply with set standards rather than ~~to~~ simply meeting supply security at the pre-reconnection point which will require more control options for better security though at higher than budgeted cost.

d) Voltage level of radial type system supply a number of distributed consumers with DG at different locations which will increase local voltage level and cost implications.

To solve some of these issues this paper proposes the connection of Wajir to the National grid by the construction of a transmission infrastructure from Garissa. Although Garissa is itself currently off-grid there is an ongoing project to interconnect it to Kindaruma power station in the Mt. Kenya region by means of a 132 kV transmission line and a new 132/33/11 kV substation at Garissa which should be completed by December 2016.

Wajir demand forecast

The peak demand for Wajir for the period 2014 to 2030 was investigated through data collection in the KPLC off-grid office and on site at the Kenya power office at the generation site. A comparison was also done with the data collected from the Least Cost Expansion Plan.

Table 4.3 Power generated in Wajir off-grid Plant

Source: KPLC Off-Grid Office

Year	2007		2008		2009		2010		2011		2012		2013	
	MW	KWH	MW	KWH	MW	KWH	MW	KWH	MW	KWH	MW	KWH	MW	KWH
Jan	700	287270	820	379750	830	401050	918	428593	930	459394	1060	457620	1190	563827
Feb	700	242170	850	358200	840	363640	932	414064	940	426570	1020	365225	1299	565565
Mar	750	32570	840	376720	870	422500	958	424660	960	483416	1086	455411	1290	514,862
Apr	760	303930	840	341030	840	396430	860	410274	950	459867	1056	444432		
May	760	342310	820	379750	890	409380	939	457340	990	470652	1061	481145		
June	800	352310	850	358200	890	401500	939	429709	984	412043	1100	472383		
July	820	362310	840	376720	870	395360	922	425410	1040	446697	1199	497852		
Aug	800	358110	840	355980	875	404306	951	442614	1020	466815	1214	508539		
Sept	840	382940	780	193500	902	416484	949	440143	1080	464048	1188	453571		
Oct	820	331510	910	343080	915	411998	917	456116	1030	444869	1232	438587		
Nov	840	301940	800	309130	896	402074	938	421104	1050	409189	1158	490180		
Dec	840	301940	810	394100	854	408857	877	426433	942	403874	1158	416257		

From the data above, the average Maximum demand in MW and the units generated were averaged for the years 2007 to 2013 as shown in the tables and graphs below.

Table 4.4: Maximum Demand and Units Generated from 2007/08 to 2012/13

Year	2007/08	2008/09	2009/10	2010/11	2011/12	2012/13
Max Demand KW	840	910	915	958	1080	1232
Generated Units GWH	3.0278	4.1305	4.8336	5.1765	5.3474	5.4812

Graph of Maximum Demand in MW from 2007 to 2012

The graph below showing the maximum demand with time was generated using data from table 4.4 above.

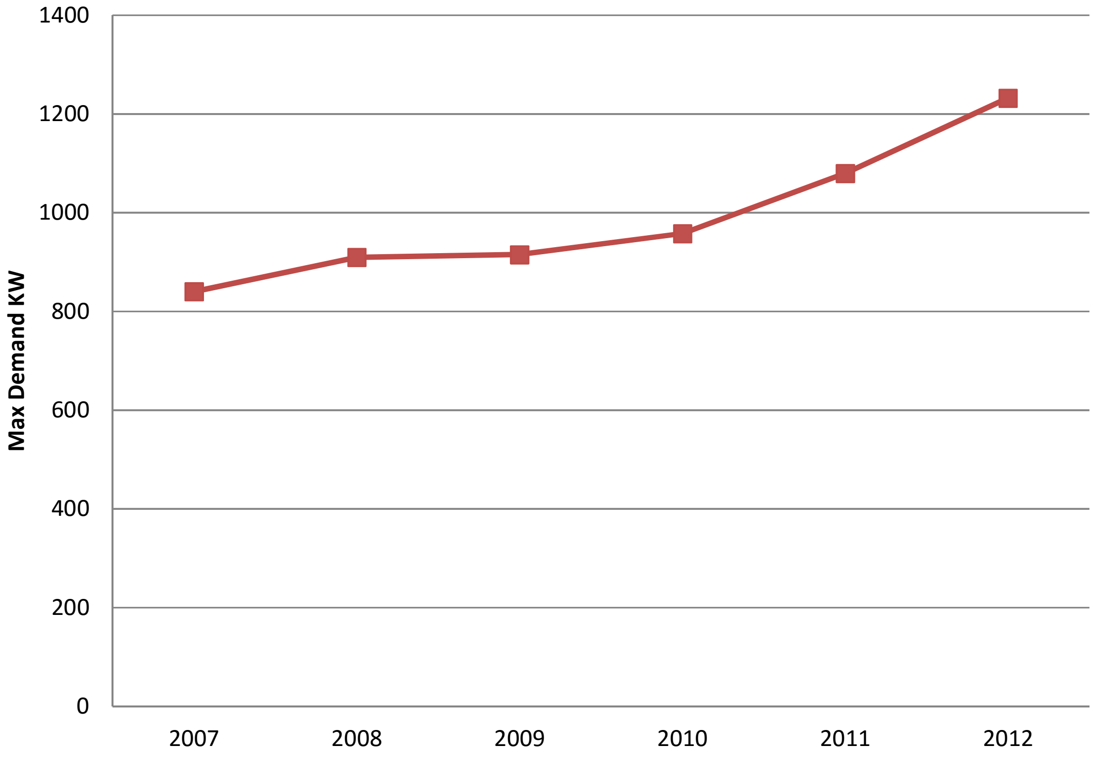

Fig 4.3: Graph of Maximum Demand in MW from 2007 to 2012

Graph of Units Generated in GWH from 2007 to 2012

The graph below showing the Units Generated in GWH with time was generated using data from table 4.4 above.

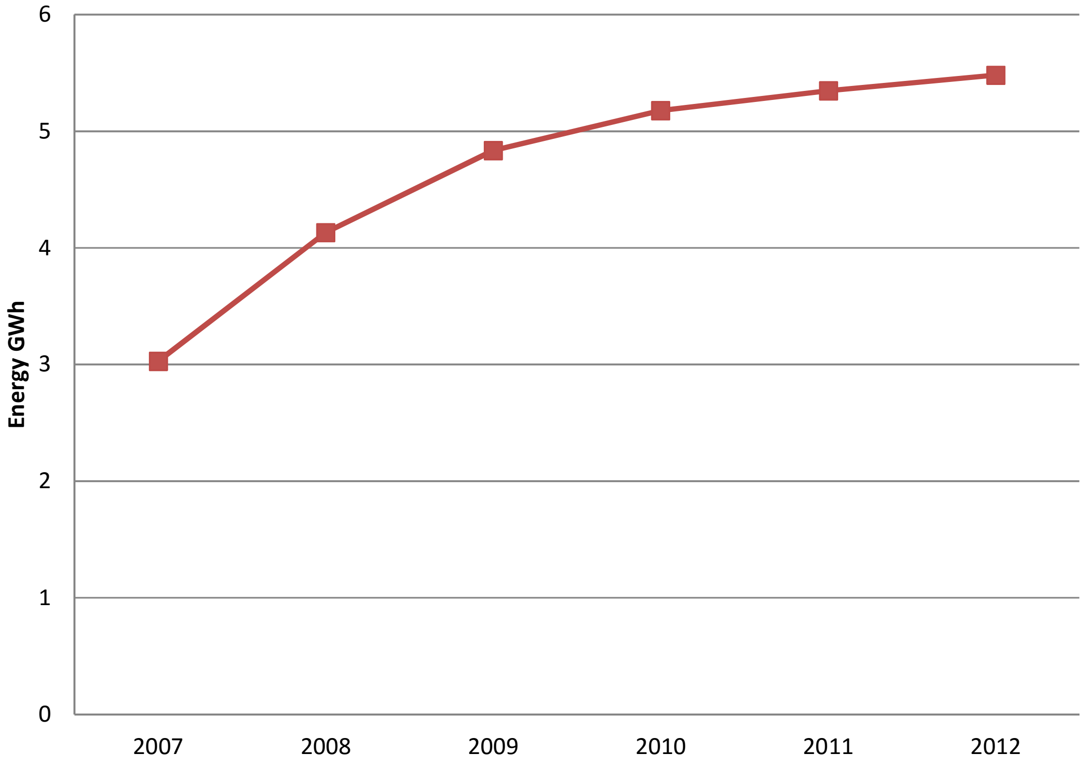

Fig 4.4: Graph of Units Generated in GWH from 2007 to 2012

From the analysis of load data collected from the KPLC off grid office data from the Least Cost Power Expansion Plan, the average annual increment in the maximum demand for Wajir had a calculated value of ***14.1%.*** Using this factor of ***1.141***, and without considering any vision 2030 flagship projects in Wajir, the forecast to 2030 is as shown below:

Table 4.5: Forecasted Maximum Demand and Units to be generated for the period 2014/15 to 2029/30

Year	Wajir (kWh)	Wajir (MW) Max Demand		Year	Wajir (kWh)	Wajir (MW) Max Demand
2014	7136	1.604		2023	23389	5.257
2015	8142	1.830		2024	26687	5.998
2016	9290	2.088		2025	30450	6.844
2017	10600	2.383		2026	34744	7.809
2018	12095	2.718		2027	39642	8.910
2019	13800	3.102		2028	45232	10.167
2020	15746	3.539		2029	51610	11.600
2021	17966	4.038		2030	58887	13.236
2022	20499	4.608				

The peak demand is forecast to increase from around *1.8MW* in 2014 to *13.23* MW by 2030.

Using a factor of *1.141* calculated from the data collected from KPLC off grid office, the graph below shows the forecasted maximum demand growth curve for the period 2015 to 2030.

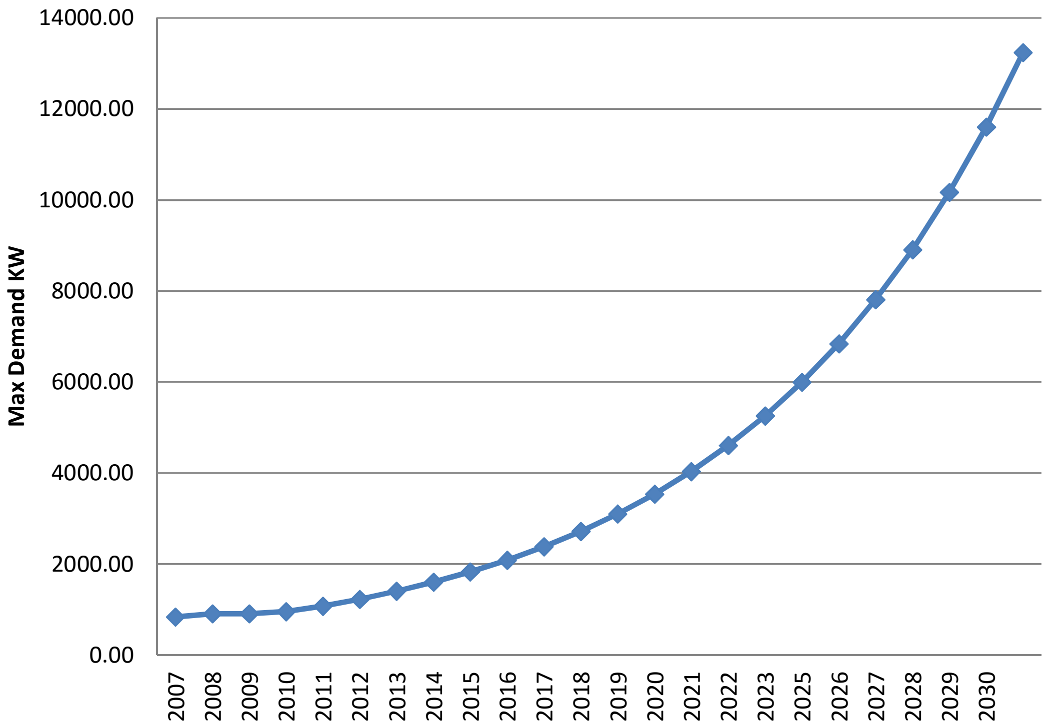

Fig 4.5: Graph of Projected Maximum Demand for the period 2014/15 to 2020/30

Using a factor of 1.141 calculated from the data collected from KPLC off grid office, the graph below shows the forecasted units generated growth curve for the period 2015 to 2030.

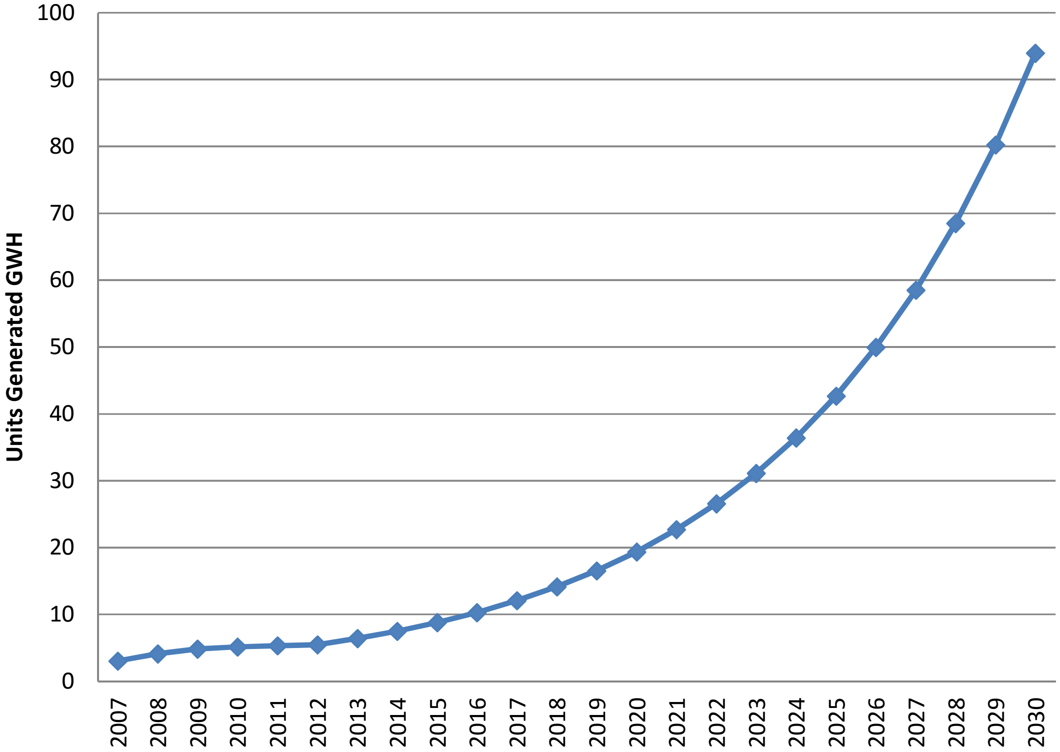

Fig 4.6: Graph of Projected Units to be generated for the period 2014/15 to 2020/30

4.3 Assessment of Cost per kWh for Energy from Off Grid Generation Plant

4.3.1 Capital Investment

The initial investment cost of installation of the diesel power plant and other costs related to the extension of the distribution lines to homes was estimated as shown in the table below. The plant to be constructed should generate at least 15MW (60GWh) in order to cater for the load forecasted up to 2030.

Table 4.6: Off Grid Plant Capital Investment

	USD	**USD/KW**
3 acres of Land at (at $10,000 per acre)	30,000	2
Civil Engineering works:		
A 50m^2 ceiling with iron columns, No. 24 sheets Iron zinc roof and cement floor 15cm thick reinforced with 4.2m iron bars	600,000	40
42m^2 brick wall 0.30 m thick , 4 m reinforced concrete for installation of engine platform	165,000	11
Electric generator and gasifier	240,000	16
Electric Installations		
Electric installations and panel feeding outlets and 600m extension lines to families	420,000	28
Machinery and Equipment		
10 by 150 HP Duetz Engine and giving 3 by 1,000 KW AEG electric Generator	100,000,000	6667
Fuel gasifier with accessories (gas cooler, filter, piping etc)	2,355,000	157
Transport and Insurance costs	135,000	9
Assembly, Installation, testing and commissioning costs	735,000	49
Total Investment	**105,100,000**	**6979**

Using equation (3.2), the amortization was calculated as shown below:

$$A = \frac{(105{,}100{,}100 \times (0.1) \times 1.1^{40})}{(1.1^{40} - 1)} = \$10{,}747{,}460$$

4.3.2 Cost of Operation and Maintenance of the Generation Plant

The operation costs include the annual salaries and allowances, transport costs, Training expenses and other general office expenses. The maintenance costs include material, machines, uniforms and protective clothing, tools and spare parts. This data was collected from the KPLC Off-Grid office for the financial year 2009/2010 to 2012/2013

The table below gives a summary of the data:

Table 4.7: Operation and Maintenance cost for the financial years 2009/10 to 2013/14

Financial Year	**Operation and Maintenance cost (KES)**	**Generated Units kWH**	**Cost Per KWH (KES/kWH)**
2009-10	5,111,404.83	3028	1.6882
2010-11	10,767,496.75	4131	2.6068
2011-12	11,342,783.23	4834	2.3467
2012-13	23,525,848.35	5177	4.5447
2013-14	25,401,814.48	5347	4.7503

Using an average annual increment of *5%,* the average annual Operation and Maintenance cost was taken as *$ 33,005* and using equation (3.3) where,

I = *$105,100,000*

P = Rated power = *12MW*

Therefore I_{UP} = *105100000/12000 = 8758.33*

A = *$10,747,460*

K_A = A/I = *0.1*

K_{EM} = Annual O&M expenditures/I = *$ 33,005/$105,100,000 = 0.000314*

The overall discounted cost, *C*, of a delivered electric kWh, excluding fuel cost, is then calculated using equation 3.3:

Taking F_C = *0.60*

$$C = \frac{8758.33 \times (0.1 + 0.000314)}{0.6 \times 8760} = \$0.17/kWh$$

4.3.3 Cost of fuel to run the Generation Plant

Table 4.8: Cost of Fuel to run generation Plant for the financial years 2009/10 to 2013/14

Financial Year	**Operation and Maintenance Cost (KES)**	**Class B Diesel (Fuel) KES**	**Units Generated KWH**	**Litres of Fuel used**	**Cost KES Per KWH**	**Litres per KWH**
2007-08						
2008-09	**-**	**85,486,420**	**4,367,010**	**1,263,986**	19.58	0.289439685
2009-10	**5,111,405**	**106,359,623**	**5,003,719**	**1,559,596**	21.26	0.311687367
2010-11	**10,767,497**	**142,376,221**	**5,323,762**	**1,545,350**	26.74	0.290274058
2011-12	**11,342,783**	**191,759,554**	**5,311,708**	**1,561,076**	36.10	0.293893414
2012-13	**23,525,848**	**210,127,399**	**-**	**-**	-	-
2013-14	**25,401,815**	**255,793,337**	**-**	**-**	-	-

From the analysis, the average amount of fuel in liters per unit is ***0.2963*** *Liters/kWh*

Going by the current international global diesel prices per litre [15], the price of diesel is *$0.83* per liter on 10, June 2015. This gives a cost of *$0.245929/kWh*.

Therefore the overall discounted cost, of a delivered electric kWh, including fuel cost is:

$ 0.17 / kWh + $0.245929/kWh = **USD 0.42 /kWh per annum.**

4.4 Extension of transmission grid to Wajir

4.4.1 Technical Assessment

a. Voltage Selection

The following empirical formula was used in the selection of the voltage:

$$E = 5.5\sqrt{\frac{L}{1.6} - \frac{kVA}{150}} \tag{4.1}$$

Where

E is the optimal line to line voltage

L is the length of the line in km taken as 270km

kVA is the total power (power factor equal to 0.9) that shall be transferred assuming use of a 23MVA transformer.

The optimum voltage was taken to be 132KV

b. Conductor Selection

The selection of a conductor is dependent on the following properties: power delivery requirement which is determined by the current carrying capacity and electrical losses; the line design requirements such as the distances to be spanned; the sag and the clearance requirements where strength, weight, diameter, corrosion resistance, creep rate, thermal coefficient of expansion, fatigue strength, operating temperature, short circuit current and thermal stability are taken into consideration; cost and the environmental considerations such as the ambient temperatures and the wind loading.

N.B The selection was done according to IEC 60364 standards for bare conductors.

4.4.2 Economic Assessment of Transmission Investment

The transmission line costs consist of the Capital cost, cost of transmission losses and the operation and maintenance cost.

a. Cost of Transmission Losses

Losses are unavoidable and are a cost of delivering power. The losses in a system can be broadly defined as:

Loss (%) = 100 x (Energy input – Energy output) / (Energy Input) (4.1)

$$Loss\ (\%) = \frac{Energy\ input - Energy\ output}{Energy\ Input}$$

Losses occur at every point in the power system from the point of generation, through the transmission to the distribution system. Every piece of equipment in the system has impedance that causes heating whenever power is flowing through it. The magnetic field in transformers causes flux to flow in the core where losses occur. Iron losses are a function of the composition and construction of the transformer and are constant with typical loading.

Excessive losses represent:

a) Wasted energy in the form of more fuel burnt than necessary which is an increased cost to the country.

b) Wasted capacity in the form of increased generation and transmission capacity required.

c) Reduced amount of energy for customers because less energy is supplied and there is less money available for upgrades and/or expansions.

d) Increased import of energy increases the utility purchases leading to increased use of other energy sources as larger equipment sizes are needed.

Losses can be categorized as either technical losses or non-technical losses.

Technical Losses include resistive heating of conductors, transformer losses, high impedance faults, phase imbalance, equipment sizing, voltage and power factor quality and poor connections and maintenance.

Non-technical losses include defective meters, lack of metering, inconsistent or erroneous meter readings, meter theft, meter tampering, direct connection and other errors and lack of energy account.

Taking a Wolf^{TM} ACSR conductor, selected as per IEC 60364, the following are the transmission line parameters:

DC or AC resistance at 20 ºC = Resistance per km at 20ºC (ohm/km)

=0.1865

Temp coefficient of resistance per ºC is *0.00403*

The Average operating temperature is *55ºC*

$$AC\ resistance\ at\ 55\,^{0}\,C = (Resistance\ pr\ km\ at\ 20^{0}C[ohm/km]) \times (1 + 35 \times Temp.Coefficient\ \ of\ resistance\ per\ ^{0}C)$$

$$= 0.18565\ [ohm/km] \times (1 + 0.00403 \times 35[^{0}C])$$

=0.2128 [ohm/km]

The peak load in Wajir is an Average of 30MW. The operating Voltage for the line is 132kV. Assuming a power factor of 0.95:

$$Load\ [MVA] = \frac{Peak\ Load\ [MW]}{Power\ factor} = \frac{30\ [MW]}{0.95}$$

=32.7 [MVA]

$$Current\ [A] = \frac{load[MVA]}{\surd 3 \times 1000 \times 132[kVA]}$$

=143.1 [A]

$$Thermal\ Losses\ per\ km\ per\ circuit\ =\ I^{2}R$$

$$= \frac{143.1^{2} \times 3 \times 0.2128\ [ohm/km]}{1000}$$

=13.1[kW]

$$\boldsymbol{Percentage\ power\ loss\ per\ km} = \frac{Thermal\ losses\ per\ km\ per\ circuit}{Load\ [MW]/100}\ [\%]$$

=0.042%

$$\boldsymbol{Percentage\ Energy\ loss\ per\ km}$$
$$= Percentage\ power\ loss\ per\ km\ \times (0.3 + (0.7 \times Load\ factor))$$

Assuming a load Factor of *55%*

$$= 0.042\%(0.3 + (0.7 \times 55\%))$$

=0.029%

The estimated distance from Garissa substation to the proposed Wajir substation is approximately *267km*

% power loss = Percentage power loss per km X Line Length

$$\%\ \boldsymbol{Power\ loss} = Percentage\ power\ loss\ per\ km\ \times Line\ length[km]$$

$$= 267[km] \times 0.042\%$$

=11.2%

$$\%\ \boldsymbol{Energy\ Loss} = Percentage\ energy\ loss\ per\ km\ \times Line\ Length$$

$$= 267[km] \times 0.029\%$$

=7.7%

The lines parameters used are captured in table 4.9 below:

Table 4.9: Transmission Line Parameters

Parameter	Unit	Value
Nom Al area	mm^2	150
AC Resistance at 20C	ohm/km	0.1865
Temp coefficient of resistance	Per ^oC	0.00403
Average operating temperature	^oC	55
AC resistance at 55C	ohm/km	0.213
Voltage (line)	kV	132
Peak Load	MW	31.09
Power factor		0.95
Load	MVA	32.7
Load	A (Amp)	143.1
Thermal losses/km/circuit	kW	13.1
% power loss	per km	0.042%
Load factor		55%
% energy loss	per km	0.029%
Line length	km	267
% power loss	-	11.2%
% energy loss		7.7%

Transmission Power Losses in kW = 3 I^2R

= 3 X (Forecast Load / Transmission Voltage / $\sqrt{3}$/Power Factor$)^2$ X Transmission line resistance per km x Line Length / 1000

Transmission Energy Losses in MWh

=Transmission Power Losses in KW X (0.3 X Load Factor + 0.7 X Load Factor^2)

The required capacity should include the transmission power and energy losses. The table below shows the calculated figures.

Table 4.10: Transmission Line Capacity

Year	Forecast Load		Tx Power losses	Tx Energy losses	Capacity Required	
	kW	MWh	kW	MWh	kW	MWh
2014	1604	7136	12.20	34.90	1616.20	7170.90
2015	1830	8142	16.70	47.50	1846.70	8189.50
2016	2088	9290	22.00	62.60	2110.00	9352.60
2017	2383	10600	29.00	82.50	2412.00	10682.50
2018	2718	12095	38.20	108.80	2756.20	12203.80
2019	3102	13800	50.00	142.40	3152.00	13942.40
2020	3539	15746	66.10	188.10	3605.10	15934.10
2021	4038	17966	87.20	248.30	4125.20	18214.30
2022	4608	20499	115.60	329.10	4723.60	20828.10
2023	5257	23389	153.80	437.90	5410.80	23826.90
2024	5998	26687	206.30	587.30	6204.30	27274.30
2025	6844	30450	278.50	792.80	7122.50	31242.80
2026	7809	34744	378.40	1077.20	8187.40	35821.20
2027	8910	39642	518.70	1476.80	9428.70	41118.80
2028	10167	45232	718.90	2046.80	10885.90	47278.80
2029	11600	51610	1008.60	2871.50	12608.60	54481.50
2030	13236	58887	1434.20	4083.00	14670.20	62970.00

4.4.2 Power system simulation

Using PSSE software, the Kenya power system was simulated using tools to investigate system response to addition of the new transmission line to the power system. From the simulation there was need in include a reactor bank at the Wajir and Mwingi substations for voltage control due to Ferranti effect. This is because the transmission line is long and lightly loaded in the initial stages.

a) Network Layout model

The basic known input data used to model the existing network layout included the following:

i) Transmission line impedances and charging admittances.
ii) Transformer impedances and tap ratios.
iii) Admittances of shunt-connected devices such as static capacitors and reactors.

iv) Load-power consumption at each bus of the system.
v) Real power output of each generator or generating plant.
vi) Either voltage magnitude at each generator bus or reactive power output of each generating plant.
vii) Maximum and minimum reactive power output capability of each generating plant.

For the purpose of the study, the subsystem modeled comprised of the following 132kV buses.

i) Juja road substation to Kilimambogo TEE1
ii) Garissa substation to Wajir proposed substation
iii) Kamburu generation station to Kindaruma generation station
iv) Kilimambogo TEE1 to Mang'u substation
v) Kindaruma generation station to Kilimambogo TEE2
vi) Kindaruma to Mwingi substation
vii) Kilimambogo TEE2 to Mang'u substation
viii) Mwingi substation to Kutui substation
ix) Kitui substation to Wote substation

Currently 132kV Garissa substation is supplied from Kindaruma hydro generation plant through 132kV Mwingi substation using the existing 132kV transmission line.

b) Network parameters studied

The following parameters were studied:

i. The magnitude of the voltage at every bus where this is not specified in the input data and the phase of the voltage at every bus, except swing buses.

The analysis of a network of transmission lines requires a method of solving for the voltages and currents at all points in a network built up by the interconnection of many such transmission line equivalent circuits. Given these elements, the engineer can calculate the conditions that would exist at any point on a real transmission network for a proposed set of loads and generator outputs.

Voltage magnitude at the buses in the subsystem is monitored with the main purpose of ensuring the voltage levels are within the tolerances as required for system stability and as dictated by the grid code.

ii. The real power, reactive power, and current flow in each transmission line and transformer.

The branch loading was monitored to ensure that the lines and transformer were not over loaded and ascertain adequacy of the system to accommodate the proposed/forecasted generation or load in the subsystem.

The total system power generated in the entire country was ***1945.7 MW*** at the time of the simulation.

iii. The reactive power output of each plant for which it is not specified.

The branch loading above will advise on the additional reinforcement to be considered so as to ensure the subsystem operates at normal system conditions.

Losses may be computed for each line and transformer in the subsystem, this however may not have a big impact considering the scale developments proposed. A comparison can be made on the global losses in the system (with and without the proposed developments).

c) Equations to be solved By PSS®E

PSS®E includes five power flow solution activities, each of which operates on the bus voltage estimates in the working case to attempt to bring them to a solution of Kirchhoff's laws.

The power flow calculation is a network solution problem. The network of transmission lines and transformers is described by the linear algebraic equation:

$$I_n = Y_{nn}V_n \qquad (4.2)$$

Where:

I_n = Vector of positive-sequence currents flowing into the network at its nodes (buses).
V_n = Vector of positive-sequence voltages at the network nodes (buses).
Y_{nn} = Network admittance matrix.

If either I_n or V_n is known, the power flow calculation is straightforward. In practice however, neither I_n nor V_n is known and the task of the power flow program is to devise successive trials of both I_n and V_n that satisfy both Equation 3.1 and all the load and generation conditions specified in the problem data. After V_n has been determined, all individual transmission line and transformer flows can be obtained directly from the individual component equations.

Each activity makes successive adjustments to the bus voltages in accordance with a different iterative schemes. These are the Gauss-Seidel methods and the Newton-Raphson methods.

d) Results of the Network Simulation

The results of the simulation are detailed in the table below and the snap shots from the PSS/E showing the network before the addition of the circuit to Wajir, after addition of the circuit and the final diagram shows the network with voltage compensation.

i. Simulation of the System without the Transmission Line to Wajir

Table 4.11 Branch data of the System without the Transmission Line to Wajir

FROM BUS	TO BUS	CKT	LINE R	LINE X	CHARGING	RATEA	LENGTH (KM)
JUJA RD 132	KILBOGO TEE1 132	1	0.0436	0.09887	0.01875	97.2	40
GARISSA	WAJIR 132	1	0.19622	0.44489	0.08437	97.2	267
GARISSA	MWINGI 132	1	0.19622	0.44489	0.08437	97.2	180
KAMBURU 132	KINDARUMA 132	1	0.08721	0.19773	0.0375	97.2	80
KILBOGO TEE1	MANGU 132	1	0.0218	0.04943	0.00937	97.2	20
KINDARUMA 132	KILBOGO TEE2 132	1	0.08721	0.19773	0.0375	97.2	80
KINDARUMA 132	MWINGI 132	1	0.0436	0.09887	0.01875	97.2	40
KILBOGO TEE2	MANGU 132	2	0.0218	0.04943	0.00937	97.2	20
MWINGI 132	KITUI 132	1	0.06541	0.1483	0.02812	97.2	60
KITUI 132	WOTE 132	1	0.06541	0.1483	0.02812	97.2	60

Table 4.12 Bus Voltage of the System without the Transmission Line to Wajir

BUS	BASE KV	VOLTAGE	V_{MAX}	V_{MIN}
GARISSA	132	1.05147	1.05	0.95
KILBOGO TEE1	132	1.0249	1.05	0.95
KINDARUMA	132	1.04489	1.05	0.95
KILBOGO TEE2	132	1.02556	1.05	0.95
MWINGI	132	1.04629	1.05	0.95
KITUI	132	1.04027	1.05	0.95
MWINGI33	33	1.02458	1.05	0.95
KITUI3	33	0.99619	1.05	0.95
GARISSA33	33	0.97433	1.05	0.95

Table 4.13 Generation and load of the System without the Transmission Line to Wajir

TOTAL	SYNCHR	PQLOAD	LOSSES	SWING
MW	1945.7	1878.5	67.2	41.7
MVAR	634.3	1006.4	572.3	21

Table 4.14 Load data of the System without the Transmission Line to Wajir

BUS	MW	MVAr
MWINGI33 33.000	1.5	1
KITUI3 33.000	2.2	1.4
GARISSA33 33.000	3.1	2

This figure shows the transmission system simulation before the inclusion of the extension to Wajir from Garissa.

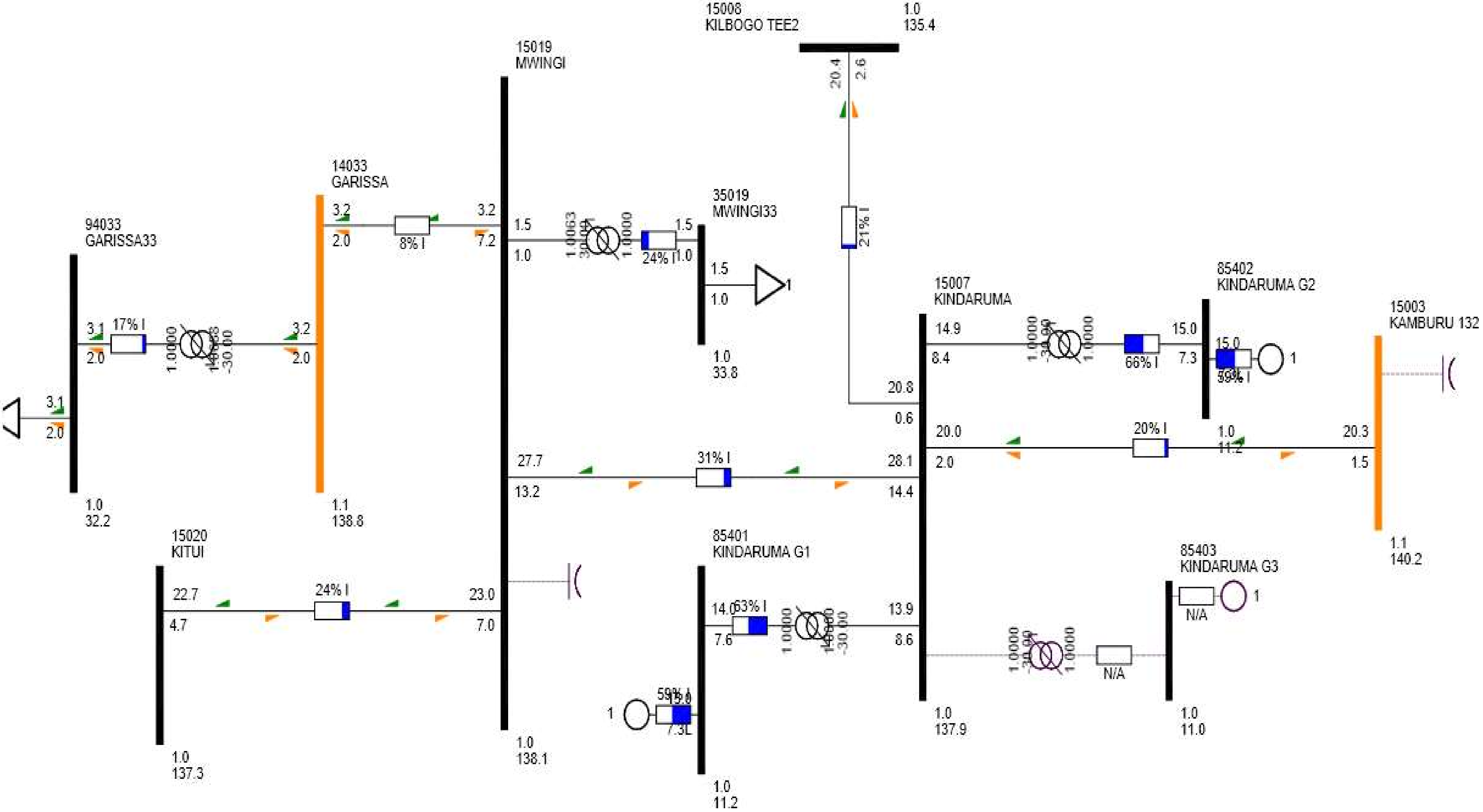

Fig 4.7 Simulation of the System without the Transmission Line to Wajir

ii. Simulation of the System with the link to Wajir without reactive compensation

Table 4.15 Branch data of the System with the link to Wajir without reactive compensation

FROM BUS	TO BUS	CKT	LINE R	LINE X	CHRGING	RATEA	LENGTH
JUJA RD 132	KILBOGO TEE1 132	1	0.0436	0.09887	0.01875	97.2	40
GARISSA	WAJIR 132	1	0.19622	0.44489	0.08437	97.2	267
GARISSA	MWINGI 132	1	0.19622	0.44489	0.08437	97.2	180
KAMBURU 132	KINDARUMA 132	1	0.08721	0.19773	0.0375	97.2	80
KILBOGO TEE1	MANGU 132	1	0.0218	0.04943	0.00937	97.2	20
KINDARUMA 132	KILBOGO TEE2 132	1	0.08721	0.19773	0.0375	97.2	80
KINDARUMA 132	MWINGI 132	1	0.0436	0.09887	0.01875	97.2	40
KILBOGO TEE2	MANGU 132	2	0.0218	0.04943	0.00937	97.2	20
MWINGI 132	KITUI 132	1	0.06541	0.1483	0.02812	97.2	60
KITUI 132	WOTE 132	1	0.06541	0.1483	0.02812	97.2	60

Table 4.16 Bus Voltage of the System with the link to Wajir without reactive compensation

BUS	BASE KV	VOLTAGE	VMAX	VMIN
GARISSA	132	1.09526	1.05	0.95
WAJIR	132	1.10552	1.05	0.95
KILBOGO	132	1.02656	1.05	0.95
KINDARUMA	132	1.0522	1.05	0.95
KILBOGO	132	1.02854	1.05	0.95
MWINGI	132	1.05888	1.05	0.95
KITUI	132	1.05069	1.05	0.95
MWINGI33	33	1.03728	1.05	0.95
KITUI3	33	1.0063	1.05	0.95
GARISSA33	33	1.01569	1.05	0.95
WAJIR	33	1.02856	1.05	0.95

Table 4.17 Generation and load of the System without the link to Wajir with reactive compensation

TOTAL	SYNCHR	PQLOAD	LOSSES	SWING
MW	1949	1881.5	67.5	45.1
MVAR	623.6	1007.6	572.8	20.3

Table 4.18 Load data of the System with the link to Wajir without reactive compensation

BUS	**MW**	**MVAr**
MWINGI33 33.000	1.5	1
KITUI3 33.000	2.2	1.4
GARISSA33 33.000	3.1	2
WAJIR 33 33.000	3	1.2

This figure shows the transmission system simulation with the extension to Wajir from Garissa. With this addition, the bus voltage in the various substation increases beyond the acceptable overvoltage of 10%. For voltage control, reactive power is required in the system.

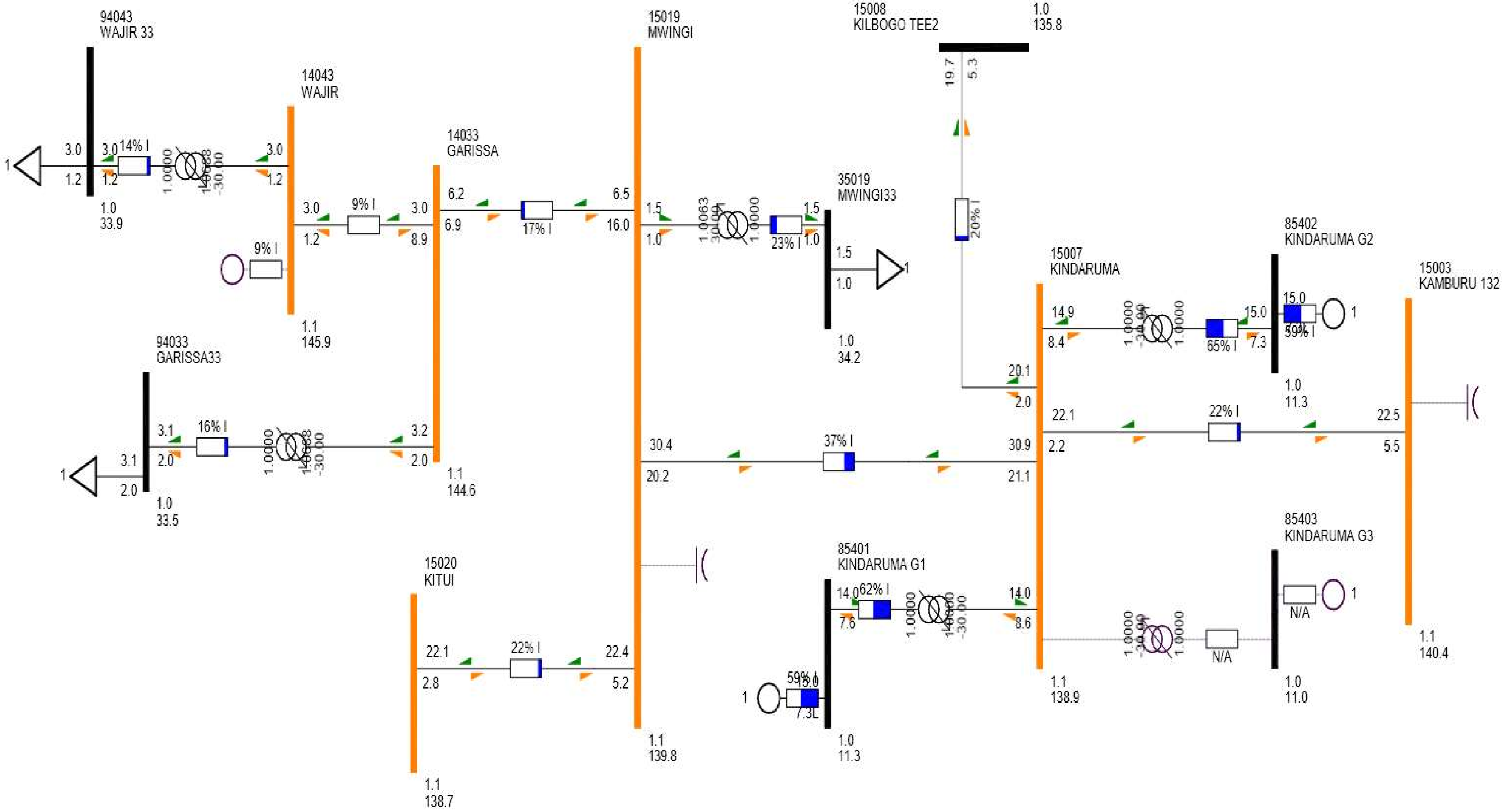

Fig 4.8 Simulation of the System with the Transmission Line to Wajir without reactive compensation

iii. Simulation of the System with the Transmission line to Wajir with reactive compensation

Table 4.19 Branch data of the System with the link to Wajir with reactive compensation

FROM BUS	TO BUS	CKT	LINE R	LINE X	CHRGING	RATEA	LENGTH
JUJA RD 132	KILBOGO TEE1 132	1	0.0436	0.09887	0.01875	97.2	40
GARISSA	WAJIR 132	1	0.19622	0.44489	0.08437	97.2	267
GARISSA	MWINGI 132	1	0.19622	0.44489	0.08437	97.2	180
KAMBURU 132	KINDARUMA 132	1	0.08721	0.19773	0.0375	97.2	80
KILBOGO TEE1	MANGU 132	1	0.0218	0.04943	0.00937	97.2	20
KINDARUMA 132	KILBOGO TEE2 132	1	0.08721	0.19773	0.0375	97.2	80
KINDARUMA 132	MWINGI 132	1	0.0436	0.09887	0.01875	97.2	40
KILBOGO TEE2	MANGU 132	2	0.0218	0.04943	0.00937	97.2	20
MWINGI 132	KITUI 132	1	0.06541	0.1483	0.02812	97.2	60
KITUI 132	WOTE 132	1	0.06541	0.1483	0.02812	97.2	60

Table 4.20 Bus Voltage of the System with the link to Wajir with reactive compensation

BUS	BASE KV	VOLTAGE	VMAX	VMIN
GARISSA	132	1.02622	1.05	0.95
WAJIR	132	0.98926	1.05	0.95
KILBOGO TEE 1	132	1.02605	1.05	0.95
KINDARUMA	132	1.05178	1.05	0.95
KILBOGO TEE 2	132	1.02817	1.05	0.95
MWINGI	132	1.03976	1.05	0.95
KITUI	132	1.03524	1.05	0.95
MWINGI33	33	1.01798	1.05	0.95
KITUI3	33	0.99131	1.05	0.95
GARISSA33	33	0.96486	1.05	0.95
WAJIR	33	0.96183	1.05	0.95

Table 4.21 Generation and load of the System with the link to Wajir with reactive compensation

TOTAL	SYNCHR	PQLOAD	LOSSES	SWING
MW	1948.8	1881.5	67.3	44.8
MVAR	647.6	1007.6	572.6	20.4

Table 4.22 Load data of the System with the link to Wajir with reactive compensation

BUS	MW	MVAr
MWINGI 33KV	1.5	1
KITUI 33KV	2.2	1.4
GARISSA 33KV	3.1	2
WAJIR 33KV	3	1.2

This figure shows the transmission system simulation with the extension to Wajir from Garissa with an additional reactor bank at Wajir and Mwingi for voltage control.

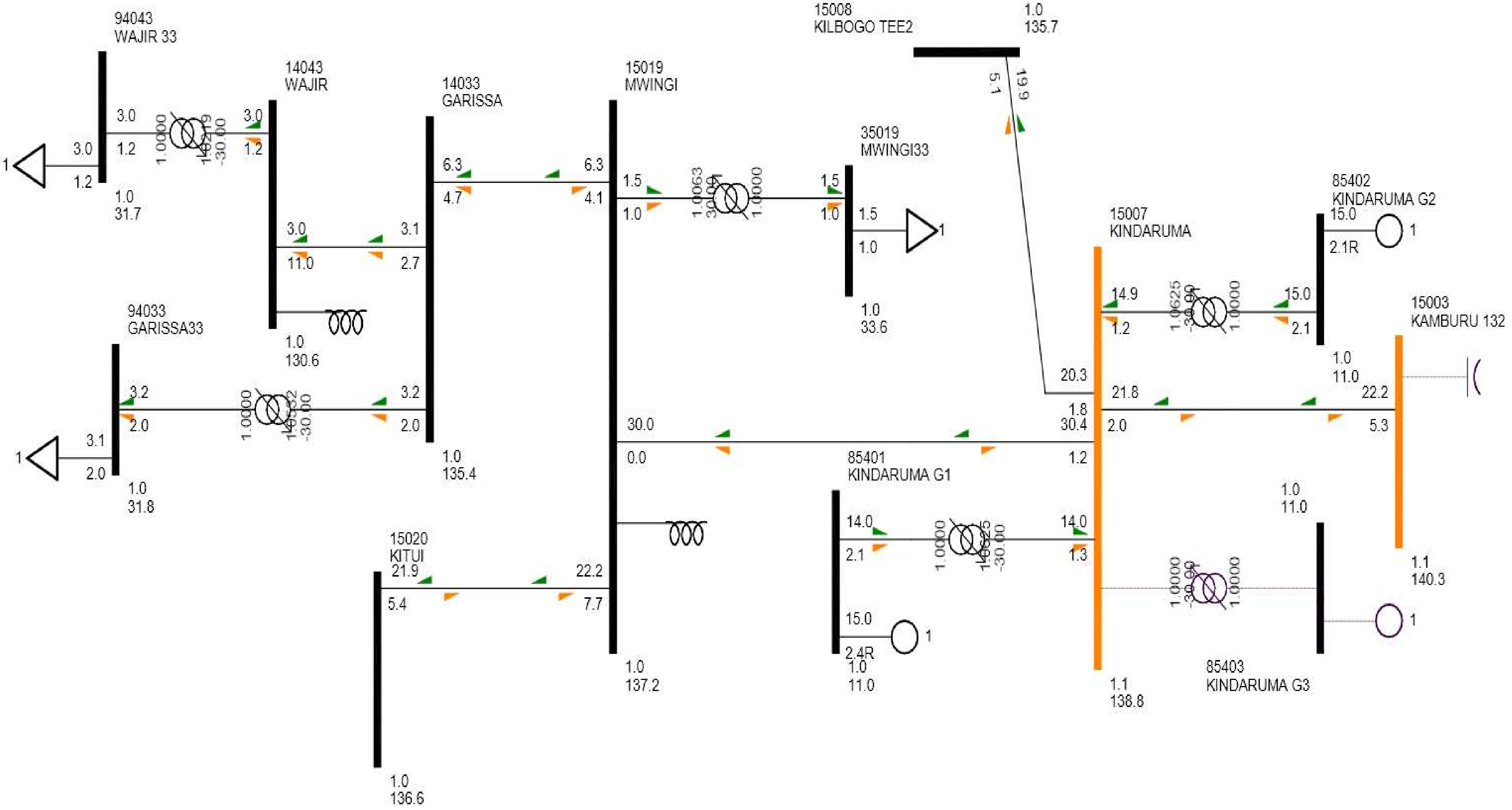

Fig 4.9 Simulation of the System with the Transmission Line to Wajir with reactive compensation

4.4.2.3 Transmission Line Capital Investment

The table below gives the line parameters and the capital cost of the installation of the transmission line and substation.

Table 4.23: Transmission line parameters and capital cost

Equipment	Quantity	Units	Installation cost (MUSD)
132 kV transmission line (SC Wolf)	276	km	23.0
Civil Works and Auxiliaries			
Civil Works - new site at Wajir	1	Lump sum	0.2113
Civil Works – Extension at Garissa	1	Lump sum	0.681
Communications Cost	1	Lump sum	0.0204
New site auxiliaries	1	Lump sum	0.141
Location			
Land Cost - Other new site	1	Land	2.723
Land Cost - Other extension	1	Land	1.362
Electrical Works			
132kv line bay extension Garissa	1	Bay	0.450
132 kV switchgear	4	Bays	1.5
33kV switchgear	6	Bays	1.1
15 MVA, 132/33kV transformer	2	Transformers	2.3
10MVAr shunt reactor	2	Reactors	0.6
10MVAr shunt capacitor	2	Banks	0.8
Total			**35.07**

The capital cost of the project was estimated at USD 35.07 million. This cost was dominated by the cost of the line. The costing allows for two 15MVA transformers at Wajir substation. It also allows for two transformer bays associated switchgear, an incoming line bay from Garissa with the associated switchgear, and an outgoing line bay extension at the existing Garissa substation with the associated switchgear making a total of four 132kV switchgear bays.

The design allows for six 33 kV outgoing feeders for distribution of power to the surrounding Wajir town and its environs currently supplied by the existing off grid plant.

The PSSE load flow analysis indicated a need to install Shunt capacitors due to a 5% voltage drop with power transfer at unity power factor. Due to the length of the line and the low loading especially in the initial years of running the line. A shunt reactor would be highly recommended for voltage control during switching of the transmission line.

The amortization cost assuming 50 years lifetime at a constant annual discount rate of 5% of the investment of USD 35,070,000 using equation (3.2) is therefore:

$$A = \frac{35{,}070{,}000 \times 0.05 \times 1.05^{50}}{1.05^{50} - 1} = \boldsymbol{USD\ 1,920,543.03}$$

4.4.2.4 Operation and Maintenance Cost of Transmission Infrastructure

The operation and maintenance cost for the transmission system is usually given as a percentage of the capital cost. The maintenance for a 132 kV transmission line includes line patrols, vegetation management, emergency patrols and non-routine maintenance such as RIF or IR scans and mitigation. The average cost of this maintenance is approximately to be about 0.75% in the first year and increased by a factor of 10% annually to reflect increase in maintenance cost due to aging and wear and tear of the transmission infrastructure. [16].

O&M cost over the years from 2018 to 2030 are as shown in Table 4.24.

The present value of the demand was calculated as *256,462,690 kWh* at a *5%* discount rate.

Using excel, the **Net Present Value** for the transmission line using the cash flows in table 4.24 was calculated to be ***USD 33,169,926***

Therefore the cost per kWh of transmission was then calculated as the ratio of the present value of demand increases to the present value of the costs of the investment (including O&M on new investment).

USD 33,169,926 / 256,462,690 kWh = USD 0.13 /kWh per annum.

In addition, assuming that all the power generated is from Kindaruma and the interconnected seven forks hydro power stations, an additional $0.0825 / KWh was added as the tariff for hydro power plants exceeding 10MW capacity. [17]

The total cost for USD 0.13 /kWh + $0.0825 / KWh = **USD 0.2125/kWh**

This cost assumes no income from wheeling tariff for the power transmitted.

Table 4.24: Transmission line investment estimated cash flows

YEAR		Capital Cost (USD)	O&M Cost (USD)
2015	50% Capital cost	17535000	
2016	25% Capital cost	8767500	
2017	25% Capital cost	8767500	
2018			65756
2019			72332
2020			79565
2021			87522
2022			96274
2023			105901
2024			116491
2025			128140
2026			140954
2027			155050
2028			170555
2029			187610
2030			206371

Therefore the cost per kWh of transmission was calculated as **USD 0.2125 /kWh per annum**.

5. Conclusions and Recommendations

5.1 Conclusions

From the analysis of the demand forecast, the peak demand for Wajir is expected to rise from the current level of around ***1.604 MW*** to ***13.236 MW*** by 2030.

A study to compare the cost of off grid generation to the cost of investing in transmission infrastructure was carried out. From the analysis, the cost of building the transmission infrastructure was found to be **USD 0.2125 /kWh per annum** while that of remaining off grid and putting up a diesel plant to sufficiently supply the load until 2030 was found to be **USD 0.42 /kWh per annum.**

A successful simulation of the power system transmission was undertaken using PSS/E software to investigate the effect of adding the transmission infrastructure to the system and the effect on the Kenyan transmission system parameters.

From the simulation, it was found that there was need to include a reactor bank at the Wajir and Mwingi substations for voltage control due to Ferranti effect because the transmission line is long and lightly loaded in the initial stages.

5.2 Recommendations

From the results obtained, the option of putting up a transmission line from Garissa Substation to Wajir County would be recommended because it is the most economical in the long run. In addition, other social-economic benefits that would result from the construction of the transmission line include the reduction of the carbon footprint as a result of using the renewable energy from the hydro-electric and geothermal generation.

A further study would need to be conducted to look at the social-economic benefits of the two options which were not considered in this research.

Certain costs that were not included in the calculation for the transmission infrastructure such as the connected generation cost including the capacity and energy cost in relation to the fuel cost will need to be factored in in a future study.

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