OPTIMUM SIZING OF MINI-GRID WIND POWER PLANT WITH ENERGY STORAGE SYSTEM FOR RURAL ELECTRIFICATION IN ZAMBIA: A CASE STUDY OF MPIKA DISTRICT

By

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DECLARATION

I, Elijah Chibwe, hereby declare that the work presented in this dissertation is the product of my research findings and that it has not been submitted for any other qualifications at this or any other University. The work of other persons utilized in this dissertation has been duly acknowledged.

Signature: …………………………….. Date……………………………………….

APPROVAL

This dissertation by Elijah Chibwe is approved as fulfilling the requirements for the award of the Degree of **Master of Engineering** in **Thermo-Fluids Engineering** by the University of Zambia.

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Supervisor:..…………………. Signature: …………………Date:………………………………

ABSTRACT

The Government of the Republic of Zambia (GRZ) has set an ambitious target of raising the rural electrification rate from 3.4% (in 2008) to 51% by the year 2030.However, as at 2017 - almost 10 years down the line, the Rural Electrification Authority (REA) indicated that access to electricity in rural areas stood at only 4.4% which implies that, if things remain unchanged, the 51% rural access to electricity may not be achieved in the target year. In Zambia, the delay in rural electrification may be attributed to the sparsely settlement in rural areas as most rural communities are established away from each other as well as from the national grid and, hence, require huge investments to extend the national grid. It would be helpful for Zambia to consider exploiting other efficient and least-cost options for generating and supplying power to rural areas.

This study employed a combined theoretical and applied approach to assess the technical and financial viability for setting up small wind power system with mini-grid to supply electricity to some rural areas as opposed to grid extension. Using the case of Mpepo Chiefdom in Mpika District, the study sized a wind power system with an energy storage system (ESS) and assessed its viability for rural electrification based on community's energy demand and wind speed, and compared the cost of wind power system against grid extension. The study considered the Battery Energy Storage (BES) system and the Hydrogen Fuel Cells (HFC) as ESS for power back up in times of low supply.

The study established that some parts of Zambia receive wind speeds higher than 4m/s and suitable for power generation as standalone mini-grid system for rural electrification. Based on the financial analysis in this study, the WPP without ESS would offer a cheaper option than the WPP-HFC and WPP-BES systems. However, on account of reliability and stability of power supply, the WPP-BES system would to be more viable than the WPP without ESS and, would also provide a least cost option compared to WPP-HFC.

Further, the study revealed that for communities experiencing wind speeds of 4m/s and above, and located more than 74Km from the point of connection to the national grid, the WPP-BES would be a least cost option compared to the grid extension. Based on the foregoing, the study recommends that rural areas, whose locations are in high wind zones and more than 74km from the national grid, be considered for electrification using the WPP-BES.

Keywords: Rural electrification; wind power plant; grid extension; mini-grid, electrification rate, technical and financial viability.

DEDICATION

This research work is dedicated to my dear grandmother - Rosemary C. S. Kasanda and my lovely mom, Ms. Gladys C. Mibenge (MHSRIP), for being wonderful people in my life.

ACKNOWLEDGEMENT

I am glad to express my unreserved gratitude to my Supervisor, Prof. F. D. Yamba, for his time, guidance and support during the time of this research work.

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My conscience would never be at peace if this report ever went without acknowledging the support I received from all the individuals who had a hand in this work – directly or indirectly.

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ABBREVIATIONS AND ACRONYMS

AR	Applied Research
BES	Battery Energy Storage
CSO	Central Statistical Office
DC	Direct Current
ESS	Energy Storage System
ERB	Energy Regulation Board
ESAP	Electricity Service Access Project
GETFiT	Global Energy Transfer Feed-in Tariff
GFRP	Glass Fibre Reinforced Plastic
GRZ	Government of the Republic of Zambia
GWA	Global Wind Atlas
HDI	Human Development Index
HFC	Hydrogen Fuel Cell
IA	Implementation Agreement
IEC	International Electrotechnical Commission
IPP	Independent Power Producer
IRR	Internal Rate of Return
MOE	Ministry of Energy
NEP	National Energy Plan
NPV	Net Present Value
PMGS	Permanent Magnet Synchronous Generator
PPA	Power Purchase Agreement

PSDMP	Power Systems Development Master Plan
REA	Rural Electrification Authority
REF	Rural Electrification Fund
REFiT	Renewable Energy Feed-in Tariff
REMP	Rural Electrification Master Plan
RGC	Rural Growth Centre
7NDP	Seventh National Development Plan
SCIG	Squirrel Cage Induction Generator
SHS	Solar Home System
UNESCO	United Nations Educational, Scientific and Cultural Organization
WPD	Wind Power Density
WPP	Wind Power Plant
WRM	Wind Resource Mapping

CHAPTER 1:INTRODUCTION

1.1 Background

Access to clean and affordable energy, i.e. electricity, is one of the key Sustainable Development Goals (SDGs) and is remarkably instrumental in stimulating economic and social development. It is evident that availability of electricity facilitates effective and efficient delivery of most basic services such as safe drinking water, public lighting, health care and education, among others. A high correlation usually exists between consumption of electricity and improvements in the Human Development Index (HDI), especially at low levels of HDI (Samanta, 2015). Lack of access to electricity has thus proven to be one of the significant barriers to alleviation of poverty in rural areas of Zambia.

Based on the 2010 census of population report, the majority of Zambia's population - about 61% - reside in rural areas and mainly depend on subsistence farming to earn their livelihood. In most cases, these places do not have access to electricity to aid the residents better their livelihood through economic activities such as irrigation and processing, and for domestic use in their homes. Rural communities mostly depend on traditional and unclean energy sources like wood and kerosene which deny them opportunities for productivity enhancement and value addition, as a result. In re-echoing the importance of electricity to human life, U. S Department of Energy (2007) claims that access to electricity is principally crucial to human development, as certain basic activities such as lighting, refrigeration, running household appliances, and operating equipment cannot easily be carried out by other forms of energy.

Zambia recognised the importance of electricity as an essential catalyst in the development of rural areas soon after the country's independence in 1964. Since that time, the responsibility of electrifying rural communities was vested in Zesco Limited, a national power utility, until when the mandate was later shifted to the Rural Electrification Authority (REA) on its creation, through the act of Parliament, in 2004. As a vehicle to eradicate poverty by stimulating the rural economy, the Government of the Republic of Zambia (GRZ) established the Rural Electrification Fund (REF) in 1994 by committing the sales tax on electricity, and has been trying to increase the electrification rate in rural area by executing projects funded by the REF. In order to enhance rural electrification, Zambia developed the Rural Electrification Master Plan (REMP) in 2008. The

REMP aims at providing a systematic implementation plan for execution of rural electrification projects and increase the rural electrification rate from 3% in 2008 to 51% by the year 2030.

In the face of all these initiatives, household electrification and access to sustainable quality electricity service remains a dream for the majority of households in Zambia. Presently, Zambia's access to electricity in rural areas stands at 4.4% (REA, 2017). One of the major reasons for this is that most of Zambia's rural population reside in areas where geographical distribution, 'long distances from the grid', coupled with the low purchasing power of the consumers create hurdle in providing uninterrupted electricity supply.

A number of recent studies have suggested that mini-grids can provide a quicker alternative and least-cost approach for electrifying certain rural areas, especially those that are far away from the national grid. REA has already started rolling out mini-grid projects for instance Mpanta, Lunga and Chunga, as solar power plants, and Kasangiku, a small hydro power plant.

Wind is another energy resource universally available in Zambia, besides solar. Wind is the flow of gases on a large scale caused by density variations due to solar heating on the earth's crust. As underscored by Mwenda (2014), wind carries huge amounts of energy and can be harnessed for power generation when its effective speed exceeds an average of 3m/s. According to the wind resource mapping study conducted by the Ministry of Energy (MOE) in the period 2016 to 2018, Zambia receives considerably high wind speeds which can support power generation in certain locations.

This study investigated the technical and financial viability for exploiting the available wind resource for electricity generation and supply to some rural communities in Zambia using mini-grids and supported with Energy Storage System (ESS). The integration of renewable energy sources and ESS has been one of the new trends in power-electronic technology (Mwaba, 2015), which can be utilized for rural electrification.

1.2 Problem Statement

In the face of abundant energy resources, Zambia's majority rural population does not have access to electricity. Access to electricity is important not only for lighting and heating needs but for economic activities such as irrigation, manufacturing and processing as well. Like many other developing countries across the globe, Zambia is a victim of low access to electricity especially in rural areas. The country has been struggling to unlock its economic potential in rural communities due to lack of clean and sustainable power supply. The Zambian Rural Electrification Master Plan (REMP) identifies rural electrification as a vehicle to eradicate poverty by stimulating the rural economy growth in country.

Zambia aims at meeting an ambitious 51% rural electrification target by the year 2030 from 3.4% recorded in 2008. Conversely, the technological approach employed has proven too slow to deliver the desired quick-wins as it is generally based on the grid-extension, which has proven to be costly, with significantly low investment in off-grid systems – mini-grids for instance. While CSO (2015) confirms in the "Living Conditions Monitoring Survey Report" that most rural communities are not electrified and are located away from the national grid, REA claims that it requires huge investments to extent the national grid to these settlements.

As a remedy to this dilemma, the GRZ through the MOE has committed to exploiting other possible least-cost options (mainly off grid solutions) for generating and supplying power to rural communities. However, while there has been a number of solar and hydro mini-grid projects developed in the country, no wind power project has been developed yet, despite the country having good wind speeds in certain areas.

1.3 Purpose of the Study

In order for the country to realise the 51% rural electrification rate target by 2030 as set in the REMP, from the 4.4% reported in 2017, and speak to the poverty reduction goals outlined in the Seventh National Development Plan (7NDP), the purpose of this research work is to assess the technical and financial viability of setting up small wind power plants with a mini-grid distribution system for rural communities to supplement the traditional grid-extension, which has proven short of realising the vision 2030, and complement the solar mini-grid technology, which can serve the purpose but is not available when the sun is not there.

1.4 Dissertation Statement

In line with the requirements as provided in the problem statement and purpose of study above, the thesis of this work was to design and optimise a mini-grid wind power generation system for electricity supply to some rural communities in Zambia. The aim of this work was to assess the viability of setting up a technically workable mini-grid wind power generation system which would be economically reasonable for rural electrification in Zambia.

1.5 General Objective

- To assess the feasibility of setting up mini-grid wind power plant with energy storage system in rural communities in Zambia.

1.5.1 Specific Objectives

- To design a model for mini-grid wind power generation system based on the power demand for Mpepo Chiefdom in Mpika district.
- To size the energy storage system to ensure availability of power supply in times of low or no wind.
- To gauge the financial viability for setting up mini-grid wind power plant with energy storage system in rural areas.

1.6 Research Questions

1. What capacity of wind power system for electricity generation and supply would be required for Mpepo Chiefdom?
2. What energy storage capacity is required to supply power to the system in times of low or no wind?
3. Can a mini-grid wind power plant with energy storage system be financially viable for rural areas in Zambia?

1.7 Significance of the Study

Significantly, this study investigated the possibilities for Zambia to exploit the wind energy resource for rural electrification purposes. The finding of this study set out a basis for stakeholders in rural electrification, i.e. Public players, cooperating partners and the Private sector, to make informed decisions on which areas they can invest in wind mini-grid projects in Zambia.

CHAPTER 2:LITERATURE REVIEW

2.1 Introduction

Rural electrification has long been identified as a key to unlock the rural economy in the Republic of Zambia. In order to enhance the rural electrification process, the country has allowed for various sustainable least cost options to be adopted for delivery of electricity to the rural population. The technological options being considered include, among others, the off-grid systems, mini-grids and grid-extension (REMP, 2008). Nevertheless, in the face of the desperately needed universal access to electricity, it is prudent to acknowledge the global campaign for environment-friendly energy solutions to save the earth from consequences of climate change. Apart from solar and hydro, wind is believed to be another clean energy resource which carries a huge potential to meet the rural community's energy demands.

This section of the report presents a review of literature on the energy scenario and rural electrification in Zambia. The chapter also looks at Zambia's efforts towards, and the drawbacks in, rural electrification campaign. It further provides aspects on wind situation in Zambia and available technology, associated ESS and the financial analysis of the wind power projects.

2.2 Energy Scenario in Zambia

Zambia's major source of energy is wood fuel (i.e. firewood and charcoal), with the largest consumer group being households in rural areas. Zambia's other sources of energy are petroleum, electricity, coal and renewable energy. As of 2017, the country's electricity installed capacity stood at 2,806MW with supply dominated by hydro generation accounting for 84.3%. Generation from thermal power technologies using Diesel, Heavy fuel Oils and Coal accounts for 14% and the remaining 1.7% covers generation from renewable energy sources comprising of solar and small hydro up to 20 MW (MOE, 2017). Zambia has not yet started exploiting wind resource for electricity generation but a few wind water-pumping systems have been installed.

Due to the favorable tone of economic development, the demand for electricity in Zambia has been increasing at annual rates on the order of 3 to 4% in recent years. This poses a serious challenge on the electricity accessibility although the country has abundant renewable and non-renewable energy resources, including industrial minerals such as coal, agricultural land to support biofuels, ample forest for biomass, wind, and long and intense hours of annual sunlight to support electricity generation (PSDMP, 2011).

2.3 Rural Electrification in Zambia

The GRZ has recognised the need to electrify all parts of the country in order to enhance development especially among the rural population. According to CSO (2015), only 31.4% of the country's total population has access to electricity with urban and rural grid connectivity standing at 67.3% and 4.4% respectively.

In a bid to correct this situation, GRZ established the Rural Electrification Authority (REA) and the Rural Electrification Fund (REF) through the Rural Electrification Act No. 20 of 2003. REA was established with the primary aim to provide electricity infrastructure to the rural areas using appropriate technologies in order to increase access to electricity in rural areas from 3.4% as at 2008 to 51% by the year 2030. Since the year 2006, REA has implemented a number of rural electrification projects to supply electricity to rural communities mainly through grid extension. The Authority currently promotes various technologies, apart from national grid extension, for rural electrification programme including solar energy systems, biomass and biogas, wind and mini hydro power (ERB, 2015).

2.4 Zambia's Efforts towards Rural Electrification

In working towards poverty reduction, the Zambian government has set the national targets to increase the rural electrification rate to 51% and the urban electrification rate to 90% by 2030 as enshrined in the REMP. According to ERB (2015), the country faces the urgent task of further developing power sources to meet the growing demand for power and conditioning the transmission and distribution networks to raise the electrification rate nationwide. Therefore, Zambia has taken a number of initiatives aimed at increasing electricity service access, especially to its rural population.

Integrated efforts from GRZ, cooperating partners, and the private sector have been directed into accelerating electricity service access. This has been through policy formulation and re-alignment, technical and financial support. In line with policy development, the National Energy Policy (NEP) was developed in 1994 and revised in 2008 to be the overarching guide for developments in the energy sector. In harmony with the 7NDP, the NEP sets out Government's intensions of ensuring that the energy sector's potential to drive economic growth and reduce poverty is harnessed. Further, in the same endeavour, the GRZ formulated the Electricity Act in 1995 which was amended in 2003, the Energy Regulation Act of 1995 which was also amended in 2003, and developed the Electricity Grid Code in 2006.

In recognition of the significance to rural electrification in Zambia, the government of Zambia created the REF in 1994 and, further, enacted the Rural Electrification Act in 2003 which formed a basis for the establishment of REA. In the same effort, the REMP was developed in order to enhance rural electrification effectively (Ministry of Energy, 2017).

Apart from policy formulation and enhancement, Zambia has also implemented a number of projects, including the Electricity Service Access Project (ESAP), intended to promote and attain increased access to electricity in rural areas through grid extension projects. In addition to the 152 grid extension projects the government has implemented through REA since 2006 in all the ten provinces of the country, the rural electrification program is currently undertaking various projects based on hydro, solar and wind technologies as provided in table 1 as part of rural electrification commitment.

Table 1: Rural Electrification Projects currently being undertaken by REA

Project Type	Project Sites	Project Capacity
Mini Hydro	Kasanjiku Falls	0.64MW
	Chikata Falls	3.5MW
	Zengamina II	1.74MW
	Chilinga Falls	Feasility
	Chavuma	Feasility
Solar Mini-Grid	Chunga	200kWp
	Lunga	300kWp
Solar Market Package (SSMP)	Mpika	159kWp
	Kalomo	268kWp
	Lukulu	280kWp
Wind	Lunga	Resource Assessment

Source: Rural Electrification Authority, Zambia.

Working towards the same goal, REA has identified 1,217 Rural Growth Center (RGC) under the REMP. The RGCs were selected as rural locality with a high concentration of residential settlements and the centres of rural economic activities, and hence priority for the electrification. The selection employed the "Technical Aspect Analysis", the "Decentralized Planning Process" to identify the RGCs in rural areas as the electrification target. Next, "Demand Criteria or potential daily maximum demand in each RGC" and "Supply Criteria or the "Unit Life Time Cost in Net Present Value" were used to cluster or group the RGCs into 180 Project Packages and to select the optimal electrification technology for each of the RGCs. The REMP suggests the following as the possible electrification methods:

1. Extension of existing grid,
2. Isolated mini-grid with renewable energy power generation,
3. Solar home system (SHS),
4. Mini-grid with diesel power generation, if none of the above is feasible.

2.5 Challenges in Rural Electrification

Zambia has set an ambitious target of raising the rural electrification rate from 3.4% (in 2008) to 51% by the year 2030. However, as at 2017 - almost 10 years down the line, CSO showed that access to electricity in rural areas had only risen to 4.4% which implies that, if things remain unchanged, the 51% rural access to electricity may not be achieved in the target year. The rural electrification program, currently, seems to be facing challenges regarding inadequate funding to the REF. According to REA, the high investment cost of grid-extension coupled with the low private sector involvement in the rural electrification campaigns hinders the projects progress.

From the MOE's point of view, besides the huge cost involved in extending the national grid, rural electrification campaign has stagnated due to spacy settlements. The Living Conditions Monitoring Survey conducted in 2015, established that most rural settlements in Zambia are established away from each other as well as from the national grid and hence require huge investments if they are to be electrified. This scenario entails that a lot of resources would be utilized to electrify only a few people whose energy demand may not be adequately translate to revenues enough to repay the investment cost incurred – even up to the end of the project life. As part of the remedy to this challenge, the government has resorted to creating new districts where public facilities, including schools, health centers and markets, can be placed to attract people into denser and close settlements to make public service delivery easier.

In addition, it is believed that electrifying rural areas has been a challenge partly due to rural communities' low ability to pay for the electricity, even when they are willing to pay. As established in the "social aspect analysis" conducted during the Socio-Economy survey as part of the REMP, the estimated ability to pay for electricity monthly bill for households and business entities were about K35.50 and K60.25 respectively, as at 2006. Similarly, the connection fee charged by Zesco Limited as "K2,873.00 for Single Phase and K4,887.00 for 3 Phase" was much higher than the rural households' ability to pay (average monthly income of K910.76) and willingness to pay K2,508.48.

2.6 Wind Energy Technology

2.6.1 Wind Energy

The development of renewable energy resources and their technologies is a subject of well-proven technological and economical importance. In the whack of fast depleting and costly fossil fuels, environmental concerns which come against the growing demand for power supply to meet the electrification needs, it is essential for every country's energy strategy to consider exploitation of environmental-friendly alternative energy resources. Wind energy is a source of clean, non-polluting electricity, which is quite competitive, if installed at favourable wind sites. Wind energy technology is increasing substantially its share in the electricity generation portfolio in many countries (Earnest, 2015).

The Zambian government, like many governments across the globe, has recognised the value of the wind resource to the national energy mix and has taken necessary steps to kick-start exploitation of the wind energy resource. In the period 2015 to 2016, Zambia experienced prolonged droughts which hampered the country's power generation portfolio – being hydropower generation dependent. As a mitigation measure, the government through the MOE resolved to diversify the energy mix to include alternative power generation technologies, including wind technology (MOE, 2017).

To support development in the wind technology space, Zambia conducted the wind resource mapping exercise covering 8 wind potential sites across the country. The wind measuring facilities (Wind Masts) were installed in 2016 to capture wind information at 80m height and data was collected for a period of two years. The information on the wind regime in Zambia has set a basis for exploiting the country's wind resource for electricity generation.

According to the U.S Department of Energy (2004), the wind energy technology has moved far beyond the small multi-bladed machines that pumped water and powered direct current appliances in the 1930s and 1940s to become quiet, sleek multi-megawatt power plants that power thousands of homes today as shown in figure 1.

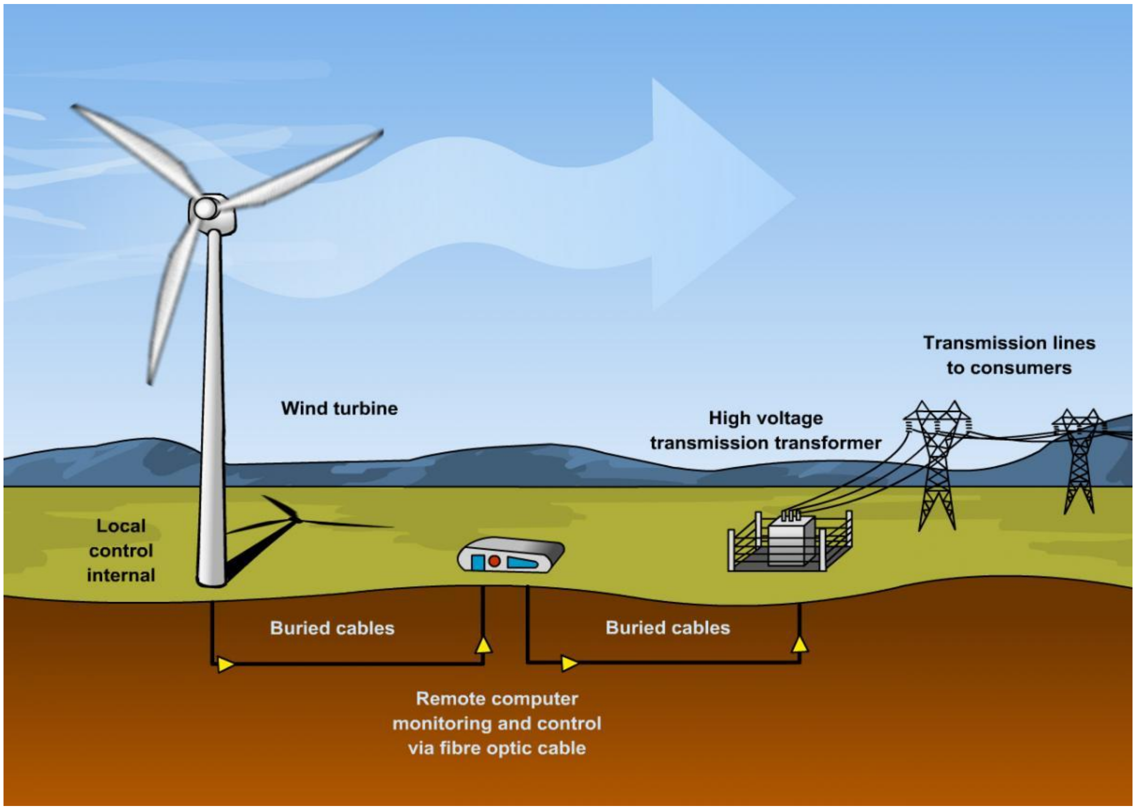

Figure 1: Wind Power Generation System Configuration, Source: Wind.Energy.Gov.

2.6.2 Wind Power Potential

Wind is air in motion. It has mass and consequently contains kinetic energy. This power can be turned into electric power, heat or mechanical work by means of wind power plants. The power of the wind can be very strong as it is proportional to the cube of the wind speed. According to Earnest (2015), the power extractable from wind is theoretically expressed as given in equation 1.1.

$$P_{kin} = \frac{1}{2}\rho A \upsilon^3 \quad (1.1)$$

Where,

P_{kin} is kinetic power in watts

ρ is air density in (Kg/m^3)

A is rotor swept area in (m^2)

υ is wind speed in (m/s)

The density of air varies with the height above sea level and temperature. Therefore, the standard value of density $1.25\,Kg/m^3$, which is the density of air at sea level at $1bar$ and temperature $9\,^oC$, is normally used. The power of the wind at a given height at a site is usually specified as power density in (W/m^2) and the energy content as ($kWh/m^2 - year$). The wind power density (WPD) provides a useful way for evaluating the wind resource available at a potential site. It gives the actual indication of wind energy potential than only the wind speed at any particular site. Hence the power of the wind per m^2 can be expressed as in equation 1.2:

$$P_{kin} = \frac{1}{2} \times 1.25 \times \upsilon^3 = 0.625\upsilon^3 \qquad (1.2)$$

This indicates that the power harnessed from wind is proportional to the cube of the wind speed. Therefore, the wind power plants should be installed at sites with the highest possible wind speed. The modern wind maps give information about the power density or energy content for different areas by isolines or by colour (Earnest, 2015). In Mpika, the average power density of the wind is estimated to be $186\,W/m^2$ at $100m$ height at 10% windiest area. The mean power density in the area is distributed as shown in figure 2.

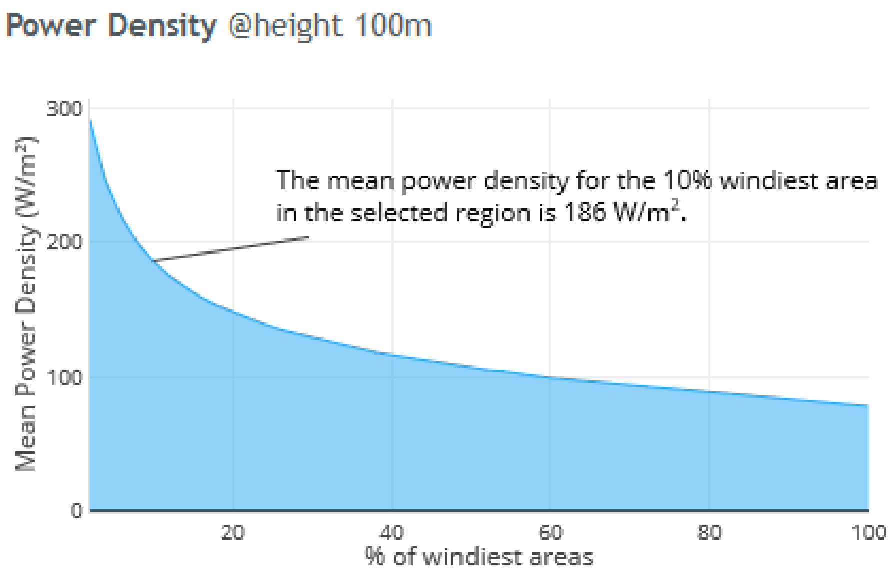

Figure 2: Power density for Mpika. Source; Global Wind Atlas.

2.6.3 Wind Speed Distribution

In reality, the speed and direction of the wind change continuously. The wind changes during day and night, in different seasons and from year to year. For wind turbine design purposes, the wind speed is measured at a site for a period of at least one year and the wind speeds are sampled at regular intervals for the purpose of calculating the mean wind speed for the site (Hill, 1996). For the measured wind speeds (υ), the mean wind speed (υ_m) is determined using equation 1.3.

$$\upsilon_m = \frac{\sum \upsilon}{n} \qquad (1.3)$$

Where, n is the number of wind speeds sampled.

According to the Global Wind Atlas (GWA), Mpika receives a mean wind speed of $5.85\,m/s$ at $100m$ height. The percentage distribution of wind speed in the area is predicted as shown in figure 3.

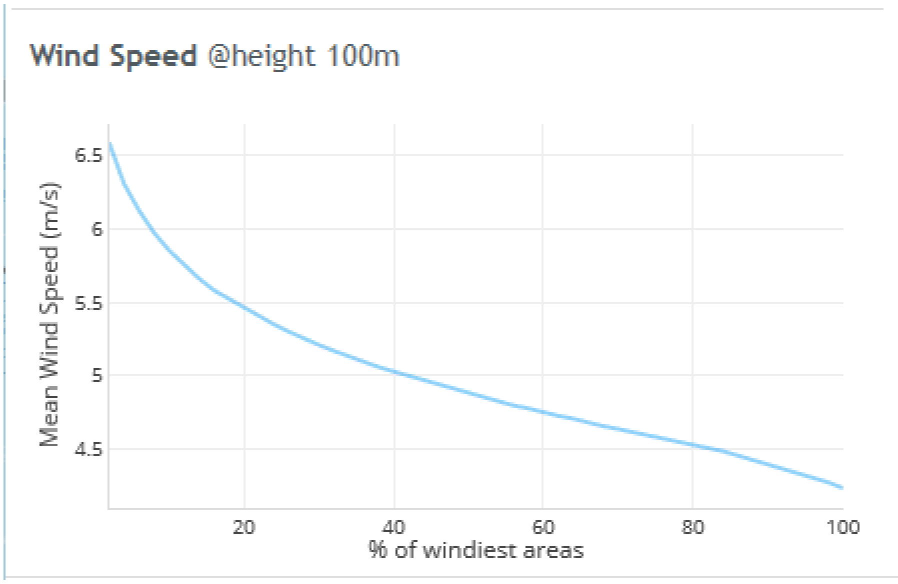

Figure 3: Wind Speed Distribution in Mpika. Source; Global Wind Atlas.

As a general rule, the wind speed increases with increasing height. This increase depends on the roughness of the terrain, i.e. in areas with high roughness the wind speed will increase more with height than over a smooth terrain. For design purpose, the wind speed at hub height is used (Hill, 1996). In most cases, the available wind data represent a different height than the hub height. It is therefore recommended to use equation 1.4 to find the wind speed (υ) at hub height (h) if the average wind speed (υ_m) at a height (h_m).

$$\frac{\upsilon}{\upsilon_m} = \left(\frac{h}{h_m}\right)^{\alpha} \quad \text{...(1.4)}$$

Where,

the value of the exponent α *depends on the roughness of the terrain: for open plain,* $\alpha = 0.15$*; and* $\alpha = 0.3$ *for low forests.*

The wind direction is analysed and represented through a wind rose. The wind rose for Mpika is as shown in figure 4. The wind frequency rose indicates that Mpika receives wind mostly blowing from the western side, partly from north-east and rarely from the south-east.

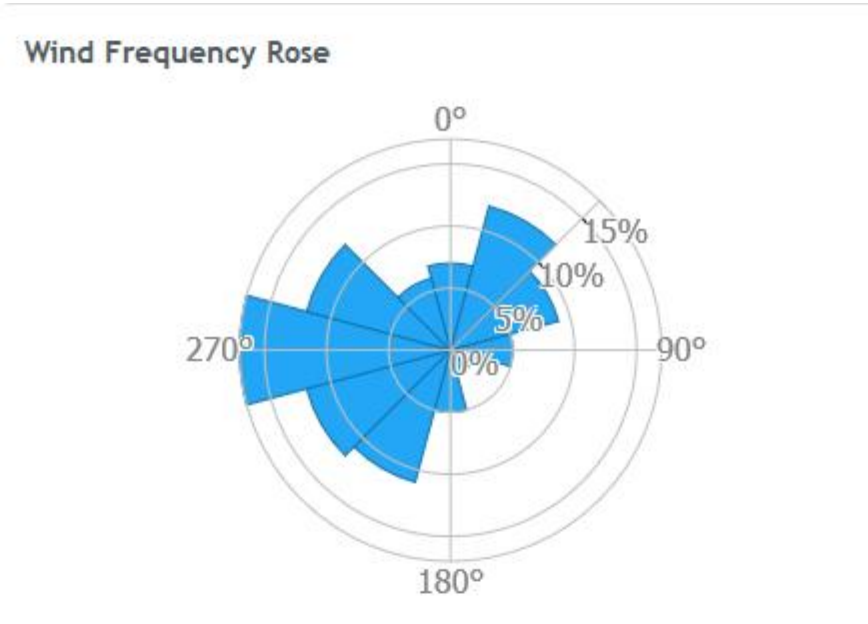

Figure 4: Wind Frequency Rose. Source; Global Wind Atlas

2.6.4 Air Density Variation

The power of the wind depends on the density of air. The density of air varies with temperature and height above sea level. Empirical observation reviews that the influence of air density variation on power of the wind is negligible, except in tropical climate and at heights of $500m$ or more above sea level at which point the density should be considered in calculation (Hill, 1996).

2.6.5 Wind Power Plant Siting

To extract maximum power from the wind, it is cardinal to accurately site the wind power plant at the most appropriate spot. As presented in equation 1.2, the slightest increase in wind speed results in substantial increase in power output. The wind resource maps give an initial idea of the probable wind project sites. For Mpika, the wind resource map is as provided in figure 5.

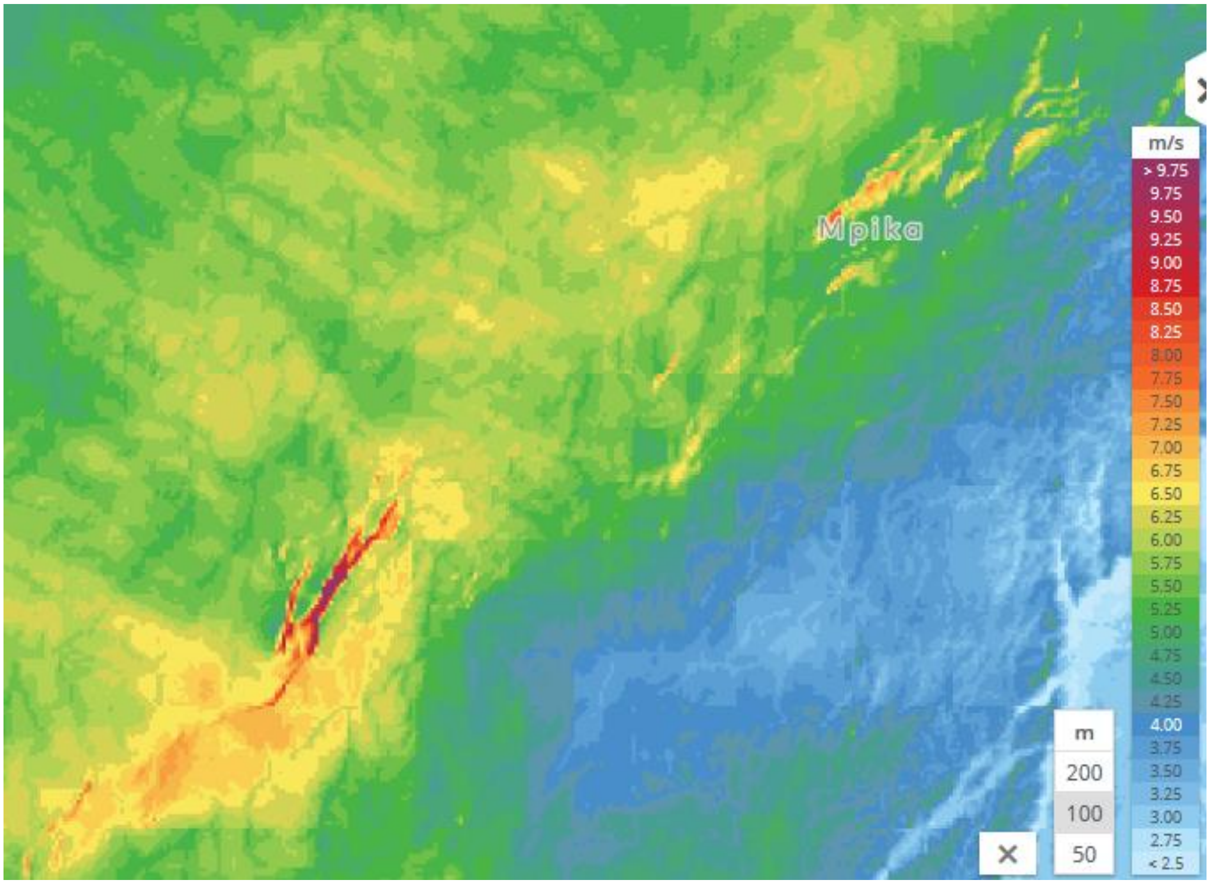

Figure 5: Wind Resource Map for Mpika. Source; Global Wind Atlas

According to the GWA, most parts of Mpika receive wind with speeds ranging from $4.0\,m/s$ to $9.75\,m/s$ with the highest power density estimated to be $1300\,W/m^2$. This indicates the availability of enough wind resource for power generation.

2.6.6 Wind Power Plant Design Consideration

The wind power plant design process is undertaken iteratively to arrive at the most optimum design. In modern times, the wind power plant design process is aided by various softwares such as the OpenWind. For a typical wind power plant design process, the following steps are generally adopted:

2.6.6.1 Wind Resource Data Analysis

The amount of energy produced by a wind power plant depends on the wind conditions at the site where it is to be installed. However, naturally wind speed at any given site varies every second due to the turbulence caused by the land topography, thermals and weather. According to Burton, Tony, et al (2002), the wind in the low heights below $1000m$ is affected by the friction of the earth's surface. Therefore, to calculate the amount of energy a wind power plant will produce at a specific site, it is necessary to know the wind speed distribution and the wind frequency rose at the hub height at that location as shown in figures 3 and 4 respectively.

2.6.6.2 Power expected from the wind power plant

The power expected from the wind power plant is estimated based on the mean wind power density at a particular site. Its value is a combination of the effect of wind speed, wind speed distribution and air density. The wind power density is determined as a function of wind speed and air density as expressed in equation 1.2.

2.6.6.3 Wind Power Plant Components

The law of conservation of energy states that energy can neither be created nor destroyed. It can only be converted from one form to another. Energy conversion process involves use of various energy converting elements or components as shown in figure 6.

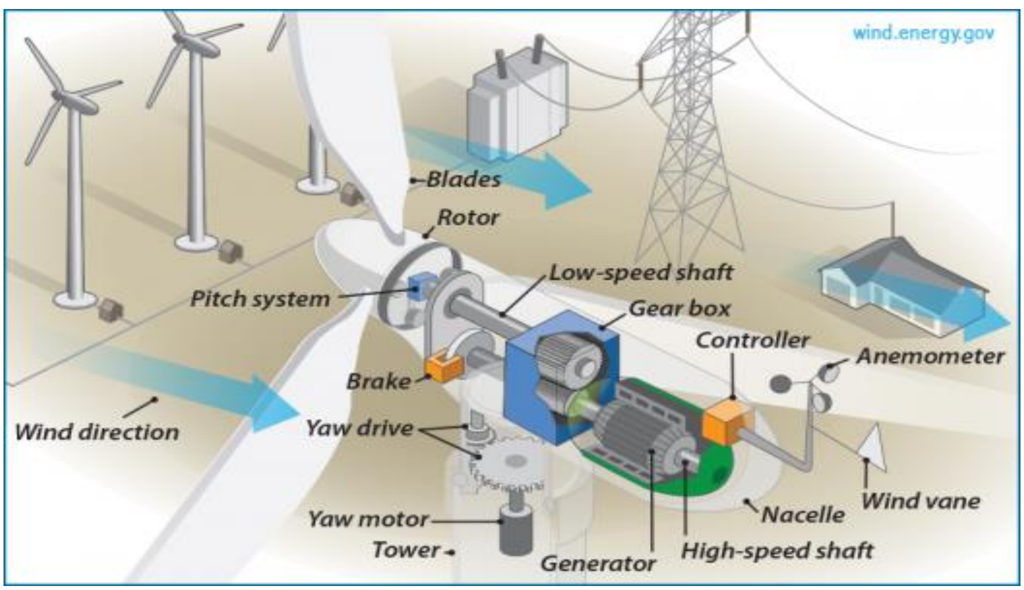

Figure 6: Wind Power Plant Design Features, Source: Wind.Energy.Gov

When converting the kinetic energy of the wind to electric energy, major component namely: rotor, nacelle, generator, tower and electric substation are used.

(i) Rotor

The rotor of a wind turbine can two-bladed, three-bladed or multi-bladed. The blades are fixed to the hub at an appropriate angle of attack for the lift force to act upon and make rotate. According to IEC 61400-2 International Standards, wind turbines are designed to rotate in a clockwise direction to harness the energy from the wind. The blades are usually built out of Glass Fibre-Reinforced Plastic (GFRP) which is relatively lighter and durable than wood or metal.

(ii) Gearbox

To multiply the relatively low rotational speed of the rotor to match the high speed requirements of the electric generator, some wind turbines use a gearbox. The gear box usually consists of two stages of helical and/ or spur gears designed to take in a certain low speed from the rotor and take out a higher speed according to the electric generator's rpm rating.

(iii) Generator

In order to convert the mechanical rotational energy of the rotor to electric energy a generator is used. A number of types of electric generators are used for this purpose. The choice of the type of generator to be used is normally based on the performance, reliability and cost. Some of the types of generators widely used include: Direct Current (DC) generator; the Multi-Pole Permanent Magnet Synchronous Generator (PMSG); and the Squirrel Cage Induction Generator (SCIG)

(iv) Yaw System (Tail Vane)

Most small wind turbine up to $10kW$ use a simple tail vane at the back of the horizontal axis wind turbine nacelle so that the turbine rotor keeps facing the wind. For the large wind turbine, the forced yaw system is used to keep the rotor facing the wind direction.

(v) Tower

Several different types of towers are available, depending upon the design and manufacturer. The turbine tower can be tubular type or lattice type. The tower must be designed to withstand extreme winds and hail. As a rule of thumb, for proper and efficient operation of a wind turbine the tower hub height should be at least $10m$ above anything around $100m$ of the tower.

(vi) Control and Protection System

The output of from the generator is variable, as wind the wind speed varies, requiring a control system to produce a stabilized constant output power. The control system for this purpose vary from simple switches, fuses and battery charge regulators to computerized systems for control of brakes, connection and disconnection switches among others. The sophistication of the control and protection system varies depending on the application of the wind turbine and the energy system support, to include inverters, transformers and the battery bank.

2.6.6.4 Grid Connectivity

While large wind power plants are generally connected to the electric grid as other conventional power plants, small wind power plants are preferably installed as stand-alone systems for residential electricity supply. According to Constantinos (2013), stand-alone wind turbines are used in isolated islands, remote villages, mountains and similar sites where the grid does not exist.

2.6.6.5 Sustainability of Wind Power

Wind is naturally an intermittent energy resource and the amount of electricity it produces at any given point in time using a given plant will depend on the wind speeds, air density and turbine characteristic among other factors. An intermittent energy resource is any energy resource that is not continuously available for constant conversion into electricity. If the wind speed is too low, normally below cut-in speed, then the wind turbine will not be able to generate electricity. On the other hand, if the wind speed is too high, higher than cut-out, the turbines will have to be shut down to avoid damage. Wind power varies from time to time and so does its electricity generation (Hills, 1996).

However, Erlich .et al (2006) note that while the output from a single turbine can vary greatly and rapidly as local wind speeds vary, as more turbines are connected over larger areas the average power output becomes less variable. According to the 2007 study on wind in the United States, ten or more widely separated wind farms connected through the grid could be relied upon for from 33 to 47% of average output as reliable, baseload power as long as the minimum wind speed is available.

2.6.6.6 Energy Storage System

Micro-grid wind power systems can be installed with electrical energy storage (EES) systems for the purpose of storing energy to be used in times of low or no power generation. As given in figure 7, the EES systems are classified into mechanical, electrochemical, chemical, electrical and thermal energy storage systems. In order to mitigate the spatial imbalance between supply and demand, energy storage systems can address the temporal dimension.

Historically, EES has played three main roles. First, EES reduces electricity costs by storing electricity obtained at off-peak times when its price is lower, for use at peak times instead of electricity bought then at higher prices. Secondly, in order to improve the reliability of the power supply, EES systems support users when power network failures occur due to natural disasters, for example. The third role is to maintain and improve power quality, frequency and voltage (Michael, 2011).

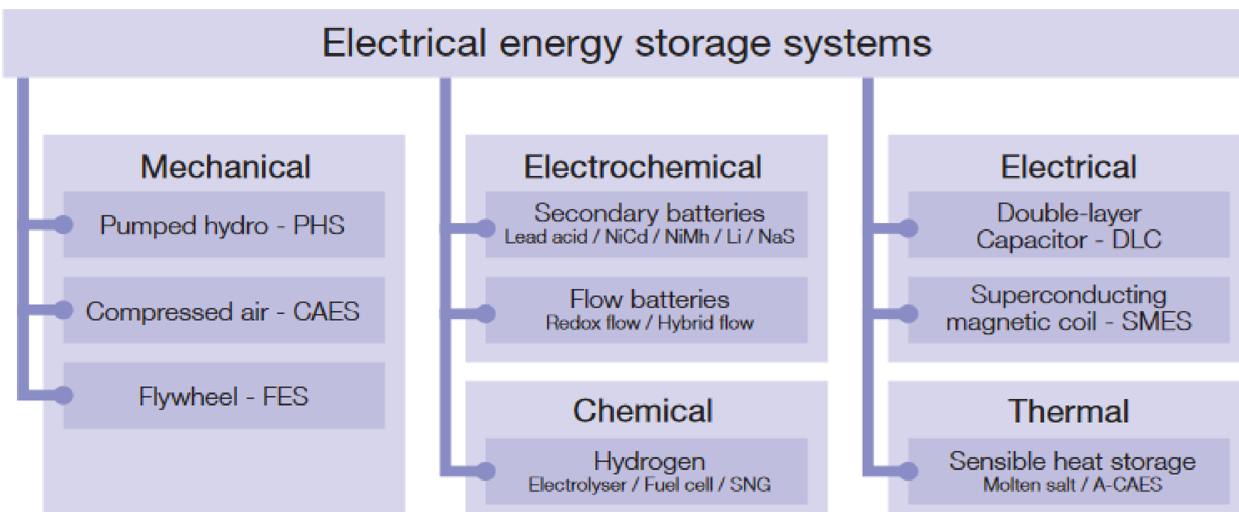

Figure 7: Classification of Electrical Energy Storage Systems. Source: Fraunhofer ISE.

2.6.6.6.1 Hydrogen Storage System

Being a combustible chemical element, hydrogen is an “energy vector”, meaning that it can be used as a portable fuel, and the point of production can be decoupled with the point of use. Hydrogen systems are unusual when compared to other types of EES in that they use two different processes for the charging and discharging of the storage system. Hydrogen production generally involves an electrolyser unit which separates water into hydrogen and oxygen using electricity.

The hydrogen is stored as either a gas in high pressure tanks, as liquefied hydrogen or metal hydrides. To generate electricity, normally an electrochemical device called a Fuel Cell is used (Chen, et al., 2009). Using an electrochemical process, the fuel is combined with oxygen from the ambient air to produce electricity with heat and water as the waste products.

In applications with renewable energy, fuel cells are playing an increasing role. A number of wind-hydrogen hybrid systems have been installed in some parts of the world. For instance, the first and largest plant that integrates hydrogen and wind power has been installed by Utsira, Norway and it operates as an isolated power system. According to Kaldellis (2007), depending on the system design, the wind-hydrogen system can generate power to supply 10 houses for 2 to 3 days without wind. Environmentally, the Fuel Cells are very friendly. The chemical process involved in the electricity generation process is quiet, greenhouse gas emission-free and is 2 to 3 times more efficient than combustion, despite the technology being costly.

2.6.6.6.2 Lithium Ion Battery Energy Storage

The lithium-ion battery or Li-ion battery (LIB) is a type of rechargeable battery in which lithium ions move from the negative electrode to the positive electrode during discharge and back when charging. The cathode of the LIB is lithiated metal oxide while anode is graphic carbon with layer structure (Rodriguez, 2010). The electrolyte is a lithium salt in organic solvent. In this case during discharging lithium migrates from anode to cathode while during charging reverse process occurs.

This technology can be sized in MW and therefore become a serious player in large scale applications and hence relevant for WPP. The LIB system is characterised by light weight, high efficiency and high cell voltage and power density. They can also be shaped into a wide variety of shapes and sizes and offer long life for deep cycles. However, the technology is quite expensive and the battery system needs replacement at the end of its service life.

2.6.6.6.3 Double Layer Capacitor

The Double Layer Capacitor (DLC) are energy storage elements with high energy density compared to conventional capacitors and high power density compared to batteries. Unlike in conventional capacitors, where no chemical reaction is used and small amount of energy is stored by physically storing electric charges between two conductive plates upon application of an electric field, these electrochemical storage devices cross the boundary into battery technology by using special electrodes and electrolyte, and have capacitance values as high as 3500 Farads in a single standard case size with long cycle life (Miller, 2008).

In a similar operation as batteries, the DLC energy storage mechanism involves bulk separation and movement of charge. The DLC is designed with two electrodes, an electrolyte (aqueous or organic) and a separator that allows the transfer of ions, while providing insulation between the electrodes. As voltage is applied to the DLC, ions in the electrolyte solution diffuse into the pores of the electrode of opposite charge. Charge accumulates at the interface between the electrodes and the electrolyte, forming two charged layers (double layer) with an extremely small separation distance. The carbon technology used in these capacitors creates a very large surface area with separation distance of just a few angstroms (0.1nm), due to their porosity. As a result, since the capacitance value is proportional to the surface area and is the reciprocal of the distance between the two layers, high capacitance values can be achieved in a very small space (Frackowiak, 2007).

The drawback associated with the DLC energy storage system is its degradation patterns. This electrochemical system degrades due to electrodes or electrolyte exposure to voltage application and the drying up of the electrolyte due to evaporation. In addition, the technology is not very developed especially for commercial level usage.

2.6.7 Operation and Maintenance of the Power Plant

Maintenance during operation of any equipment is crucial for its effective and efficient functioning. This is true for a wind turbine as well. The performance and life expectancy (typically 20 years) of wind power plants depend largely on the operation and maintenance (O&M) functions. The primary aim of the wind turbine's O&M is to improve the wind turbine yield and keep the production costs as minimum as possible.

Maintenance work includes inspection and testing of the control and safety devices, repair of small defects, and replacement or replenishment of consumables such as gearbox lubrication. During this exercise, both scheduled and unscheduled maintenance are performed. The number of repairs required varies widely between different types of wind power plants and wind farms. On average, 3 to 4 corrective actions requiring a visit by service engineers for the wind turbine. The mean downtime per failure is 2 to 4 days and the causes are mostly due to mechanical and electrical problems (U. S Department of Energy, 2007).

2.7 Wind Project Life Cycle

A wind farm has a life span of 20 to 30 years that starts with development and goes through construction, operation and ends with decommissioning or occasionally repowering, i.e. replacing of old wind power plants with newer ones. The wind project life cycle consists of several key phrases including: site feasibility study, permissions and procurement, installation and commissioning, and operation.

2.7.1 Site Feasibility Study

In the wind power project, during the feasibility study process, the wind resource for the site under consideration is critically examined. Site selection is a crucial decision which decides the success of the wind power project. The process is done through critical examination of the wind rose, frequency distribution and the power density as required for project development. According to Earnest and Wizelius (2015), if the output of this scrutiny turns out to be uneconomical it is better to end the project at an early stage and find a better site.

2.7.2 Permission and Procurement

The wind power project should not only give the best possible returns on the investment made, but also has to be compatible with the legitimate regulation of the government authority so that necessary municipal related permissions are obtained. Utility permission is a key factor to be considered in taking up wind power projects UNESCO (1997). In Zambia, permission to undertake energy projects is obtained from the Ministry of Energy while project's compliance to the national energy standards and regulation is enforced by the Energy Regulation Board. To undertake energy projects in Zambia, the project developer is required to carry out a feasibility study, obtain the Implementation Agreement (IA) and sign the Power Purchase Agreement (PPA) with the power off-taker.

2.7.3 Installation and Commissioning

Installation of a wind turbine initially requires lying of a steel reinforced foundation which should be allowed to harden for about 3 weeks. The construction phase for a wind power plant lasts for about 2 to 3 months and is normally undertaken by the supplier.

Wind power plant components are usually huge in size hence on-site storage and assembly works require an open space at the base of each tower of about 50 by 70m. In addition, due to the heights and weight of the turbines, heavy cranes are required on site for hoisting the tower section, nacelle and rotor into positions.

After installations are completed, the commissioning procedure is undertaken as mutually agreed by all stakeholders. Inspection of all engineering works accompanied with commissioning tests are done.

2.8 Financial Viability of Wind Power Projects

The optimum design for a wind power plant is not simply dictated by technology alone. It is normally a compromise between technology and economics. To maximize the benefits obtained from wind power plants, it is required to carefully build power plants that can deliver electric power at the lowest cost per kilowatt hour of energy (UNESCO, 1997). The idea is to tap into technologies that have the potential to reduce life cycle based cost of energy using optimum designs to improve the system performance through reduced operating loads, lower investment and operating costs, and boost the system's reliability.

2.9 National Policy on Wind Technology

The National Energy Policy (NEP) developed in 1994 and revised in 2008 is the overall guide for developments in the energy sector. It sets out Government's intensions of ensuring that the energy sector's potential to drive economic growth and reduce poverty. NEP promotes the national vision to provide well developed, managed, reliable and sustainable energy resources for the improvement of life for all Zambians through the development of appropriate energy technologies and resources. According to Ministry of Energy (2017) the NEP creates a general framework for the energy sector to include solar, wind and geothermal energy resources.

In Zambia, the development of the wind technology, as renewable energy, is assured of support by a number of policies and strategies including the Renewable Energy Feed-in Tariff (REFiT), a strategy that is meant to implement the Global Energy Feed-in Tariff (GETFiT), currently for solar and mini hydro projects. The country has installed 8 wind masts as part of the country's wind resource mapping campaign which started in 2016 and targeting major wind potential sites across the country. As of November 2018, the country had collected wind data for a period of two years at the 80m height.

Currently, wind technology development has been receiving much attention in Zambia. The fact that there has been much willingness from the private sector to invest in wind power generation entails the potential for development in this space. A number of Independent Power Producers (IPPs), like Mphepo Power Limited, have shown interest in developing wind power plants and have started carrying out feasibility studies in respect of wind power generation.

CHAPTER 3:METHODOLOGY AND MATERIALS

3.1 Introduction

This research aimed at determining the optimum size of stand-alone wind power generation system for rural communities in Zambia by numerical methods. The research assessed the technical sustainability of setting up a wind power generation with storage system for stand-alone mini-grid electricity generation and determine the financial viability for operating and maintaining a wind power generation with storage system in rural areas in Zambia.

The study employed the applied and theoretical approach to establish the technical feasibility and financial viability for setting up a stand-alone wind power plant for electricity supply at a selected rural community, a case study, as a solution to the current low access to electricity the country is facing. The study therefore led to the development of a sized model stand-alone wind power system for electricity generation for rural set up.

3.2 Study Area

This study considered a case of Mpepo Chiefdom in Mpika District in Muchinga Province of Zambia. Mpepo is a rural settlement area having 258 households and a human population of about 1289. This settlement area is located about 111km from the national grid, as mapped from the Geospatial model. The choice of this study site was mainly influenced by its prevailing high wind speeds and power density as indicated on the GWA. Other influencing factors considered were its rural location, moderately high population, distance from the national grid and the road network as well as the existing economic activities, i.e. farming.

3.3 Research Method

This research work employed both the applied and theoretical approach. Due to the nature of the study, the applied and theoretical approach was preferred as it offered an opportunity for the researcher to apply scientific principles and theories to solve the, low rural electricity access, problem the country is facing. According to Gary (2004), Applied Research is a form of systematic inquiry involving the practical application of science to practical problems.

3.4 Research Materials and Tools

This research used library materials, interviews, data from the geospatial model and internet browsing as the desktop data collection approach. The researcher collected relevant information which was used to determine the power requirements, power plant model size, and assessment of the power plant's operational sustainability and financial viability using numerical analysis.

The following tools and/or apparatus were used in this study:

1. A Geospatial model
2. The Global Wind Atlas
3. Microsoft Office
4. HOMER Energy

3.5 Details of Research Method

The study secured the following approach for data collection, power plant model sizing, operational sustainability assessment and financial viability analysis:

3.5.1 Power Demand Requirement Assessment

The power demand requirement in the study area was estimated from the individual household's power consumption needs based on the power rating from the anticipated basic household appliances. The total power requirement was determined as the sum of the household power requirement and the community's productive use power needs. The expression used to assess the total power requirement is as given in equation 3.1.

$$P_r = N\sum(n \times AL)_{hh} + \sum(n \times AL)_{ps} \quad \text{..........................3.1}$$

Where: P_r is the total power requirement, N is the number of households, n is the number of one type of appliance for productive use and AL is the rated appliance load.

The total power demand in the study area was projected up to 2030 and used to size the wind power plant.

3.5.2 Power Plant Model Sizing

Based on the power demand requirements and the average wind speed, the wind turbine power generation capacity was determined. Using equation 3.2, the wind turbine power output was approximated as a function of the average wind speed and the rotor diameter.

$$P_{output} = 0.26\pi D^2 v^3 \quad \text{..(3.2)}$$

Where: P_{output} is the wind turbine rated output power, D is the wind turbine rotor diameter and, v is the average wind speed.

The wind turbine power output capacity was then used to specify the number of wind turbines required for the turbine rotor sized based on the average wind speed.

3.5.3 Operation Sustainability

Using wind pattern in the study area, the monthly power generation potential was determined and used to assess the power generation deficiencies as a way to forecast the periods of low or no generation due to inadequate wind speeds.

3.5.4 Energy Storage System Sizing

Based on the annual period for low or no wind, the optimum power storage system was determined and modeled to meet the amount of power needed to compensate for times of low or no power generation from wind. The energy storage system technology was then selected based on the technical viability and financial consideration.

(a) Battery Energy Storage System

The battery storage system stores electricity in form of chemical energy using batteries. The battery is charged by an internal chemical reaction under a potential applied to both electrodes, the cathode and anode. The system includes an inverter and the battery bank.

In this study, the size of the inverter was determined using equation 3.3.

$$I_s = \frac{P_r}{P.F} + \frac{(1 + Af)}{l_e} \qquad (3.3)$$

Where: I_s is the size of the inverter in VA, P_r is the total electrical load in watts, $P.F$ is the power factor, Af is the load expansion factor and, l_e is the efficiency of inverter.

And the size of the battery bank was obtained by using equations 3.4 and 3.5.

$$P_{lb} = (P_r \times B_c) / V_b \qquad (3.4)$$

Where: P_{lb} is the total load of the battery bank in AH, P_r is the total electrical load in watts, B_c is the backup capacity and, V_b is the battery bank voltage.

$$B_s = [P_{lb} \times (1 + LF) \times (1 + Ag)] / (n_s \times DOD) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.5)$$

Where: B_s is the battery bank size in Amps per hour, LF is wire loss factor, Ag is the battery aging factor, n_s is battery efficiency and, DOD is the depth of discharge.

(b) Hydrogen Storage System

Hydrogen as an energy carrier and storage medium can be generated through the electrolysis of water as illustrated in the chemical expression (a). The hydrogen gas produced in this chemical process can be stored and used as a fuel to directly produce electricity in fuel cells to compensate for times when the wind turbines cannot generate enough power.

$$2H_2O \longrightarrow 2H_2 + O_2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (a)$$

For the purpose of this study, the hydrogen requirements needed to supply power to the community during the time of low or no power generation from the wind turbines was determined using equations 3.6 and 3.7.

To determine the total amount of hydrogen gas required to generate electricity in the fuel cells for a given backup period, equation 3.6 was utilized.

$$Q_h = q_h \times N_t \times N_{fc} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.6)$$

Where: Q_h is the total amount of hydrogen gas needed to produce backup power, q_h is the rate of hydrogen consumption by the fuel cell, N_t is the backup time and, N_{fc} is the number of fuel cells required.

And to determine the number of water Electrolysers needed to produce enough hydrogen to meet the requirements for the backup time, equation 3.7 was used.

$$N_{we} = \frac{Q_h}{q_{output}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.7)$$

Where: N_{we} is the number of water electrolyser and, q_{output} is the rate of hydrogen output.

3.5.5 Financial Analysis

The financial analysis was done based on the project investment and operation costs for the wind power plant with an energy storage system as per cost information. The financial analysis was performed and the financial viability was tested based on the project's payback period, Net Present Value (NPV) and the Internal Rate of Return (IRR).

Accounting for the time in which the initial outlay of the investment is expected to be recovered, the payback period (PbP) was determined as a ratio of the initial investment cost to the net cash flow per year as shown in equation 3.8.

$$PbP = \frac{Investment}{Cashflow} \qquad (3.8)$$

The NPV and the IRR were used to assess the profitability of the project based on equation 3.9 as suggested by Robert (2015).

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t} \qquad (3.9)$$

Where: CF_t is the net cash flow in a given time, r is the internal rate of return that could be earned on alternative investment, n is the number of individual cash flows, and t is time.

3.6 Treatment of Data

The data collected was organized and arranged for better understanding of the practical representation. It was then analyzed and presented using statistical means in order for it to be used for power plant sizing, sustainability assessment and financial viability analysis. The analysis was done using the Microsoft Office Excel, 2016 version.

3.7 Summary

This methodology was drawn with a view to meet the goals of this research work which was to determine the optimum size of a stand-alone wind power generation system for rural communities in Zambia as a possible solution to the country's low rural electrification rates. The methodology outlines the methods employed in power plant sizing, sustainability assessment and financial viability analysis.

CHAPTER 4: RESEARCH RESULTS

4.1 Introduction

This chapter presents the results obtained through the optimum sizing of the WPP with an ESS for power supply to rural communities through a mini-grid system. The chapter is divided into sections presenting the findings on the community energy requirement, wind power plant model design, and project financial analysis. The wind resource section presents the wind scenario and characteristics such as the wind speed and its frequency distribution in the study area. The energy requirement section provides the estimates of the energy demand in the study area as a sum of the domestic and productive use energy demands in the study area. Further to that, the wind power plant model design gives the technical specifications for the wind power plant suitable for power generation in the study area. Finally, the project financial analysis section presents the project financial costs, revenues and the cash flow analysis.

4.2 Wind Resource in Zambia

For the wind power plant to operate effectively, the wind turbines must be located at a site with wind speeds as high as $4m/s$ and above. Locating the wind power plant accurately at the most appropriate spot is cardinal for maximising the return on investment in wind power projects. Based on the wind power density, a slight increase in wind speed results in substantial increase in power output. It implies that when a wind power generation system is developed, the wind regime at the specific site or region should be given a greater consideration.

The research analysed the wind resource in Mpika by comparing two wind data sources, namely; the Global Wind Atlas (GWA) and, the Wind Resource Map (WRM) for Zambia. As shown in figure 8, the colour code indicates that most parts of Mpika district receive an average of $6.5m/s$ at heights of $100m$ with some places receiving average wind speeds as high as $8.5m/s$. These average wind speeds are approximate values obtained from the GWA. The GWA dataset uses microscale modelling to capture wind resource data and display it at one-kilometer resolution.

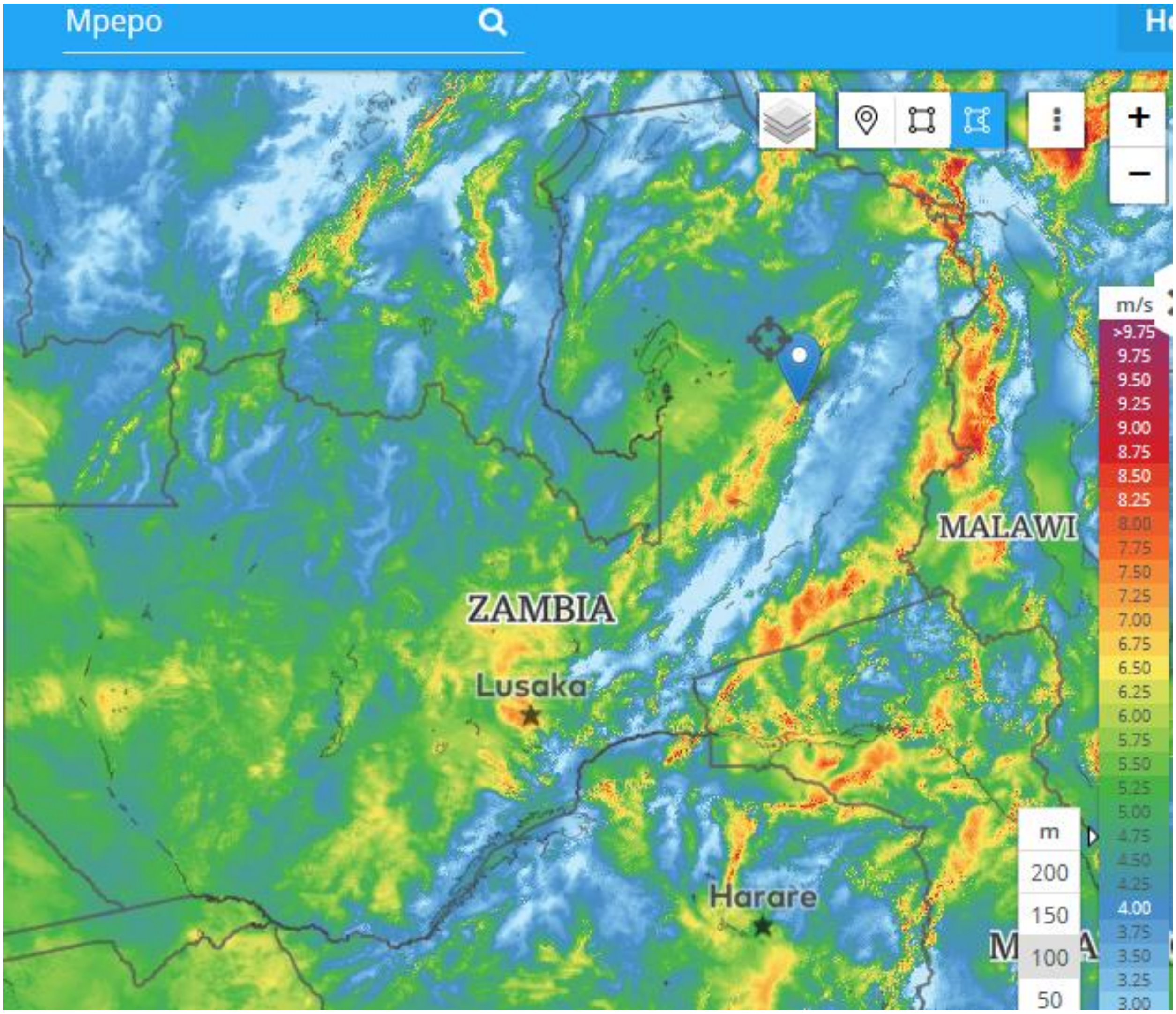

Figure 8: Wind Speeds for Mpepo Area (Source: GWA)

The wind power density for the Mpika region was also obtained from the GWA. As shown in figure 9, most parts of the Mpika region record an average of $250W/m^2$ with a few places recording wind power densities as high as $1200W/m^2$.

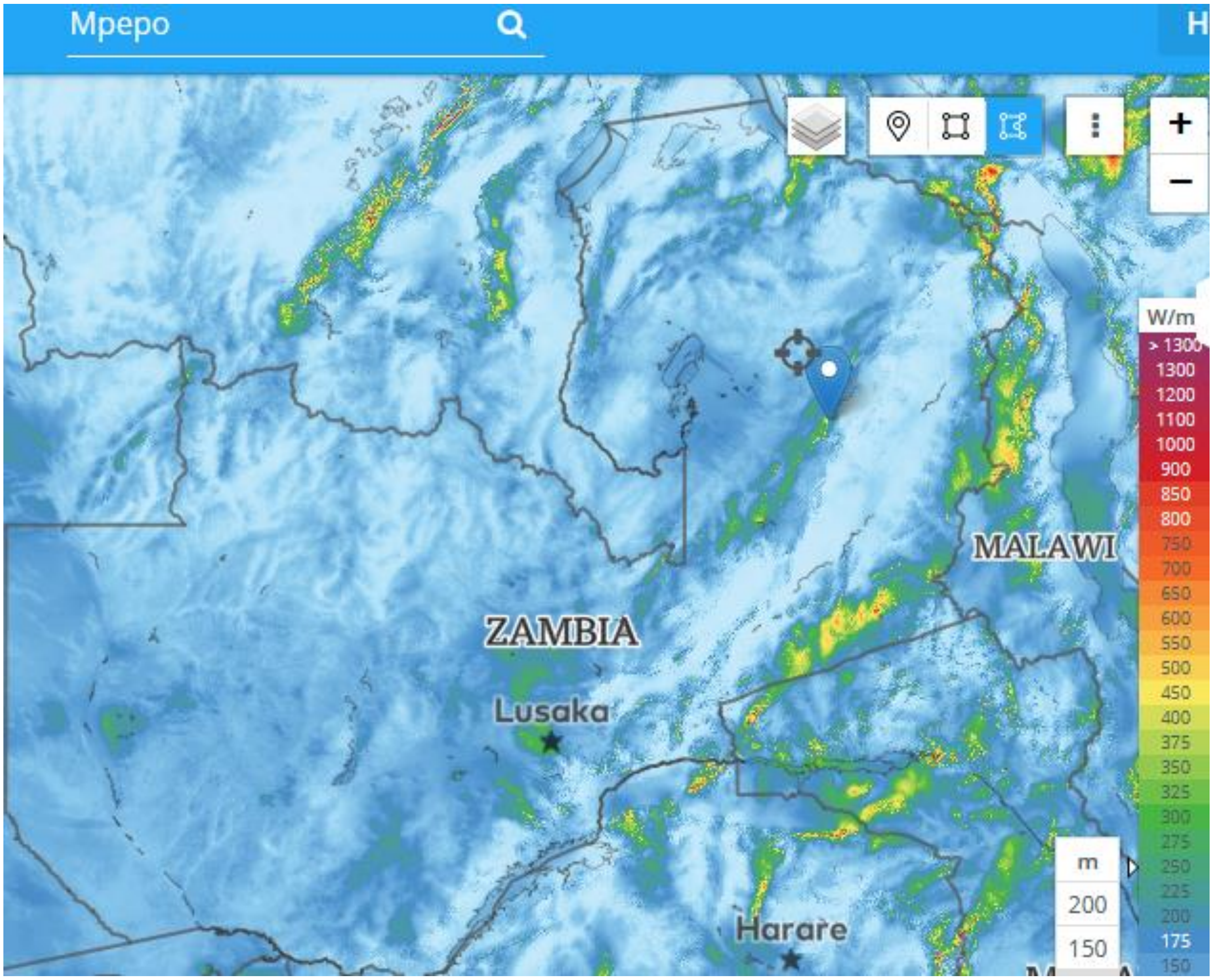

Figure 9: Power Density for Mpepo Area (Source: GWA)

From the WRM for Zambia, as provided in table 2, the actual average annual wind speed at Mpika is $6.3m/s$ measured at $80m$. This wind speed data is from the real-time wind measurement as recorded from the wind mast measuring equipment installed in Mpika.

Table 2: Actual Wind Speeds for Mpika

Site	Reference data sources included in long-term adjustment	Long term adjustment	Long-term adjusted mean wind speed, [m/s]
Choma	ERA	1.6%	6.6
Mwinilunga	VMD, MERRA-2	-0.4%	6.0
Lusaka	VMD, ERA, MERRA-2	4.3%	6.5
Mpika	VMD, MERRA-2	2.4%	6.3
Chanka	VMD	1.9%	6.6
Petauke	VMD	0.0%	5.7
Mansa	VMD, MERRA-2	1.4%	5.9

Source: Ministry of Energy, Zambia

In order to assess the probability of the occurrence of the wind speeds at the site, the research considered the frequency (Weibull) distribution established under the WRM. The wind resource in Mpika is distributed as shown in the wind frequency figure 10 (Ministry of Energy, 2018). The figure demonstrates that Mpika receives a minimum wind speed of $2.0 m/s$ with a 2% frequency and a maximum wind speed of $15 m/s$ with 0.5% frequency.

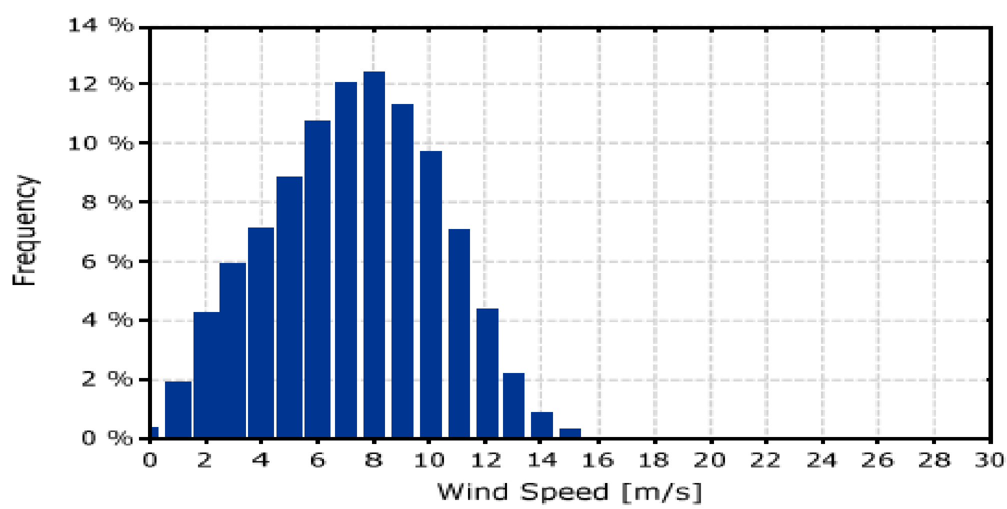

Figure 10: Weibull Distribution (Source: Ministry of Energy, Zambia)

Based on the wind characteristics assessed in this study, Mpepo area has wind resource that can be harnessed for electricity generation. According to the global wind classifications, most areas around Mpika receive wind in the fair marginal class as indicated in table 3. The wind classes are used to indicate the quality of the wind received in a particular location and is used for selecting the wind turbines.

Table 3: Wind Classes for Winds measured at 50m

No.	Wind Class	Wind Speed (m/s)
1.	Marginal	5.4 – 6.4
2.	Fair	6.4 – 7.0
3.	Good	7.0 – 7.5
4.	Excellent	7.5 – 8.8
5.	Superb	9 and Above

For the purpose of this research work, the design of the wind power plant was based on the average wind speed data, $5.5mls$ at $50m$, interpolated from the WRM data on the basis of equation 1.4, at hub height as follows:

$$v_{avg} = \frac{6.3m/s}{(80/50)^{0.3}} = 5.5m/s$$

The calculation was based on the assumption that the terrain in Mpika is a low forest.

4.3 Energy Requirement Assessment

In order to establish the capacity of the power plant required to be installed, the electricity demand for the community was estimated. The total energy requirement for Mpepo chiefdom area was determined based on the approximate sum of the power per household and the total power needs for community productive use. The details of the energy demand in the community is provided in the following subsections.

4.3.1 Household Energy Requirement

The daily energy requirement per household was estimated to be 13.29kWh considering only the basic appliances which may be critical to rural communities including lighting bulbs, television set, mobile phone charger, refrigerator and pressing iron as shown in table 4.

Table 4: Rural Household Energy Requirements

		Estimated Daily Household Power Requirement			
No.	**Load**	**QTY**	**Unit Consumption (kW)**	**Usage Time (hr)**	**Daily Usage (kWh)**
1	Lighting Bulbs	4	0.020	5	0.40
2	Television	1	0.065	4	0.26
3	Phone Charge	3	0.005	2	0.03
4	Refrigeration	1	0.400	24	9.60
5	Pressing Iron	1	1.500	2	3.00
Total Household Energy Consumption					**13.29**

4.3.2 Productive Use Energy Requirement

In addition to the household energy requirement, the community's productive use energy requirement was approximated to be 431.79*kWh* per day as provided in table 5. The approximation was based on the energy required for the community's major productive activities such as water pumping, milling, health, education, and small and medium businesses.

Table 5: Community Productive-Use Energy Requirements

	Estimated Daily Productive Use Power Requirements				
No.	**Load**	**QTY**	**Unit Consumption (kW)**	**Usage Time (hr)**	**Daily Usage (kWh)**
1	Water Pump	5	0.75	3	11.25
2	Schools	1	5.00	24	120.00
3	Health Centre	1	5.00	24	120.00
4	Hammer Mill	1	12.00	8	96.00
5	Hair Clipper	6	0.02	6	0.54
6	Welding Machine	2	6.80	6	81.60
7	Market lighting	30	0.02	4	2.40
Total Productive Use Energy Consumption					**431.79**

Based on the above energy estimates, as provided in table 6, to cater for all the 258 households with a population of 1,289, the average power demand was estimated at $160.86kW$ representing the average daily energy demand of $3{,}860.61kWh$.

Table 6: Total Energy Requirement for the Community

No. of Households	Household Energy Consumption (kWh)	Productive Use Energy Consumption (kWh)	Average Energy Requirement (kWh)	Average Power demand (kW)
258	13.29	431.79	3,860.61	160.86

Further analysis indicated that the yearly average energy demand for Mpepo would be $1{,}409.12MWh$ with an optimum yearly demand profile, as in figure 11, assessed using HOMER Energy and assuming pick demand to be in July.

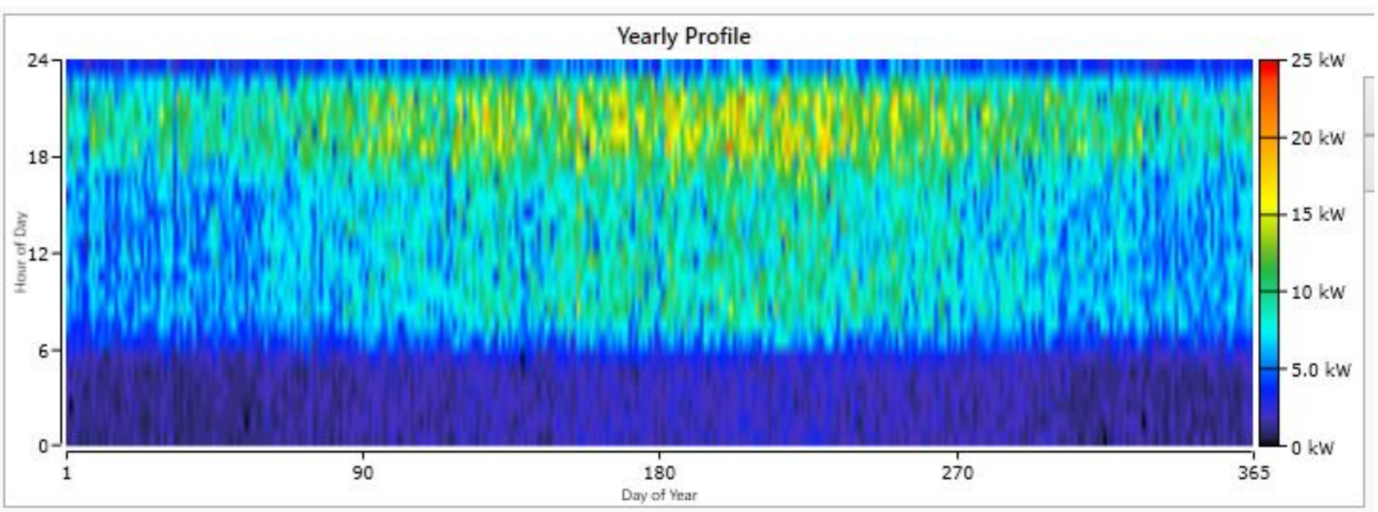

Figure 11: Yearly Energy Demand Profile for Mpepo Chiefdom

4.3.3 Power Demand Projection

For the purpose of design, a loss factor of 0.25 was applied to determine the plant capacity, giving a design capacity of $214.48kW$ as follows:

$$\text{Plant Capacity} = \frac{160.68}{(1-0.25)} = 214.48kW$$

To account for the growth in the power demand with time, the power demand was project to grow steadily from the baseline. The population for Mpepo Chiefdom is expected to steadily grow at a rate of 2.8% per annum and so should the power demand behave. Consequently, the average power demand was projected to grow from $214.48kW$ in 2019 to $290.61kW$ in the year 2030 as shown in figure 12.

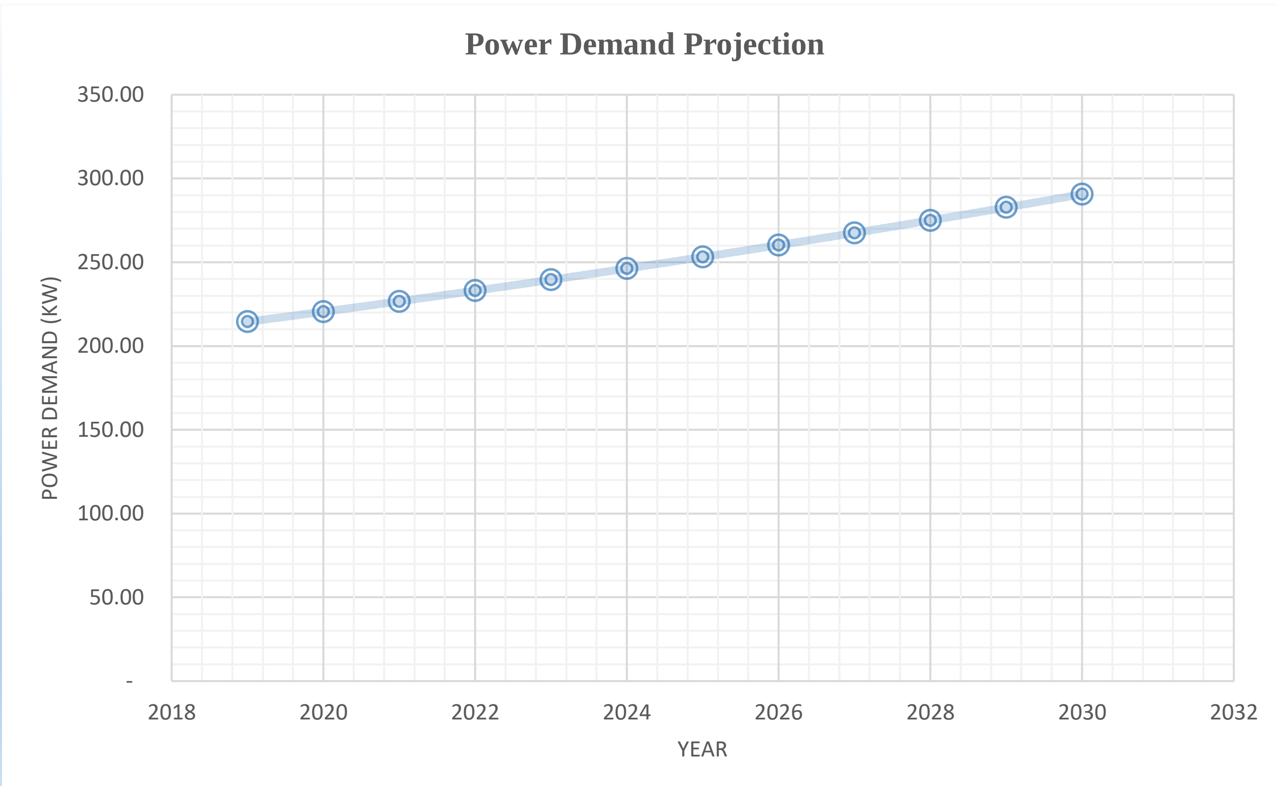

Figure 12: Community Power Demand Growth over Time

4.4 Wind Power Plant Model Design

Based on the projected power requirement and the annual average wind speed, the wind turbine power plant was designed and sized. The wind characteristics obtained from the evaluation of the site for installation of wind turbines and development of the wind farm show that small wind turbines which can operate at lower wind speeds would be appropriate to install.

As presented in the wind frequency distribution of Mpika in figure 10, the area records a minimum wind speed of $2m/s$ and a maximum of $15m/s$ thereby approving the location suitable for power generation using small wind turbines. Small wind turbines of capacity up to $100kW$ have the cut-in speed as low as $3mls$ and the rated wind speeds of up to $12m/s$ and suit to be utilized.

4.4.1 Wind Power Plant Design

Considering an average wind speed of $5.5m/s$ at hub height of $50m$, based on the wind regime in the area, a total of 18 wind turbines with power output of $95kW$ would be appropriate for power generation to meet the community power demand by 2021 and 3 wind turbines by 2030.

On the basis of the required turbine output capacity and the average wind speed, the wind turbine rotor diameter was specified to be $25.4m$ for a swept area of $506.65m^2$ as calculated based on equation 3.2 and indicated in table 7 as follows.

$$D_r = \sqrt{\frac{95 \times 10^3}{0.26\pi \times 5.5^3}} = 25.4m$$

Table 7: Wind Power Plant Design Specifications

Wind Farm Required Output (kW)	Wind Turbine Rated Output (kW)	Wind Turbines Required by 2021	Average Wind Speed (m/s)	Wind Turbine Rotor Area (m2)	Wind Turbine Rotor Diameter (m)
214.48	95.0	2	5.5	506.65	25.40

The monthly average power generation potential was determined as shown in figure 13. The figure indicates that the power plant would generate maximum power, $581.35kW$, in September and the least generation, $-144.54kW$, in January based on the average wind speeds. This entails a yearly average power deficiency of $87.9kW$. The plant would be expected to have seven months with surplus power and five months of deficiency in power generation.

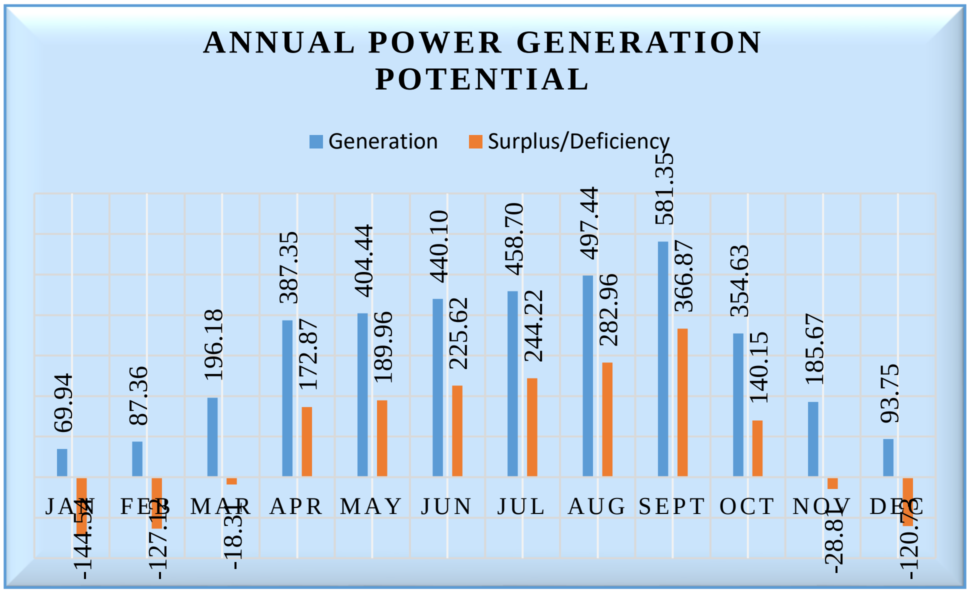

Figure 13: Monthly Average Power Generation Potential

4.4.2 Energy Storage Systems

Practically, when a wind turbine is rated for $95kW$, that is the maximum power that it can deliver when sufficient wind is available. However, due to the intermittence of the wind resource, and depending on region where the wind turbine is installed, only an average output of not more than about 33% of that may be delivered during a 24-hour period. According to Hemani (2012), this 33% is the maximum for many regions and can be lower in some regions. Owing to this intermittent nature of wind, it is recommended that the wind power system is designed with an energy storage system with capacity to store power for use in times of low or no power generation from the wind turbines.

In this research work, two options for the power plant energy storage system were considered. The hydrogen fuel cell system and the battery system were sized to meet the community's average power generation deficiency, $87.90kW$, based on the projections in figure 13.

4.4.2.1 Battery Storage System

As indicated in table 8, in order to meet the storage requirements, the total battery bank capacity of $65{,}926AH$ is required for a total load of $32{,}963AH$. The size of the battery bank was estimated based on equation 3.5, and assumptions provided in appendix 1B.

To build an energy storage system for this amount of energy, a total of 217 batteries with unit capacity of $100kWh$ would be installed. For the purposes of electricity conversion from direct to alternating and to facilitate battery charging, 3 Inverters of $60kVA$ each would be used.

Table 8: Battery System Specification

Average Power Deficiency (kW)	Total Load of Battery Bank (AH)	Size of the Battery Bank (AH)	Battery Capacity (kWh)	Number of Batteries in the Battery Bank	Size of the Inverter (kVA)	Inverter Capacity (kVA)	Number of Inverters
87.9	32963	65926	100	16	180	60	3

4.4.2.2 Hydrogen Fuel Cell System

In order to sustain the energy storage requirements stated in , the hydrogen fuel (HFC) system requires a minimum of 41 Water Electrolysers with hydrogen generation rate of $0.018m^3/hr$ to generate $134m^3$ of hydrogen gas. The hydrogen can be used to power up 18 Fuel Cells of unit capacity of $5kW$ in order to meet the back-up energy requirements of $1582kWh$ as indicated in table 9.

Table 9: Hydrogen Fuel-Cells Specifications

Back-Up Power Requirements (kWh)	Total Hydrogen Requirements (m^3)	Number of Water Electrolysers	Fuel Cell Power Output (kW)	Number of Fuel Cells
1582	134	41	5	18

On the basis of the wind resource and the average energy demand, the WPP was designed with specifications as shown in the schematic diagram in figure 14.

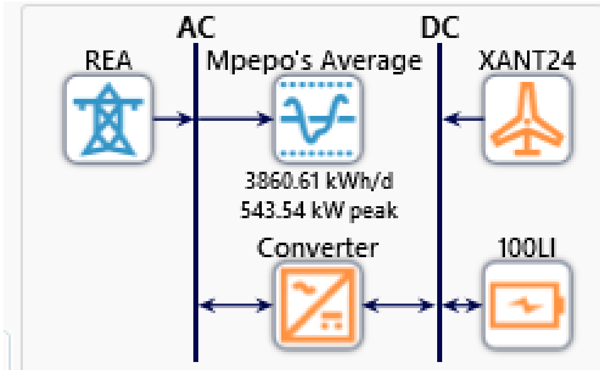

Figure 14: Schematic Diagram for WPP for Mpepo Chiefdom

4.3 Project Financial Analysis

The cost of setting up a WPP with a mini-grid power distribution system with either the BES or HFC as back-up power system included the cost of wind power plant installation as well as the operation and maintenance costs as shown in table 10.

Table 10: Investment Cost

Project Type	Investment Cost (USD)				VARIABLE COST	
	Installed Cost (WPP)	Installed cost (HFC)	Installed cost (Grid)	Total Installed cost	Cost of Operation (USD/yr)	Cost of Maintenance (USD)
Wind Turbine Plant with HFC	498,646.00	753,582.77	60,630.00	1,312,858.76	24,000.00	9,972.92
Wind Turbine Plant with BES	498,646.00	332,267.53	60,630.00	891,543.53	24,000.00	9,972.92

4.3.1 Project Investment Cost

The cost of installing a small wind power plant to supply power to Mpepo community without any form of energy storage system was $498,646.00. The total cost of investing in setting up a WPP-BES was estimated to be $891,543.53 inclusive of the cost of power distribution system, transportation and insurance, and land acquisition. On the other hand, the total cost of building a WPP-HFC system was estimated to be $1,312,858.76 including the cost of the distribution system, transportation and insurance as well as land acquisition.

4.3.2 Operation and Maintenance Costs

Estimated at 2% of the cost of installation for the wind power plant, the annual maintenance costs for WPP-BES and WPP-HFC was $9,972.92. Furthermore, the cost operations was estimated to be $24,000.00 for both the WPP-BES and WPP-HFC covering the salaries for 1 Engineer and 3 Technicians plus the running expenses per annum.

4.3.3 Cash Flow Analysis

The cash flow analysis was performed using equations 3.8 and 3.9. As shown in the appendix 1A, the installed cost for the WPP without the ESS was $ 2,617.38/kW giving a levelised cost of USD 0.08/kWh. The installed cost for WPP-HFC and WPP-BES were $4,634.53/kW and $4,083.33 respectively. The levelised cost for WPP-HFC was $ 0.15/kWh while the levelised cost for WPP-BES was $0.11/kWh. Adding a 15% margin on the levelised cost as profit to derived the proposed tariff, the payback periods for the WPP without ESS, WPP-HFC and WPP-BES would be 6 years, 9 years and 14 years respectively. The Internal Rate of Return (IRR) would be at 11% for the WPP with ESS, -0.04% for WPP with HFC and 2% for WPP-BES systems.

4.5 Conclusion

The current chapter has presented the findings of this study on the technical and financial feasibility of the wind power plant with various energy storage systems. The next chapter will focus on the discussion of the findings of this research work. It gives a detailed analysis of the technical and financial results for the wind power project as presented in this chapter.

CHAPTER 5:DISCUSSION

5.1 Introduction

This chapter discusses the findings obtained from the optimum sizing of stand-alone wind power generation plant with energy storage system for rural communities in Zambia. The chapter is divided into sections analysing the findings on the technical viability of setting up a WPP-ESS with a mini-grid electricity distribution network and the financial viability for installing, operating and maintaining a wind power generation system in rural areas in Zambia.

This research work has led to the development of a baseline which can be used to assess the technical and financial viability of setting up a WPP in any rural community in Zambia.

5.2 Project Technical Viability

As Burton and Tony (2002) advise, for any project undertaken in a particular community to mark a positive impact on the lives of the citizenry, the project has to provide intended solutions to the problems faced by the community. Universal access to clean and reliable energy sources has been marked as one of the key targets aiming at achieving sustainable development across the globe. While wind energy resource naturally provides clean energy, it’s reliability to produce power enough to effectively contribute to the collective campaign depends on the project’s technical viability. As can be seen from figure 8, a number of districts in Zambia, including Mpepo, receive considerably high wind speeds but it is not certain on whether that would sustain the respective districts’ power generation requirements.

As reviewed in the literature, David (1998) underscores that to develop a WPP, it is vital to certainly ensure that the site chosen for the project has sufficient wind resource available to produce energy to satisfy the demand. This is in order to ensure undisrupted operation of the WPP and generation of enough power to meet the demand. In this research work, therefore, it was prudent to assess whether the available wind resource would sustain generation of the total electrical energy need for Mpepo Chiefdom. In any wind power project development, the idea of how much power would be required provides the basis for designing an appropriate wind power system and choosing the suitable site for the power plant.

5.2.1 Community Power Requirements

As Slootweg and Kling (2001) has indicated, to record meaningful sustainable socio-economic growth and development, any community needs sufficient power. In the recent times, there have been coordinated efforts to realise universal access to safe and clean energy at national level. This scenario calls for assessment of the energy needs especially in rural communities where electrification rates are still low. The power needed in any given community is expected to cater for household requirement as well as for productive use.

As established in this study, Mpepo Chiefdom has an average daily energy demand of about $3{,}860.61kWh$ translating into a total of $160.86kW$. This is an approximate energy demand level accounting for the community's household and productive use requirements. However, like any other power plant types, the WPPs experience system losses. The total loses for a WPP site would typically be in the range of 10 to 25 % according to Earnest (2015). To account for the system loses, the power plant was projected for output capacity of $214.48kW$ which is 25% higher than the community power demand.

It was anticipated that the population would steadily grow at a rate of 2.8% which means that the human population in Mpepo would grow from the 1,289 in 2018 to 1,699 by 2030. This trend entails a similar growth in power demand. In that way, the WPP total energy generation capacity would be expected to grow from $5{,}147.48kWh$ in 2018 to $6{,}974.59kWh$ in the year 2030 in order to meet the demand. The capacity of the WPP was therefore designed to sustain the community's energy demand growth.

5.2.2 Wind Power Plant Sizing and Choice

Based on the theoretical approach, as established in equations 3.2 to 3.7 in the methodology, the major power plant components including the turbines, generator and storage system were sized. The WPP design incorporated an initial of 3 wind turbines with power output capacity of $95.0kW$ centered on the Class II/A for low wind regimes. The choice of the turbine was based on the available average wind speed in the project area. The simulation, using HOMER Energy, adopted the XANT24 wind turbine model based on the average wind speed of $5.5m/s$, the hub height of $38m$ with a rotor diameter of $24m$ according to the IEC-61400-1 standard. The wind turbine performance has an optimum power curve with a cut-in speed of $3m/s$ and rated speed of $12m/s$ as provided in figure 15.

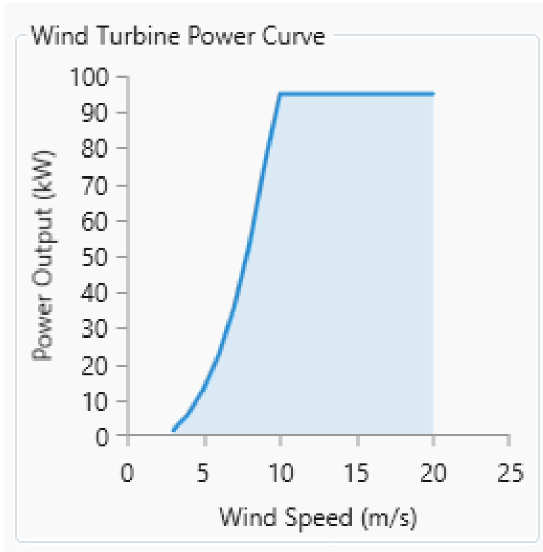

Figure 15: Optimum Power Curve for the Wind Power System proposed for Mpepo Chiefdom

5.2.3 Wind Resource Requirement

In addition to the technical parameters specified in the design, the choice of the turbine model was also influenced by the wind pattern and behavior in the study area. The amount of energy produced by the WPP depends on the wind conditions at the site where it is to be installed. According to Quarton (1996), in order to determine the quantity of power a WPP should produce at a given site, it is necessary to ascertain the wind frequency distribution at the hub height at that location. As observed from the preliminary results obtained by Ministry of Energy during the wind resource assessment in 2018, Mpika records an average wind speed of $6.3 m/s$ at $80 m$.

As presented in figure 16, the monthly wind speeds profile in Mpika corresponds to average seasonal energy demand profile in Mpepo chiefdom as shown in figure 17.

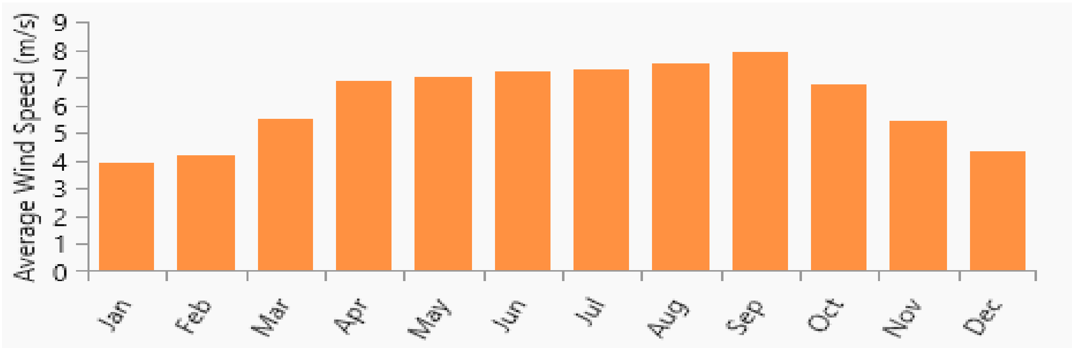

Figure 16:Average Monthly Wind Profile in Mpika

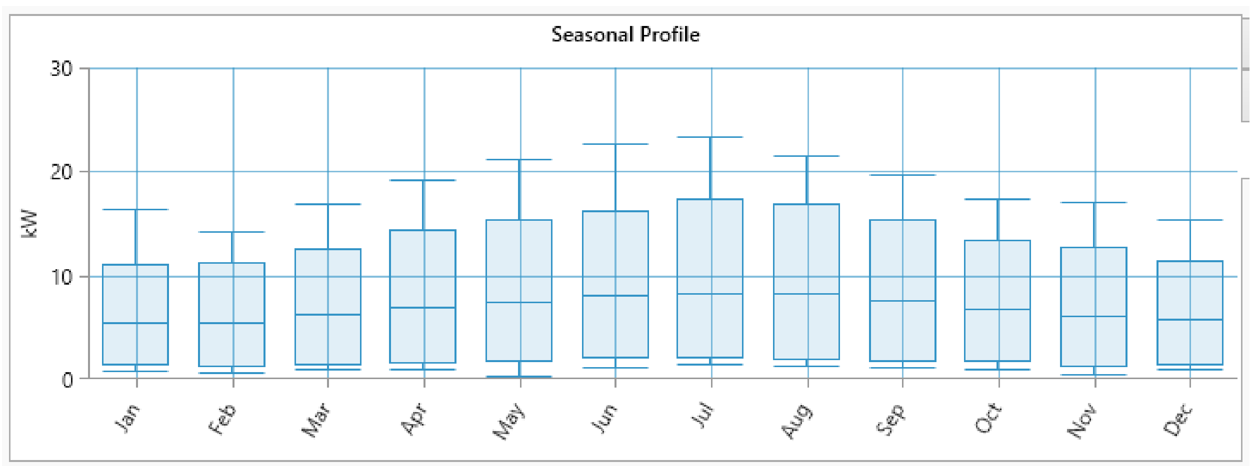

Figure 17:Average Seasonal Power Demand for Mpepo Chiefdom

It is believed that due to climate change, the wind speed varies every second due to the turbulence caused by the land topography, thermals and weather. The wind is greatly affected by the friction force due to the earth's surface and hence varies at any given site with height depending on the terrain available in that location. Analysis of the wind assessment indicated that Mpika area experiences wind shear exponent of 0.21, a parameter that specifies how the wind speed varies with height at a given location. On that consideration, the extrapolation at $130m$ hub height estimated a wind speed of $7.3m/s$ in Mpika as shown in table 12.

Table 11: Wind Speeds at Hub Height

Site	Long-term upper measurement height wind speed (m/s)	Wind Shear Exponent	Hub Height Wind Speed Estimates (m/s)
Choma	6.6	0.24	7.4
Mwinilunga	6.0	0.29	7.4
Lusaka	6.5	0.34	7.9
Mpika	6.3	0.21	7.3
Chanka	6.6	0.21	7.4
Petauke	5.7	0.26	6.5
Mansa	5.9	0.31	6.9

As reviewed in the literature, to be able to harness the wind energy, the wind turbine should be able to cut-in at lower wind speeds and operate at a lower rated speed. As presented in figure 12, the available turbines are designed to cut-in at wind speeds as low as $3m/s$ and attain maximum power generation capacity at a rated wind speed of $12m/s$. And as observed in the wind frequency distribution, figure 10, the wind scenario assessment in Mpika entails that most of the times the area receives wind ranging from $6m/s$ to $10m/s$ in speed.

Further, analysing this wind regime against the turbine's power generation potential as given by the wind profile in figure 16, it is clear that the area has good potential for wind power generation. It is on the pretext of low wind speed region that smaller rated wind turbines are preferred. According to Earnest (2015), it is believed that smaller wind turbines can produce more energy than larger wind turbines in low wind regions, as it requires lesser wind speed to spin the smaller turbine at full capacity almost all the time.

5.2.4 Power Back-up System

Wind-generated power is a variable resource, and the amount of electricity produced, at any given point, by a given plant will depend on wind speeds, air density, and turbine characteristics among other factors (Thomas, 2012). It is evident that if wind speed is lower than the cut-in speed then the wind turbines will not be able to generate electricity, and if it is higher than the cut-out speed the turbines will have to be shut down to avoid damage. It is due to this intermittent operation of the wind energy system that it is vital to incorporate an ESS to store energy for supply to the community during the times of low or no power generation from the turbines.

In this study, the ESS was intended to be a power back-up system to ensure continuous power supply and avoid interruptions in activities requiring electricity use, should the plant either generate less or no power, or shut down for maintenance or safety from high wind speeds. The technologies considered for storing energy is this study include: the battery bank system and the hydrogen powered fuel-cells.

The analysis of the wind scenario in the study area reviews that the power plant would be expected to generate excess in seven months of the year with the maximum generation being in September. On the other hand, the power plant would be expected to have generation below the community's demand in five months of the year with the least generation being in January as shown in figure 13. On average, both the hydrogen fuel cell system and the battery system were sized to meet the community's average power generation deficiency of up to $87.9kW$ and provide backup power for 18 hours (6 hours per day for 3 days). The two energy storage technology lines seemed to be technically viable for use in WPP systems, especially in standalone mini-grid systems.

5.3 Financial Viability of Wind Power Plant in Rural Areas

It is believed that in order to make a good decision about wind power projects, a thorough financial and economic analysis is necessary. Earnest (2015) emphasizes that the WPP has to generate enough income to guarantee investors, or the banks that give credit, will get their money back and a decent return on their investments. In order to achieve good financial analysis, it is vital to ascertain the amount of electric power the WPP would produce at the chosen site. In this study, the calculation reviews that more than $3,860.61kWh$ of electric units would be produced in Mpepo. The knowledge of the amount of energy likely to be generated sets the basis for estimating the possible revenues to be collected.

5.3.1 Investment Cost

As indicated in unit 4.3.1, the investment cost for the power plant included the cost of equipment, cost of transportation and insurance, and the cost of installation. The investment costs all the cases studied, i.e., WPP without ESS, WPP-HFC and WPP-BES, are huge especially on consideration that the power plants are to be installed in the rural areas where the economic activities are arguably low to support the desired returns on investment. However, an attempt was made to calculate the returns on investment using the present value method.

5.3.2 Project Revenues

The basic income for a wind power installation is the revenue derived from selling the electric power. In most instances, the power generated in Zambia is off-taken by ZESCO through a power purchase agreement signed with the company producing the power. Nevertheless, that is the route this study tried to by-pass by proposing power supply through mini-grids for rural electrification where the power generated from the WPP would be distributed to the community using a standalone mini-grid system. In view of that, this study determined the cost of producing a kilowatt-hour from both the WPP with BES and WPP with HFC systems.

The levelised cost of producing a kilowatt-hour in the WPP with BES system was determined to be in the range of $0.7/kWh to $0.16/kWh for the WPP various systems. With a 15% profit margin mark up on the levelised cost, the proposed tariffs for the WPP systems ranged between $0.9/kWh to $0.17/kWh. Based on ZESCO's tariffs, revised in October 2019, the expected annual revenues from all the power plant systems was $ 131,665.53 in the first financial year with the WPP-HFC having a possibility of additional revenue from the sale of hydrogen gas.

There are also some special bonuses for wind-generated power that emanate from ambitions to support the development of renewable energy sources and reduction of greenhouse gas (GHG) emissions that harm the environment and cost external costs to the society through the Clean Development Mechanism (CDM) – not accounted in this study.

5.3.3 Project Financial Analysis

In this study, a financial analysis was also conducted with the aid of the Excel spreadsheet based on the cash flow approach. According to Joshua (2011), a cash flow analysis is a good method for calculating the financial results year by year. It shows the flow of cash during the economic lifetime of the WPP. For the purpose of this study, the input data were the power production capacity, proposed tariff, investment cost, amortization, operation and maintenance cost and interest rates.

As presented in unit 4.3.3, the results of the financial projection for the project options were arguably not favourable. With the exception of the WPP without ESS, the levelised costs of installing the power plant with an energy storage system seemed to be high. In addition, IRRs of 11% and below do not point to favourable returns on investment.

Given to choose from the available options, the WPP without ESS offered a cheaper option than the WPP-HFC and WPP-BES systems. However, on the basis of reliability of power supply - considering that power from wind would be intermittent, the WPP-BES system would stand out to be more reliable than the WPP without ESS and, would also provide a least cost option compared to WPP-HFC.

5.3.4 Comparison of Wind Power Plant Investment Cost against Cost of Grid Extension

In a bid to establish the least cost approach for delivering power to the rural communities in Zambia, a comparison of the investment costs associated to the standalone mini-grid for WPP with an energy storage system was made against the cost of extending the national grid. As reported by the REA (2017), the cost of extending the grid is usually high, and hence it would make more business sense to set up an isolated grid for power supply to communities that are located far from the national grid.

In 2018, for instance, REA commissioned the Dimbwe Grid Extension project (GEP) in Kalomo District in Southern Province implemented at a cost of $ 0.49 million covering a total distance of 27 Km. Based on these parameters, it implies that extending the grid would cost about $ 18,244.85 per kilometer. Based on international standards, a medium voltage grid extension project would cost between $10,000 and $15,000. As provided in table 13, using an average figure as a unit cost, the cost of extending the grid to Mpepo Chiefdom which is 111Km from the connecting point would be $ 1,387,500.00.

In comparison with setting up a WPP-HFC system and a standalone power distribution system, grid extension would cost more by 3% and more than 30% compared to the WPP-BES. In this regard, the least cost option would be to install a standalone WPP-BES system in Mpepo chiefdom.

Generally, it was estimated that for rural areas located less than 74 Km from the national grid, the grid extension technology would be more cost effective while for project areas located more than 74Km from the national, the WPP-BES would offer a least cost option.

Table 12: Project Investment Cost Comparisons

Project Investment Options	Project Investment Cost ($)	Savings from Grid Extension ($)	Percentage Savings	Project Breakeven Distance (Km)
Grid Extension	1,387,500.00	0	0%	0
Wind Turbine Plant with HFC	1,346,831.68	40,668.32	3%	108
Wind Turbine Plant with BES	925,516.45	461,983.55	33%	74

5.3.5 Least Cost Project Option

As established from the financial analysis in this study, to attain universal electricity access in some rural areas, the least cost of investment would be realised through investing in the standalone mini-grids as opposed to the grid extension. This would especially be true for communities located far from the national grid. For communities which are in the higher wind speed zones ($4.0m/s$ and above), and located more than 74Km from the point of connection to the national grid, it would be more financially feasible to electrify the community with a standalone WPP-BES instead of extending the grid.

It is understood that the type of ESS employed in the power generation system affects the cost of investment. In that view, for the two ESS considered in this study, the BES system provides a least investment cost as compared to the HFC system.

5.3.6 Project Cost Recovery

This research study also estimated that tariffs for the project cost recovery of $12 cents and $17 cents for the WPP-BES and WPP-HFC respectively. These tariffs are sufficient enough to payback the project costs in a period of about 8 to 14 years. However, these tariffs are higher than the ZESCO's average electricity tariff as approved by the ERB ($ 9 cents) for domestic consumers. This implies that the tariffs would be in short fall of $3 cents to $8 cents for the WPP with ESS.

To effectively address the challenges that rural communities in Zambia are facing and improve the lives of low-income people, the government through the Rural Electrification Authority, needs to modernize their operations, re-fashion their use of capital, and deepen their engagement in collaboration to achieve collective impact, through the application of the smart subsidy. It is believed that as governments move to direct resources to their most effective use, the concept of "smart subsidy," provides a useful lens for community development.

In the realm of more innovative renewable energy generation technologies like WPP, REA would be expected to create sustainable models for utilizing public resources which should be directed towards covering the cost of electricity above the normal ZESCO tariff to alleviate the burden of paying the electricity for the people in the rural communities. As reported in the Living Condition Survey (2015), this comes with the understanding that most people in the rural communities do not have the ability to pay for the power and may not be willing to pay such a high tariff.

As Joshua (2011) emphasizes, in the absence of smart subsidy, community development efforts would fall short of their potential and may not produce needed results for low-income people. In addition, there would be need for deliberate policies and programs to promote and support productive use of power to enable users to have disposable income to pay for the electricity.

5.4 Conclusion

The current chapter has provided a detailed analysis on the findings of the research. The following chapter provides the conclusions drawn from this study and provides the recommendations on the measures that should be taken to help Zambia to successfully harness wind resource for power generation in rural communities.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.1 Introduction

This chapter presents the conclusion drawn from the study regarding the viability of setting up and operating wind power plants in some rural communities in Zambia. The chapter aims to sum up the analysis of the findings obtained on the technical and financial feasibility for installing the wind power generation system with standalone mini-grid power distribution system in rural areas as an alternative to the traditional grid extension. The chapter also provides recommendations to various energy stakeholders who are involved in rural electrification campaigns. The study also intends to aid stakeholder in making informed decisions based on the technical and financial model developed as part of this work.

6.2 Conclusion

To complement the increased emphasis on renewable energy projects as a quick-win solution to the low access to electricity in Zambia, especially in the rural communities, this study has provided the basis for the rural electrification implementing agencies to evaluate and consider wind projects for power development. It is understood that the success of a wind power project depends on the technical selection of the WPP and the site where it should be installed to realise maximum power output.

Technically, the results obtained from this study revealed that some parts of Zambia receive high wind speeds enough to extract power for rural communities' consumption. Furthermore, the study indicates that small WPP with power distribution through the standalone mini-grid system would be technically viable in some rural areas in Zambia. Consideration of the technical specifications of the WPP indicates that small wind power generation system would generate capacities appropriate for rural electrification.

On the financial basis, analysis of this study estimated that tariffs for the project cost recovery of $12 cents and $17 cents for the WPP-BES and WPP-HFC respectively. These tariffs would sufficiently sustain a payback on the project investment costs in a period ranging between 8 to 14 years. Nevertheless, these tariffs are higher than the ZESCO's average tariff for domestic electricity consumption. This entails a viability gap of $3 cents to $8 cents for the WPP with ESS to make business sense and, hence be attractive to the private investors and money lending institutions. Based on the Living Conditions Monitoring Survey, conducted in 2015, most people in the rural communities may not have the ability to pay for the power and may not be willing to pay tariffs as high as proposed.

On comparison terms, the WPP without ESS would offer a cheaper option than the WPP-HFC and WPP-BES systems. However, on account of reliable and stable supply of electricity, the WPP-BES system would to be more reliable than the WPP without ESS and, would also provide a least cost option compared to WPP-HFC, financially.

The study reviewed that for communities experiencing winds speed as low as $4.0 m/s$ and above, and located more than 74Km from the point of connection to the national grid, it would be more financially feasible to electrify the community with a standalone WPP-BES instead of extending the grid.

Considering the coverage, it is expected that this research work would serve as the basis to be used by various stakeholders, from both the public and private sectors who are involved in rural electrification, to make informed decisions regarding investment in the wind power technology space. In addition, this research work has set out the basis for further research campaign on other critical issues surrounding wind power development in Zambia.

6.3 Recommendations

This study recommends the deployment of wind mini-grid with energy storage systems for power generation and supply to some rural communities in Zambia. Based on the technical viability and cost implications, the study places more emphasis on development of WPP-BES as a considerable least cost option for rural electrification.

In order to promote wind power technology utilisation for power in Zambia and create space for the technology to be used alternatively for rural electrification in areas which are located far from the national grid, the following measures should be put in place:

1. There is need to conduct a national-wide wind resource mapping in order to ascertain the wind potential in the country at various heights from 50m and above.
2. The government should provide a policy direction towards wind power development and create an enabling environment for the technology in the country.
3. The government, through REA, should work towards promoting investments in the mini-grids for different power generation technologies.

4. REA should consider drawing up a clear subsidy mechanism for renewable energy sources which can cover up the viability gap between the tariff acceptable to the rural communities and the one profitable to the power producers.
5. The government, through the Department of Energy and the Office for Promoting Private Power Investment, should consider carrying out feasibility studies for wind projects. This should be with the intensions to come up with bankable projects in stand-alone wind power generation projects.
6. To ensure efficient operation of the wind power generation systems in the country, Learning Institutions should integrate wind power technology in the curriculum, especially at technician level.
7. In order to promote investments in wind power for rural electrification, the government through the Ministry of Energy, should consider putting in place certain incentives specific for stand-alone wind power systems.
8. Furthermore, since the WPP technology is new in the country, there would be need to gather as much information as possible and, calls for more research works in wind power development.

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Appendix 1A: Cash Flow Analysis

WIND TURBINE POWER PLANT WITHOUT ENERGY STORAGE SYSTEM

Financial Year		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Investment Cost (USD)	**593,249**											
Armotisation Amount (USD)	**57,155**											
Revenue (USD)												
Electricity Sales		131,666	141,409	151,873	163,112	175,182	188,145	202,068	217,021	233,081	250,329	268,853
Less												
Operation Cost		24,000	25,776	27,683	29,732	31,932	34,295	36,833	39,559	42,486	45,630	49,007
Maintenance Cost		9,973	10,711	11,504	12,355	13,269	14,251	15,306	16,438	17,655	18,961	20,364
Net Cashflow (USD)		**97,693**	**104,922**	**112,686**	**121,025**	**129,981**	**139,599**	**149,930**	**161,024**	**172,940**	**185,738**	**199,482**
(1+r)^t		1	1	1	1	1	1	2	2	2	2	2
Present Value (USD)		**97,693**	**97,150**	**96,610**	**96,073**	**95,540**	**95,009**	**94,481**	**93,956**	**93,434**	**92,915**	**92,399**
Net Present Value (USD)	1,045,260											
Payback Period	6											
Internal Rate of Return	11											
Installed Cost (USD/kW)	2,617											
Levelised Cost (USD/kWh)	0.08											
Proposed Tariff (USD/kWh)	0.09											

WIND TURBINE POWER PLANT WITH BATTERY ENERGY STORAGE SYSTEM

Financial Year		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Investment Cost (USD)	**925,516**											
Armotisation Amount (USD)	**89,166**											
Revenue (USD)												
Electricity Sales		131,666	141,409	151,873	163,112	175,182	188,145	202,068	217,021	233,081	250,329	268,853
Less												
Operation Cost		24,000	25,776	27,683	29,732	31,932	34,295	36,833	39,559	42,486	45,630	49,007
Maintenance Cost		9,973	10,711	11,504	12,355	13,269	14,251	15,306	16,438	17,655	18,961	20,364
Net Cashflow (USD)		**97,693**	**104,922**	**112,686**	**121,025**	**129,981**	**139,599**	**149,930**	**161,024**	**172,940**	**185,738**	**199,482**
(1+r)^t		1	1	1	1	1	1	2	2	2	2	2
Present Value (USD)		**97,693**	**97,150**	**96,610**	**96,073**	**95,540**	**95,009**	**94,481**	**93,956**	**93,434**	**92,915**	**92,399**
Net Present Value (USD)	1,045,260											
Payback Period	9											
Internal Rate of Return	2											
Installed Cost (USD/kW)	4,083											
Levelised Cost (USD/kWh)	0.11											
Proposed Tariff (USD/kWh)	0.13											

WIND POWER PLANT WITH FUEL CELL ENERGY STORAGE SYSTEM

Financial Year		**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Investment Cost (USD)	**1,346,832**											
Armotisation Amount (USD)	**129,757**											
Revenue (USD)												
Electricity Sales		131,666	141,409	151,873	163,112	175,182	188,145	202,068	217,021	233,081	250,329	268,853
Hydrogen Sales		1	1	1	1	1	1	1	2	2	2	2
Total Revenue		**131,666**	**141,410**	**151,874**	**163,113**	**175,183**	**188,147**	**202,070**	**217,023**	**233,082**	**250,331**	**268,855**
Less												
Operation Cost		24,000	25,776	27,683	29,732	31,932	34,295	36,833	39,559	42,486	45,630	49,007
Maintenance Cost		9,973	10,711	11,504	12,355	13,269	14,251	15,306	16,438	17,655	18,961	20,364
Net Cashflow (USD)		**97,694**	**104,923**	**112,687**	**121,026**	**129,982**	**139,601**	**149,931**	**161,026**	**172,942**	**185,740**	**199,484**
(1+r)^t		1	1	1	1	1	1	2	2	2	2	2
Present Value (USD)		**97,694**	**97,151**	**96,611**	**96,074**	**95,541**	**95,010**	**94,482**	**93,957**	**93,435**	**92,916**	**92,400**
Net Present Value (USD)	1,045,271											
Payback Period	14											
Internal Rate of Return	-0.04											
Installed Cost (USD/kW)	4,635											
Levelised Cost (USD/kWh)	0.15											
Proposed Tariff (USD/kWh)	0.17											

Appendix 1B: Assumptions and Parameters used

GENERAL INFORMATION			
Average Room Temp	21.3	ºC	
Air Density at 1Bar, 21.3ºC	1.225	Kg/m3	
Population	1289		
Households	258		
Power Coefficient	0.26		
Generator efficiency	0.92		
Wind Turbine Power Output	95.0	Kw	
Average Wind Speed	5.5	m/s	
Capacity Factor	0.6		
Loss Factor	0.25		
Population Growth Rate	2.8%		
Power Factor	0.9		
Load Expansion Factor	0.2		
Inverter Efficiency	0.8		
Required Backup period	18	hours (6hr per day for 3 days)	
Battery Bank Voltage	48	Volts	
Battery Efficiency	0.9		
Wire Loss Factor	0.2		
Depth of Discharge (DOD)	0.8		
Battery Operating Temp	46		
Battery Capacity	100	Kwh	
Inverter Capacity	60	Kva	
Fuel Cell Power Output	5	Kw	
Rate of Electrolysis	0.00472	m^3/kWh	At 60% efficiency at stored as liquid
Rate of Electricity Generation	1.6	kWh/m^3	
Hydrogen Output	0.018	m^3/hr	
Time of Hydrogen Generation	180	Hr	6hrs per day for 30 days
Rate of Hydrogen Consumption	0.0011	m^3/hr	For the 5kW Fuel Cell
Battery Life	10	Years	Source: IRENA, 2017
Service Life for Fuel Cells	17	Years	
Project Life	20	Years	
COST INFORMATION	**USD**		**ADDITIONAL INFORMATION**

Total Installed Cost of Wind Project	2,200	USD/Kw	Source: IRENA, 2017
Battery	210	USD/kWh	Lithium ion (cobalt type). Source IRENA, 2017
DC/AC Inverter	240	USD/Kw	
Water Electrolyser	6,370	USD/Unit	
Hydrogen storage tanks	5,000	USD/m^3	50m^3
Number of Hydrogen storage tanks	2		
Fuel Cell	12,500.00	USD/Unit	
Cost of Acquiring Land	0.05	USD/m^2	
Land Requirement	100,000	m^2	
Cost per connection	235	USD/connection	Source: USAID, Inensus mini-grid, Senegal
Number of connections	258		
Maintenance Cost	2%		of the Installed Cost
Cost of Extending the Grid	12,500.00	USD/Km	
Distance from Mpepo to the Grid	111.00	Km	
Installed cost PEM fuel cell	476.28	USD/Kw	EUR 420, exchange rate 1.134 as at 6/6/2020: source; IRENA
FINANCIAL RATES			
Standard Inflation rate	7.4%		
Nominal rate	8%		
Standard Discount rate	10%		
Exchange Rate USD to ZMK	10		As at 26/07/2018
Interest rate	5%		
OPERATION COSTS			
Salary for 1 Engineer and 3 Technicians	22200		USD/Annum
Running Expenses	1800		USD/Annum
REVENUES			
Proposed Electricity Tariff (WPP-BES)	0.13	USD/kWh	
Proposed Electricity Tariff (WPP-HFC)	0.17	USD/kWh	
Hydrogen gas unit sale price	0.03	USD/m^3	
ZESCO Tariff	0.09	USD/kwh	