The Wind-Hydro Energy Mix: A Case Study for Zambia

By

Brian Sinkala Mainza

A dissertation submitted to The University of Zambia in
Partial fulfillment of the requirements for A Master's Degree in Renewable Energy Engineering

THE UNIVERSITY OF ZAMBIA

LUSAKA

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DECLARATION

I, Brian Sinkala Mainza, do declare that this work is my own and that the work of other persons utilized in this dissertation has been duly acknowledged. This work presented here has not been previously presented at this or any other university for similar purposes.

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

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(Candidate)

We the undersigned have read this dissertation and have approved it for examination.

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Date……………………..………………………………………………

APPROVAL

This dissertation by Brian Sinkala Mainza is in partial fulfillment of the requirements for the award of the Master of Renewable Energy Engineering by The University of Zambia.

Examiners

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ABSTRACT

The aim of this research is to examine the wind-hydro energy mix by analyzing the characteristics of wind energy variation in a year and that of hydro. The research uses the calculated values of wind power from the wind speeds recorded at 80m above the ground and the values of the actual generated hydropower for seven years. The useful information used is for the monthly wind speeds in a year and the monthly hydro production profile in a year. The profiles are compared in the wet and dry seasons of the year in Zambia as the seasons are directly related to water levels in water reservoirs and hence hydro power production.

The wet season is a regular period of the year when there is prolonged rainfall while the dry season is a prolonged period of continuous dry weather. The information about the wind speeds for power generation where obtained from the recently completed wind resource mapping in Zambia.

The research found that the annual wind generation potential is at the minimum in the rainy season and maximum in the dry season and the daily wind energy production potential is at the maximum in the night when demand is at the minimum and vice versa. In the same vein, the annual hydro generation potential is the maximum during the rainy season and minimum during the dry season. This is because of the increase in the water levels in river, lakes and dams, which are the source of the water for power generation. Since wind is highest when hydro is lowest and vice-versa, wind energy can be used to complement hydropower to avert power shortages that occur during the dry season.

Another aspect is that there is a difference in the relationship between the wind and large hydro as well as the wind and mini hydropower. The power generation from large hydro power plants is not necessarily low in any season except for the month of February in all the past seven years. This is because of the large dams in which water is stored and it is release in a regulated manner. Mini hydro's however use weirs and run off rivers which are highly affected by water levels. The difference in the power generation over the seasons therefore is significantly visible in the mini-hydro power stations. The wind-hydro complementarity is therefore more applicable with mini hydropower. Most of the mini hydro power stations are in the Northern region of Zambia and the wind regime in the region is viable for power production. Therefore, there is need to consider the wind-hydro energy mix to reduce the seasonal power reductions which causes power outages in the country. From the average power produced from mini-hydro stations for seven years, the total maximum deficit during the year is 48%. The recommendation is that the installed capacity of wind in a network fed by mini-hydro power should be at least 48% of the total mini-hydro generation to cater for the reduction.

Key words: Wind, hydro, energy, power

DEDICATION

I dedicate this research work to my family for the inspiration and my late mother who build in me a disciplined child, and never compromised on my education.

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It is indeed my sincere opportunity to render my gratitude and appreciation to my supervisor, Professor Francis Yamba whose guidance and supervision helped me in my research work. His insistence on perfection helped me dig deeper in the search of ideas and information.

I would like to further thank, the University of Zambia and the School of Engineering for granting me the opportunity to do research and interact with very knowledgeable individuals in the area of renewable energy engineering.

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LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

ABBREVIATIONS

kW	Kilowatt
kWh	Kilowatt-hour
MW	Megawatt
MWh	Megawatt hour
VSWT	Variable Speed Wind Turbine
PSHP	Pumped Storage Hydro Plant
ZMD	Zambia Meteorological Department
MOE	Ministry of Energy
DOE	Department of Energy
ERB	Energy Regulation Board

TABLE OF CONTENTS

CHAPTER ONE

1.0. INTRODUCTION

1.1. Background

Zambia's source of electricity is predominantly hydro generated power. By convention in Zambia, hydropower of capacity less than 20MW is considered renewable energy while capacities greater than 20MW are considered non-renewable energy for ease of operation in project formulation and implementation (REFiT, 2017). This is mainly because of the amount of infrastructure and disturbance to the environment that big hydro causes as compared to small hydro. Other renewable energy resources available for exploitation are solar, wind, bioenergy and geothermal. Renewable energy is the energy from an energy resource that is replaced rapidly by natural processes such as energy generated from the sun or from wind. Most renewable forms of energy, other than geothermal and tidal power, ultimately come from the Sun.

The share of renewable energy in the Zambia's national energy mix is negligible and government has been making efforts to promote it so that it complements with hydro power to avert the effects of climate change. The challenge with the promotion of renewable energy is that besides other factors such as the intermittence of renewable energy, the 6000MW potential of hydro power in Zambia has only been exploited halfway. In addition, hydro power is stable and does not disturb grid stability. The penetration of renewable energy has therefore been a challenge regardless of hydro being susceptible to climate change. With Zambia having about 40% of the water resources in Southern Africa, hydro power appears to be the easiest option among the choices of the sources of power.

The National Energy Policy of 2008 recognizes renewable energy as a key source of energy that can be utilized besides other energy sources (NEP2008). Solar energy is largely used by people in rural areas to light small lamps and charge phones especially in areas where there is no electricity grid. In the recent past however, there has been increased interest to invest in the solar resource by established solar energy company. The Rural Electrification Authority took the first step by constructing a 60 kWp, off grid solar power plant in 2012 and there are several private off grid solar power plants which have been constructed since then.

The momentum for solar power plants gained even more momentum at the height of a power shortage in the 2015/2016 rainy season in which poor rains and the consequent low water reserves were recorded. The country was subjected to load shedding of up to 8 hours for residential customers. Industries were also heavily affected to an extent of reducing production and this had a negative effect on the economy. At this point, there was a recognition that hydropower is susceptible to climate change and it is risky to be sorely dependent on it. There was need therefore to diversify the energy mix to include renewable energy sources which are climate change resilient.

There has been a direct response from the government to have programmes to spearhead the growth of renewable energy in the Country. These efforts are being coordinated through programmers structured as Special Purpose Vehicles (SPV) to drive the agenda. Some of the SPVs being used by the government are the Scaling Solar Project with target of 600MW which is being implemented in rounds, and the Renewable Energy Feed in Tariff (REFiT) with a total target of 200MW, of which 120MW is from solar and the rest from mini hydro. Scaling solar programme has so far achieved the installation of 88 MW (54MW and 34MW) on-grid solar power plants.

Other programmes being implemented to promote renewable energy are the Renewable Energy Resource Mapping Project, the Scaling-Up Renewable Energy Project (SREP) and the Sustainable Energy for All (SE4ALL). Due to its ease of deployment as compared to other renewable energy sources, solar has attracted so many potential developers while other renewable energy sources have remained untapped. Wind energy for example has not received as much attention and yet it has a potential for exploitation in the country, has less land requirements and other advantages. In addition, the cost of wind energy deployment is reducing on the international market. Through the Resource Mapping Project, the Ministry of Energy has information on the wind speeds available for power generation. Hydro being the predominant source of electricity in Zambia, any renewable energy resource will supplement hydropower generation and a renewable energy source, which both supplements and complements hydro, is ideal for the seasonal nature of power generation. The indicative figures of the wind speed variation are that the wind speeds are high during the dry season and low during the rainy season. The implication therefore is that wind energy could be the best compliment for hydropower. It must be noted that the research uses power produced by the two sources to indicate their characteristic behavior over the same period of time which is the same trend when the same analysis is dealt with in energy values as power is energy with respect to time of which has been defined in terms of the year. Therefore, the title is energy mix even when the units of values used are watts.

Wind energy is one of the most important energy sources, which have remained untapped in Zambia. The common use of the wind energy resource in Zambia is mainly for water pumping and advertising using boards made in the Savonious turbine form.

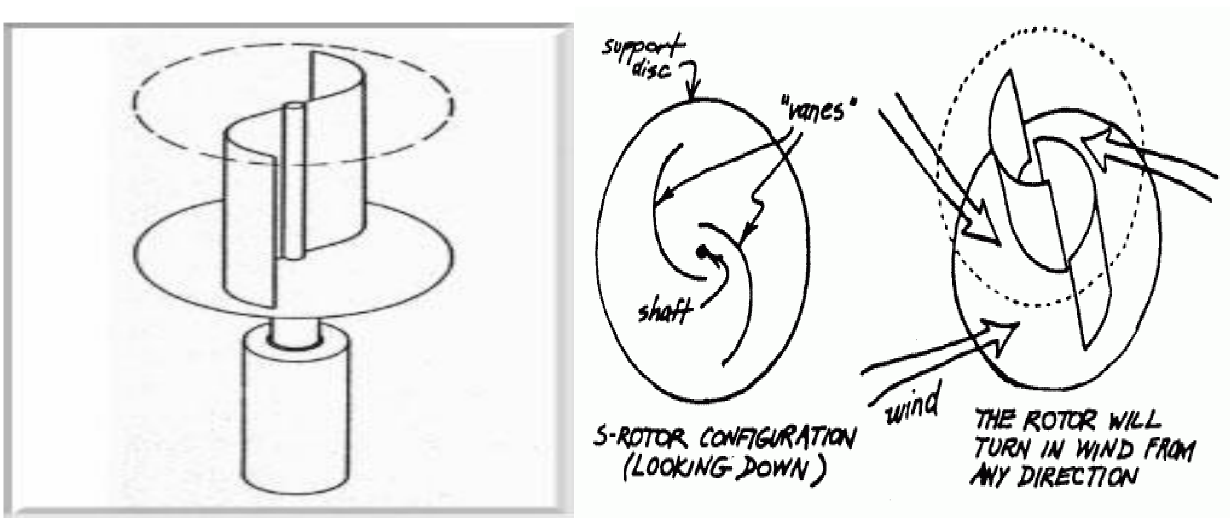


Figure 1. 1 Savonious Turbines

Currently, there is no wind energy being used for electricity generation largely because there has been a lack of information on the prevailing wind speeds, which could be used for power generation. The information that has been available from the Zambia Meteorological Department (ZMD) for a long time is the wind speed of 3m/s maximum at an elevation of 10m. This information is mainly used for weather forecasting (ZMD).

The wind energy data which is used for power generation is collected at site specific locations of higher heights and over a period of two years or more (MEASNET, 2009 P. 29). This is to ensure the data collected is consistent and can be used to project power outputs throughout the year and to observe whether it's consistent and not showing drastic variations between the two years. The data collection also helps to give an indication of the wind energy hot spots. Among other reasons such as our abundant hydro potential, the lack of information about wind speeds at high heights has contributed to less interest by developers in exploiting wind energy (MoE, 2016). Investors in renewable energy have focused on solar where a feasibility study to assess the available resource is not as costly as in the case of wind. The Zambian government therefore saw the need to assess the availability of the wind resources in the Country for electricity generation to promote investment in other renewable energies apart from solar.

The collection of valuable information on the wind speeds for power generation, focusing on wind energy hot spots and other factors that affect wind speeds is called the Wind Resource Mapping. The World Bank, in liaison with the Department of Energy, engaged a Consultant to conduct the resource mapping exercise. Using a multi-criteria analysis specifically tailored to Zambia, eight (08) potential sites for installation of wind measuring masts were selected. The sites were selected with a view of providing maximum potential for improved accuracy of mesoscale mapping. The mesoscale map for the wind regime was obtained from satellite data to give a brief outline of the expected situation at the end of the project. The wind masts were installed in Chisamba, Choma, Petauke, Lundazi, Choma, Mwinilunga, Mpika and Nakonde. This was representative of the sites with potential high wind speeds (ESMAP Report, 2017).

As stated in the introduction, almost all the electricity generated in Zambia is hydro. To effectively achieve the energy mix which may ensure energy security, the energy mix of hydro and any other renewable energy resource must be carefully investigated. The wind–hydro energy mix is one that has a potential of assisting the country to achieve the required national energy mix to avoid power outages in the dry season where the water for power generation is being rationed so that there is adequate supply of power throughout the year.

Zambia would do well to emulate the rest of the world in exploiting wind energy to produce power. As of the end of 2016, the worldwide total cumulative installed electricity generation capacity from wind power amounted to 486,790 MW, an increase of 12.5% compared to the previous year. Installations increased by 54,642 MW, 63,330 MW, 51,675 MW and 36,023 MW in 2016, 2015, 2014 and 2013 respectively. Since 2010 more than half of all new wind power was added outside the traditional markets of Europe and North America, mainly driven by the continuing boom in China and India. At the end of 2015, China had 145 GW of wind power installed. In 2015, China installed close to half the world's added wind power capacity. Several countries have achieved relatively high levels of wind power penetration, such as 39% of stationary electricity production in Denmark,18% in Portugal, 16% in Spain, 14% in Ireland and 9% in Germany in 2010. As of 2011, 83 countries around the world are using wind power on a commercial basis. Wind power's share of worldwide electricity usage at the end of 2014 was 3.1 % (Global Wind Report, 2016).

The global positive trends and developments in wind energy are encouraging and Zambia must endeavor to have wind energy installed to increase capacity of renewable energy. In addition, wind energy is comparatively cheaper to other renewable energy sources and has less land requirement per megawatt as compared to solar.

1.2. The Problem Statement

In Zambia, there is significant seasonal reduction in power generation. Since power production is predominantly hydro, the power production usually reduces during the dry season and increases in the wet season. The power reduction is dire for drought-hit years. There is need for an energy mix to reduce the seasonal variations in the annual energy production. Considering that wind speeds have seasonal characteristics, there is need to establish if there is a unique relationship from empirical data between the two sources of energy. The inter-relationship, if any, has the potential to assist in alleviating power deficits in certain parts of the year due to reduced generation.

It can also give a basis on which priorities can be set to exploit wind energy resource for development in the national power development agenda.

1.3. Significance of Study

The study of the wind-hydro energy mix is important to Zambia in order to determine the complementarity of the wind and small hydro energy sources and how they can assist reduce the variability of annual energy supply. The two sources of energy under consideration are seasonal in nature and pose a challenge of energy extraction when they are not in the required quantity. The river flows and depth significantly reduce in the dry season as compared to the rainy season while the wind speeds vary at different time of the year. Considering that Zambia is predominantly hydro, there is a reduction in the power production and hence supply in the later parts of the dry season. This is worse in places which are supplied by mini hydro's and the effect of low water levels is more significant. The wind speeds however are high in times of low water levels for power production. This shows that the two sources of energy may be complementary and can assist reduces power shortages in the certain parts of the year and reduce the variability of the annual power production curves.

The study also helps us understand the areas which should be of our concern in terms of the effects of power deficits at certain times of the year so that there is a consideration in terms priority areas. The study can also assist to set a basis for setting priorities of the renewable energy sources for implementation adding other factors of consideration such as the cost and ease of exploitation.

Some studies in other countries show that the optimization process of wind and hydro has a potential of improving the total power standard deviation from the worst by over 61%. Scholars have stated that there are benefits of appropriately joining the two sources and suggest investing in two sources if there are seasonal challenges of access to power (Rosa, 2017).

As the global concern about environmental care increases, countries are led to seek sustainable growth in their economies, for it is a widely acknowledged fact that the use of renewable energy sources plays an important role in this process. Indeed, these sources are the fastest-growing ones in the electricity sector in the World, with expectations of a 2.9% per year increase between 2012 and 2040.

This study is therefore signification as it seeks a solution to power deficit at certain time of the year, guarantee power security and create a robust and resilient energy sector in Zambia.

1.4. Thesis Statement

The basis of this research is to come up with information on the wind- hydro energy mix that has a potential to ensure sustainable and adequate energy supply throughout the year especially in years when the rains are not enough. Now, there has never been any power generating plant that uses wind as an energy source but there have been lately attempts by some foreign companies trying to invest in wind power projects. Unfortunately, there has been a challenge with feasibility studies as the data collection is difficult without having to install masts with enough height to record faster winds. However, the resource mapping exercise to collect wind speeds was recently finalized and it is the source of the valuable information that will be used in this research. This research is therefore important in providing information that can be used for planning and prioritizing renewable energy sources.

The section of the analysis of the relationship between wind energy and hydro is essential because Zambia is currently reliant on hydropower and an appropriate energy mix is important to guarantee energy security. Further, seasons and the time of day have a direct effect on the wind speed and it is the reason why in rainy seasons, where hydro generation reaches peak, and the dry season, where hydro is low must have a relation with changes in the wind regime which can be important to document.

1.5. Objectives of the Research

General Objectives

The general objectives of this research proposal on the wind-hydro resource in Zambia is:

To determine the annual hydropower production profile and the potential annual wind power production profile in order to analyses their variation for all seasons of the year. The purpose is to understand if the two energy sources can complement each other in order to eliminate seasonal power reduction and hence deficit.

Specific Objectives

The specific objectives of the research are as follows:

i. To analyze the annual energy variation of small and large hydropower production in order to compare its characteristic behavior across seasons of the year.
ii. To assess the seasons of minimum and maximum power production of the small and large hydropower.
iii. To understand the whole process that is done in collecting wind energy data. That is from the site assessments to the installation of the wind masts and the data collection.
iv. To calculate the potential energy production from wind energy recorded at all the eight wind masts under the Zambia Wind Resource Mapping project at 80m heights.
v. To pair the potential wind farms in certain areas with mini hydro stations in those areas for possible complement.

vi. To propose a way of facilitating the utilization of wind energy to increase energy access: The information gathered from this research has the potential to set a basis for prioritization of wind energy resource for utilization in Zambia to complement hydropower that is a dominant source of power now.

1.7. Research Questions

i. What are the annual hydro and wind energy production profiles?
ii. What the prevailing wind regime in Zambia?
iii. What are the hotspots which can be recommended for wind energy development?
iv. How does the total hydro energy generation in Zambia change during the year?
v. How does the wind energy regime relate to hydropower in Zambia?
vi. Can the wind-hydro energy mix be the best energy mix in Zambia?
vii. What are the conclusions about the wind energy potential in Zambia?

CHAPTER TWO

2.0. LITERATURE REVIEW

2.1. Introduction

The Wind-Hydro energy mix or complement has not been done before in Zambia both in terms of study and implementation. This is because, except for water pumping, wind has never been exploited for power generation and the Country's source of power has been hydro as stated in preceding chapters. The information therefore on the hybrid of the two sources of power is not available for Zambia particularly and the material which will be relied on regarding the mix is that from other countries who have done research on the subject. However, there is data on the wind regime at lower heights and hydro for Zambia treated as separate sources of energy. Zambia has the largest number of rivers in Southern Africa and there is enough information on the hydrology of the Country. The literature reviewed below is therefore in four parts: The desirable wind speeds for power generation, the wind-hydro energy mix from other countries, the wind energy and the hydrology for Zambia.

2.2. Wind-Hydro Power Complementarity in Brazil

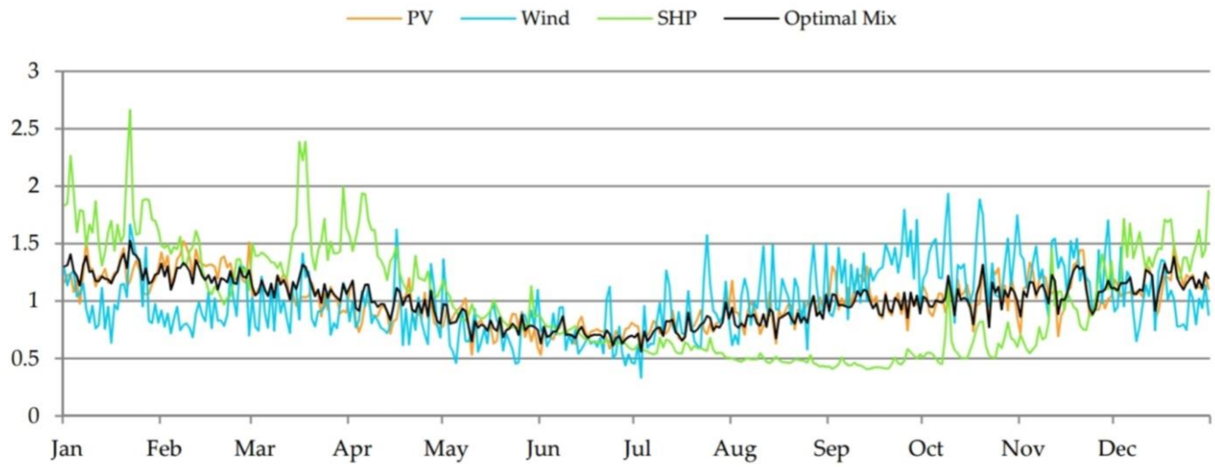
Brazil is one of the Countries, which have studied the complement of wind and hydropower. A research paper done in 2008 evaluated the long-term incentive program for wind power in Brazil by applying the GIS model to the available wind data base as a criterion of optimizing the operation of Brazil's hydropower reservoirs. They found that the optimization of the operation of the power system be conducted through a wind-hydro complementary, with a focus on the northeast of Brazil. The paper further states that it is noteworthy that the São Francisco River is the most important resource of electricity generation to the northeast of Brazil, and the largest wind speeds occur exactly when the flow of water of São Francisco River is at a low level (Costa, 2017).

According to specific targets and criterion, the wind power development in Brazil should related to the advantages of this technology to the country´s electric power system. Thus, a new incentive policy should focus on the reason for promoting wind power considering the country´s context. The wind-hydro complementarity is a very important natural phenomena present in some regions of Brazil. In this context, the wind power can provide an interesting power manager between two renewable sources.

In order to present the wind-hydro complementarity phenomena in Brazil, particularly at the northeast region, the article was divided into the following next sections. Section 1 presented the Brazilian wind potential and how wind- hydro complementarity can be observed at the northeast region. Sections 2 processed the Brazilian wind database under GIS tools to size and locate the northeast region potential and evaluate the electricity that could be generated from wind- hydro complementarity. Section 3 presented the results and evaluated the most suitable incentive mechanism that could be applied to boost the interconnected power system through wind-hydro complementarity and the last section, Section 4 presented the conclusion of the paper.

Though the objective of the paper was to establish the ideal wind-hydro complement as an incentive to the feed-in-tariff mechanism, one of the conclusions was that in order to optimize the hydroelectric system, the most suitable mechanism is the one that allows the continuous and reliable growth of wind power plants at the selected sites i.e., the hydro sites. The other most interesting observation is that there is a natural complement of wind and hydro in that the largest wind speeds occur exactly when the flow of water of São Francisco River is at a low level. (Sayigh, 2008).

Other literature in Brazil verified that combining hydro, PV, and wind resources in Rio de Janeiro State can reduce their daily variability by up to 61%, if compared to isolated sources. This significant reduction supports the safe insertion of renewable energy sources into the grid, in order to reduce environmental and social (health) impacts connected to traditional thermal plants; weaken the dependence on non-renewable resources; and diminish electricity generation costs. The outcome of the research was put in a graph and they indicate the variations are optimized through a mixed of the three technologies in Brazil as indicated in the Figure 2.1 (Souza, 2017).



Months of the year

Figure 11.1 Indicates the optimized mix generation throughout the year for Brazil (Souza Rosa, 2017).

The Figure 2.1 clearly shows that the wind energy (in blue), is low when the hydro in green is high in the first five months of the year**.** The power generation rather becomes the same in June and July. Thereafter, power production from wind energy becomes higher than that of hydro. The black line indicates the energy produced because of the optimization. The PV does not vary much through the year and almost passes exactly where the optimization line passes. PV therefore acted as a boost to the power generation of the two sources. The variations of the hydro production were because of the lack of the dam for the Small Hydro Power plants (SHP) which were being considered which are usually constructed on run off rivers and weirs. The complement therefore is very important for the two sources in the reduction of annual variations.

Johannes Schmidts and Rafael Cancella did similar works in Brazil in 2014 and the conclusions in terms of the combination of wind and hydro reducing the annual variations was the same. They however went further to identify that the North Eastern Winds were preferred over winds from the Southern Brazil because of its higher complementarity with hydropower resources (Schmidt's, 2014).

2.3. Hybrid Wind–hydro Power Plant Simulation Model Description

To indicate the effectiveness of the wind-hydro hybrid system, a Pump Storage Hydro Power plant (PSHP) and a Variable Speed Wind Turbine (VSWT) connected to an isolated system were modeled in MATLAB (Technical University of Madrid license) with Simulink. Frequency regulations were provided by the VSWT and the PSHP. Therefore, the simulation model included the dynamic behavior of an isolated power system, a PSHP and a VSWT.

Figure 2.2 shows the comparison of the dynamic responses of the system between the strategies in which VSWT did not contribute to the regulation, and the various other strategies of contribution in instances when a linear wind speed variation takes place.

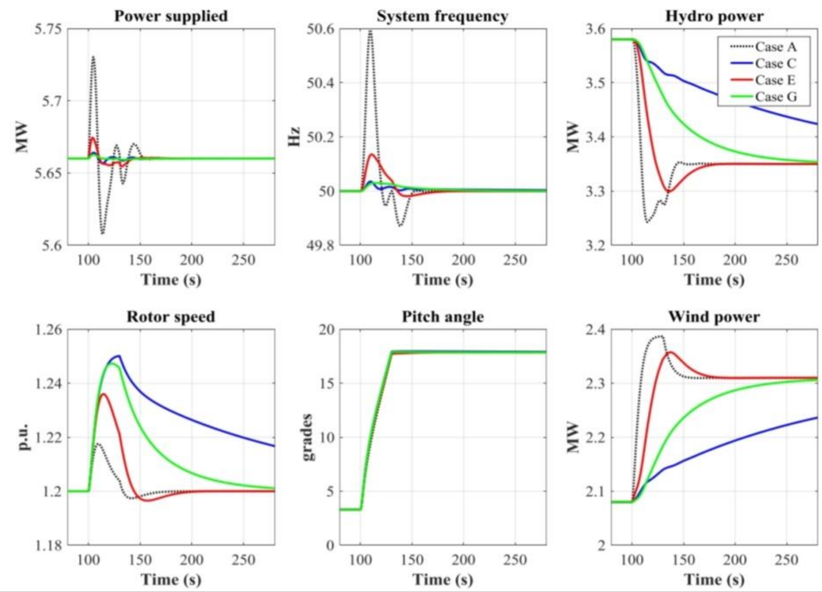


Figure 11.2 Comparison of the dynamic responses of the system between the base case and the cases in which the VSWT contributes to the regulation assuming different control strategies during a wind speed ramp.

As indicated from the simulation, there is a complement between hydro and wind energy, and they have a potential to bridge the variations of power shortages. While the seasonality aspect is not dealt with, the actual functioning of the power plant is possible with the combination of the two sources of energy. Though this is a theoretical consideration of practical challenges, simulations assist in understanding the operations of mechanical or electrical systems.

2.4. Operational Constraints and Economic Benefits of Wind-Hydro Hybrid Systems Analysis of Systems in the U.S./Canada and Russia

In a study done for the European Wind Energy Conference, in 2003, the paper stated that there is an increasing recognition of benefits from the synergy of wind-hydro, especially in cold weather climates, but little analysis has been performed to quantify the extent of these benefits. In addition, each location presents a unique set of technical and economic conditions that significantly affect results. The paper reviews current experience with such systems, and recent analysis and data that examines and quantifies potential benefits. The paper also highlights the factors that should be considered to perform a comprehensive assessment of the benefits from such systems.

An example of where the value of wind-hydro is recognized is in the Northwestern section of the United States. Despite some of the lowest power prices in the country, wind plant capacity installed in the states of Washington and Oregon has grown from less than 25 MW at the end of year 2000 to around 450 MW at the end of 2002. Decreasing wind energy prices, water shortages and growing demand for power in the region, and especially neighboring California, were factors driving this growth, along with increasing recognition that wind and waterpower, two variable resources can complement each other.

The paper highlighted, among other conclusions, that wind power plants can provide energy during critical winter months when hydro production is limited by low water flow and when electricity demand peaks in regions with extremely cold winters. It also states that there are aspects of the wind-hydro system applications that have never been quantified including: environmental benefits and constraints (fish ladders, etc.), navigation and recreational uses. In some locations, these are minor issues, but in others, they may have a significant impact on the overall system value (EWEC, 2003).

2.5. Wind, Solar and Hydro Resources for Combating Seasonal Power Shortage in Nepal

In a paper presented to the World Sustainability Forum of 2014, Professor Surendra B. Kunwar of Nepal wrote that the power generation, predominantly coming from run-of-river type hydropower plants, has fallen short of demand in Nepal. The shortage is acute during the dry post-monsoon months, when river flows are at their minimum. Huge amount of fossil fuel is used to generate power during shortages. Large hydroelectric projects are under construction, but many natural and man-made factors have delayed their construction by years. A survey of the measured wind speed, incoming solar radiation and river water discharge at various sites in Nepal has been done. Wind and solar energy potentials have been found to be high during the dry season, when hydropower generation is low. River flow, and consequently, the hydropower generation are high during the monsoon season, at which time wind speed and solar radiation are very low. With a well-planned transmission system, wind and solar power could compensate reduced generation from hydropower plants during the seasons with low water flow in rivers. In the short term, installing wind and solar energy technologies- which have short gestation periods- is observed to be the right choice. Such a power system, with wind and solar power complementing hydroelectricity, has the potential to save capital and reduce carbon emissions for Nepal.

After analysis of the wind potential through tables and graphs, the paper concluded that Nepal has been spending a huge proportion of budget on importing fossil fuel to lessen the present power deficit, and on hydropower construction to meet the future electricity needs. Yet, there are problems with both these actions. The externalities- capital and environmental- of generating power from fossil fuel are obvious. However, even hydropower plants in operation thus far have exhibited problems serious enough to hinder alleviating the power crisis of Nepal. One of those issues is the overrun of the project development and construction by years and even decades. This hints at the possibility of cost overrun as well. Thus, with such slow development of hydro projects, for at least a decade or so the power crisis will not be mitigated. This problem could be addressed by the adoption of solar and wind power technologies in suitable sites. Firstly, in several places of Nepal, it has been found that solar and wind energy resources peak when hydropower generation is very low and vice-versa. Secondly, solar and wind farms do not take decades to come into operation. They have relatively short gestation periods. It is a common practice to build wind farms with a design life of twenty years. This design life perfectly fits the power puzzle of Nepal, as experience has shown that the hydropower project of capacity 144 MW took some twenty years to complete. Thus, if a transmission system with extensive network connecting all the solar and wind energy hotspots is built, the acute power deficit in the dry season can be mitigated.

Though the paper adds solar to the energy mix, it is still related to this paper because of the wind energy complement to hydro which as stated is available when the other is not. (Kunwar’s. B, 2014)

2.6. Wind literature in Zambia

Generally, the wind energy studies done in Zambia have used information from low elevation wind masts of about 10m. At such an elevation, the wind speeds are too low to be developed for large scale electricity generation. The data that was recorded for low elevation wind speeds in 2014 and has been used in the analysis of annual wind speeds in Zambia are shown in Table 2.1 and are by region and in specific locations of were the wind masts were located.

Table 2. 1 The table shows the average wind speeds in Zambia taken by the Zambia Meteorological Department (ZMD, 2014).

No.	Station	Province	Longitude	Latitude	Average wind speed *v (m/s)*	Number of years of data collection
1	Chipata	Eastern	32.58	-13.57	4	28
2	Chipepo	Central	27.88	-16.8	5.2	2
3	Choma	Southern	27.07	-16.85	3.1	30
4	Isoka	Northern	32.63	-10.17	1.9	24
5	Kabompo	North Western	24.2	-13.6	1.5	29
6	Kabwe (Met.)	Central	28.48	-14.42	5.9	27
7	Kabwe (Agric)	Central	28.50	-14.40	3.3	30
8	Kafironda	Copperbelt	28.17	-12.63	1.8	30
9	Kafue	Lusaka	27.92	-15.77	3.8	28
10	Kalabo	Western	22.7	-14.95	4.9	11
11	Kaoma	Western	24.80	-14.80	1.8	29
12	Kasama	Northern	31.13	-10.22		
13	Kasempa	North Western	25.83	-13.47		
14.	Kawambwa	Luapula	29.25	-9.8	2.4	18
15	Livingstone	Southern	25.82	-17.82	3.6	17
16	Lundazi	Eastern	33.2	-12.28	2.3	23
17	Lusaka	Lusaka	28.32	-15.42	5	16
18	Lusaka (Airport)	Lusaka	28.43	-15.32		

19.	Lusitu	Southern	27.63	-16.18	5	6
20.	Magoye	Southern	27.63	-16.13	3.5	24
21.	Mansa	Luapula	28.85	-11.10	3.2	24
22.	Mbala	Northern	31.33	-8.85	3.8	30
23.	Mfuwe	Eastern	31.93	-13.27	2.6	24
24.	Misamfu	31.22	-10.18	3.6	30	
25.	Mkushi	Central	29.00	-13.60	5.5	3
26.	Mongu	Western	23.17	-15.25	5.9	17
27.	Mpika	Northern	31.43	-11.90	3.4	27
28.	Msekera	Copperbelt	32.57	-15.55	3.5	20
29.	Mount Makulu	Lusaka	28.32	-15.55	3.5	28
30.	Mumbwa	Central	27.07	-14.98	2.7	21
31.	Mwinilunga	North Western	24.43	-11.75	2.4	29
32.	Ndola	Copperbelt	28.66	-13.00		
33.	Petauke	Eastern	31.28	-14.25	3.2	29
34.	Samfya	Luapula	29.32	-11.21	3.4	7
35.	Senanga	Western	23.27	-16.12	3.3	22
36.	Serenje	Central	30.22	-13.23	3.2	22
37.	Sesheke	Western	24.30	-17.47	3.1	29
38.	Solwezi	North Western	26.38	-12.18	2.9	29
39.	Zambezi	North Western	23.12	-13.53	3.1	29

The wind speeds were recorded over a period of up to 30 years by the Zambia Meteorological Department and collected primarily for purposes of weather forecasting and not for energy production. The Zambian wind regime has a characteristic which can be divided into 3, the low, medium and high average speeds. They are all important as they can be used to determine when the wind turbine can begin to rotate, begin to generate power and at what speed it may not work (Musonda, 2015).

The Figure 2.3 of the low elevation wind speeds indicates low speeds in rainy season and high speeds in the dry season and indicating a continuous rise in the wind speeds starting from April-the end of the rain season.

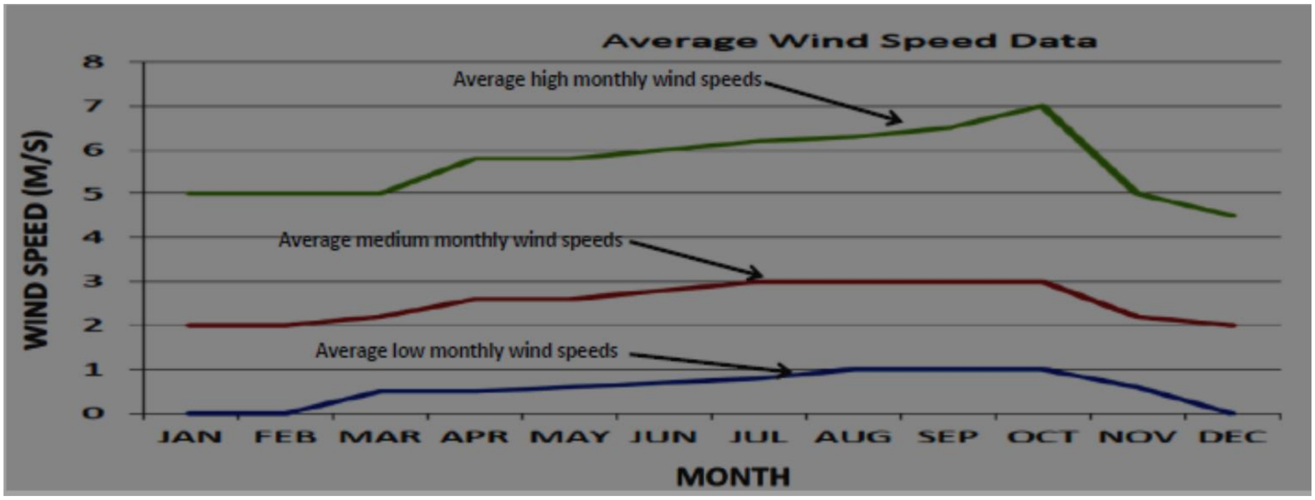


Figure 11.3 Average wind speeds recorded at 10m by Zambia Meteorological Department

Literature so far available for review of wind speeds in Zambia has not comprehensively done calculations for wind power that would be converted to electricity and how it can blend with the major source of energy currently in Zambia which is hydro. However, a study of the wind-solar energy mix proved useful though it was for small output suitable for charging phones (Musonda, 2015) and that there was intermittence in the production of energy.

The intermittence of the two sources of energy is a huge concern in its deployment especially if it's injected in the grid, meaning that there are no batteries considered as the case is with most large renewable energy projects because of the cost implication. Although wind is intermittent as stated, it has the advantage of being available throughout the 24 hours of the day unlike solar energy. In the United States, wind power is more popular than solar. Out of all the renewable energy produced in the U.S. in 2017, 21% came from wind, while just 7% came from solar power. Utilities and large-scale operations prefer heavily utilize wind energy while homeowners prefer solar energy.

The primary benefit of wind over solar power is that wind turbines aren't dependent on sunlight. This means that they can generate power 24 hours a day, whereas solar panels only generate power during sunlight hours. Wind comes with a significant caveat, however: in order to be effective, wind turbines need to be situated high above any obstacles that would block the wind (US, DOE, 2017).

The advantages of wind energy are more apparent than the disadvantages. The main advantage includes unlimited, free, renewable resource, economic value, maintenance cost and placement of wind harvesting facilities. First and foremost, wind is unlimited, free, renewable resource. Wind is a natural occurrence and harvesting the kinetic energy of wind doesn't affect wind cycles in any way. In addition, harvesting wind power is a clean, non-pollution way to generate electricity. Unlike other types of power plants, it emits no air pollutants or greenhouse gases. The wind turbines harmlessly generate electricity from wind passing by. Wind energy is far more ecofriendly than the burning of fossil fuels for electricity.

The country has a challenge to diversify the energy mix to avoid its dependence on hydro which is susceptible to climate change. Wind energy can assist Zambia from the dominance of hydro in power generation. Once turbines and energy centers have been installed, the cost of maintaining turbines and generating wind power is very negligible. The ability to place the turbines anywhere if the wind regime is okay is another advantage. Offshore winds tend to blow harder and more uniform than on the land, providing potential for increased electricity generation and smoother, steadier operation than land-based wind power systems.

The two major disadvantages of wind power include initial cost. Firstly, constructing turbines and wind facilities is very expensive. The second disadvantage is technological immaturity.

High cost of energy can, in part, be addressed directly with technology innovations that increase reliability and energy output and lower system capital expenses. Offshore wind energy produces energy than onshore wind energy, but costs much more to establish. The primary costs of wind turbine include construction and maintenance. New technology is needed to lower costs, increase reliability and energy production, solve regional deployment issues, expand the resource area, develop infrastructure, manufacturing facilities and mitigate known environmental impacts. There is a recent downward trend regarding the cost of energy from wind.

Other disadvantages are as follows:

Aesthetic impact: Many people are concerned with the visual effect that wind turbines have on the beautiful scenery of nature. They believe that giant wind turbines distract viewers from the beautiful surroundings.

Wildlife: Wind turbines may be dangerous to birds. Many birds and bats have been killed by flying into the rotors. Experts have now conducting research to learn more about the effects that wind turbines have on marine habitats.

Cost of transmission: Although placing wind turbines in desolate places may be an advantage, it may be a disadvantage in that the cost of travel and maintenance on the turbines increases and is time consuming. This also means the power must be transmitted over long distances to areas of consumption with the consequences being installation of costly transmission infrastructure for long distances, albeit transmission losses. Offshore wind-turbines require boats and can be dangerous to manage.

Noise: Some wind turbines tend to generate a lot of noise which can be unpleasant.

2.7. Hydrology of Zambia

Almost all the power produced in Zambia is hydro power. Hydro power is the energy derived from the potential energy of falling water or fast running water which may be harnessed for useful purposes. Zambia has used hydro energy for power generation since 1921 through the construction of the 22MW Mulungushi power station to supply the Copper mines (ZESCO, 2018). The current total installed capacity for Zambia is 2897.21MW and represents 83% of the total power generated in the Country (MOE, 2017). The typical hydrological situation for large dams used for hydro power generation in Zambia is as shown in Figure 2.4. Lake Kariba has been used as an example (ZRA, 2018).

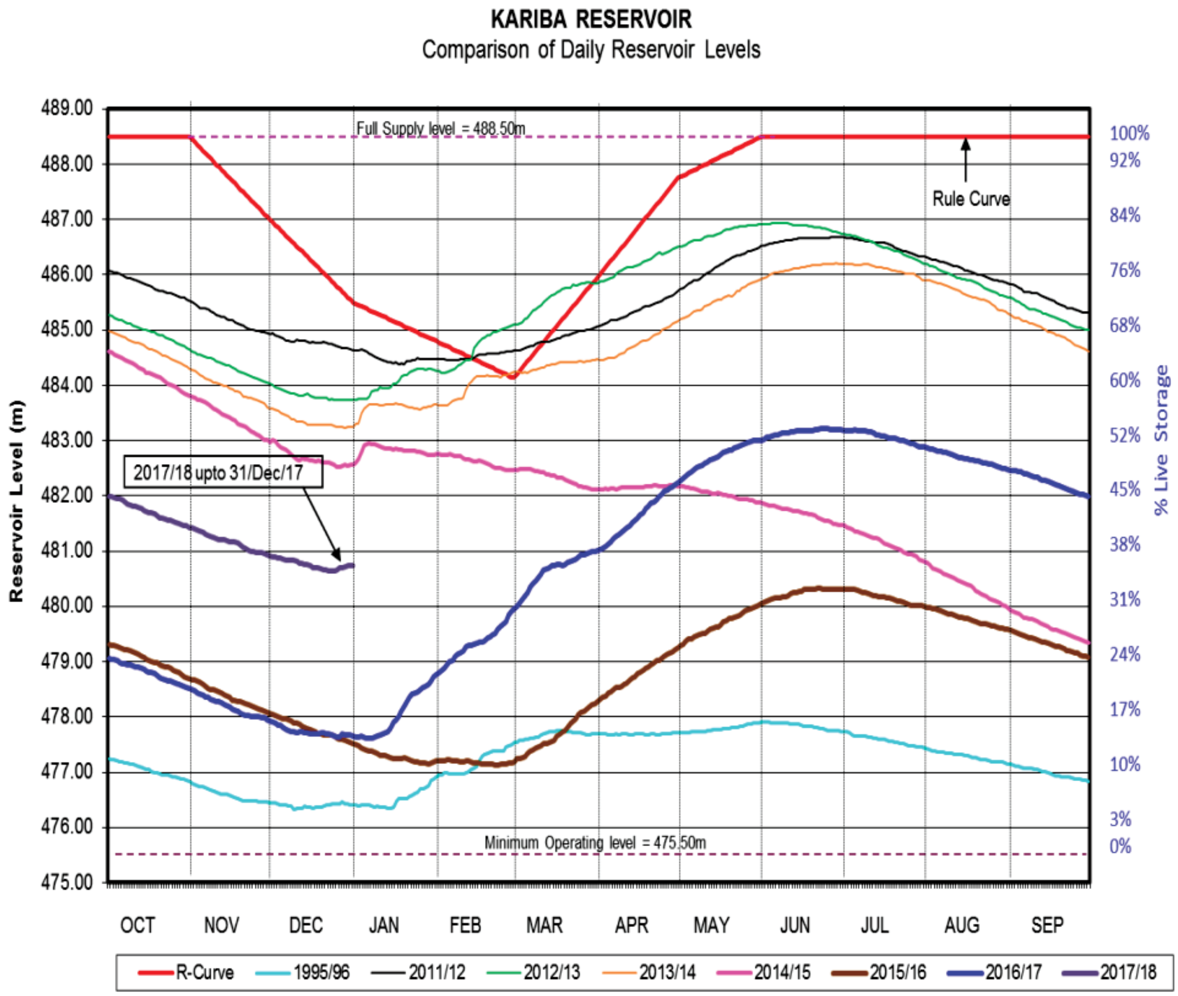


Figure 11.4 Lake Kariba hydrology for selected years to December 2017

As can be seen from Figure 2.4, the reservoir levels of the Lake Kariba reach their maximum levels in middle of the year. It takes water about three to four months for the lake to fill up after the rains have let up. The reservoir begins going down towards November before they start rising in December (ZRA, 2018).

In a study that was done to investigate the Water Supply and Demand Scenarios for the Zambezi River Basin (on which Lake Kariba is), it was predicted that the future monthly generation of power from Lake Kariba with 'Business as Usual' hydropower development will be as indicated in Figure 2.6. The Paper has other scenarios such as future generations with and without hydropower development in the same basin and with and without irrigation. Other factor covered under the research are the discharges from various dams in the Zambezi basin including those that are not in Zambia such as the Cahora

Bassa and Lupata hydro schemes in Mozambique (Fetcher, Yamba, 2014). As can be seen in Figure 2.5, the predicted power generation for the future has diminishing generation from February/March and has the lowest in November. The generation then picks up from the December as the rainy season begins. The graphs for other scenarios are similar as the power generation keeps reducing until late in the year. In Figure 2.6, the changes in the reservoir of Lake Kariba coincides with the predicted generation in the of power at the Lake Kariba.

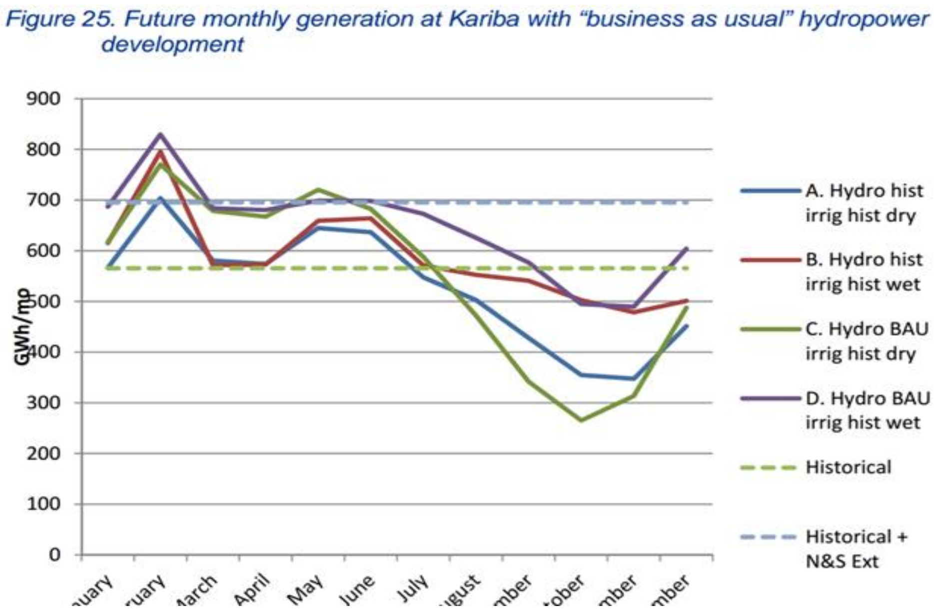


Figure 2. 1 Future monthly generation at Kariba with 'business as usual' hydropower Development (Fetcher, Yamba, 2014).

The rain season in Zambia begins in late October or early November and normally ends in late March or early April. This implies that the dry season is from April to October.

Zambia has about 40% of all the water resources in Southern Africa (ZDA, 2019) and in that case hydro power is the easiest stable power to develop as compared to other energy sources. The number of water sources of Zambia gives an idea why hydro is the largest source of electrical power in Zambia as shown in Figure 2.7.

Figure 2. 2 The River Map of Zambia (Geology.com)

The abundance of water for hydro power generation has made Zambia the champion of hydro power in Africa. With the potential of about 6000 MW capacity, Zambia has continued to install hydro power plants and up rating the existing plants while appreciating the need to incorporate renewable energy in its national energy mix. It's therefore important that any other source of energy apart from hydro which is to be included to the national energy mix is analyzed to determine how it complements hydro power. This might not be necessary for non-intermittent renewable energy such as geothermal as they provide base load power.

As stated in the preamble of this Chapter, there is no information available specifically for the Wind-Hydro energy mix for Zambia reasons being that the information for the wind speeds that can used for power generation has only been generated in the past three years. Therefore, research on the wind energy for power generation is difficult without information unless now. The information therefore relied on is that for hydro power and low elevation wind speeds studied separately.

CHAPTER THREE

3.0. METHODOLOGY

3.1. Introduction

This chapter of the research explains is divide into two parts. The first is the methodology used to measure the wind speeds, which are used in the calculation of the wind energy produced. It begins by explaining the determination of the best sites for the installation of the wind masts. The wind masts are towers on which wind measuring instruments are mounted at different heights. It also gives details of the measuring instruments that are installed on the wind mast and the purpose of each of the instruments. When the wind speeds are recorded, the chapter gives the calculation that is done to come up with the energy that can be extracted from the wind speeds and used for power generation.

The second part of this chapter describes the how the analysis of the hydro power information was done for this research using the hydro power generation profiles from the hydro power plants in the Country.

The profiles of the two power sources assisted in drawing graphs to indicate the results of having a hybrid of the two-source s of energy.

3.2. Wind Mapping Using Satellite Data

In order to determine the wind hot spots on which the wind masts should be installed, the first step was to develop the preliminary wind data maps from satellite data. As stated, this was used to obtain an idea of the possible hotspots for wind across the Country. The consulting company DNV GL developed a mesoscale map using their DNV GL Wind Mapping System software. Figure 3.1 shows the mesoscale map developed by the company.

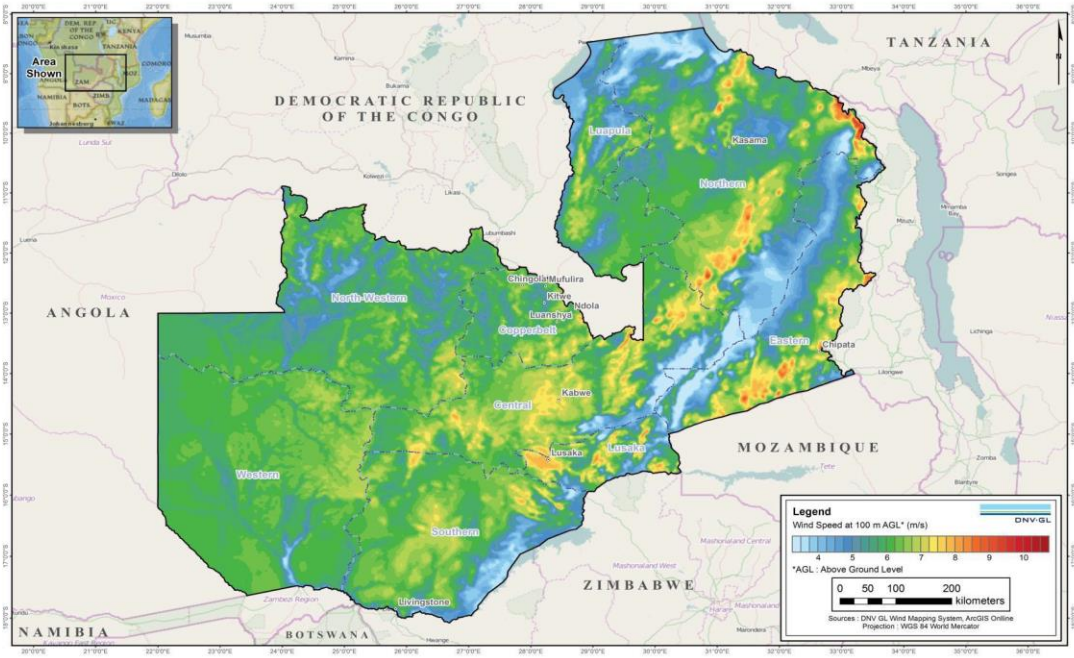


Figure 12.1 Preliminary and unvalidated mesoscale wind speed map, created using the DNV GL Wind Mapping System (ESMAP, 2015).

The map indicates the areas with possible high wind speeds. Using the DNV GL Analog Ensemble, the map was developed in consideration of the periods April 2013 to April 2014. The right bottom corner shows the meaning of the colours in the map. From the left to right the colour changes from light blue, areas with the highest wind speeds and changes colours with decreasing wind speeds on the right side.

3.3. Site Identification for verification of Satellite Data

After the production of the map and a number of other maps necessary for estimation of the wind regime was done, there was need to verify the information by means of actual measurements of the wind speeds in the different areas. That means finding the places where measuring equipment can be installed to verify the satelite data. 35 points across the Country were selected. Using the multi criteria approach to develop the wind speed uncertainity index, the potential sites were downgraded to 12 sites.

The selected 12 sites across the Country were visited to assess the condition of the place were they are located. The points of interest were to investigate the following, with consultation with the local authorities, which included Chiefs and District Commissioners, before the equipment can be installed:

i. Availability and adequacy of chosen location for wind measurements purposes
ii. Access to the sites and any construction impediments for mast construction
iii. Preliminary soil investigation to determine tower anchoring method
iv. Micro-positioning of tower center and 3 anchor points, staking of tower center
v. Evaluation of any terrain obstruction and land cover
vi. Evaluation of wireless signal, if any, for data communication
vii. Environmental and social survey Project Briefs (ZEMA)
viii. Security

Site meetings to collect the actual coordinates and assess the ground were held in all the places and shown in Figure 3.2. The meetings were held with the Zambia Environmental Management Authority (ZEMA) and the Civil Aviation in attendance.

Figure 12.2 Site meeting with stakeholders

A representatives of the Civil Aviation were important to ensure the 80m height of the wind masts to be installed were not standing in airplane pathways. ZEMA on the other side ensures the installation of the mast will not adversely disrupt enviromental stability. After the site visits and consideration of what was on the ground, 8 sites were finally selected and approved by ZEMA and the Civil Aviation department for the installation of the masts. The sites are marked in red in Figure 3.3.

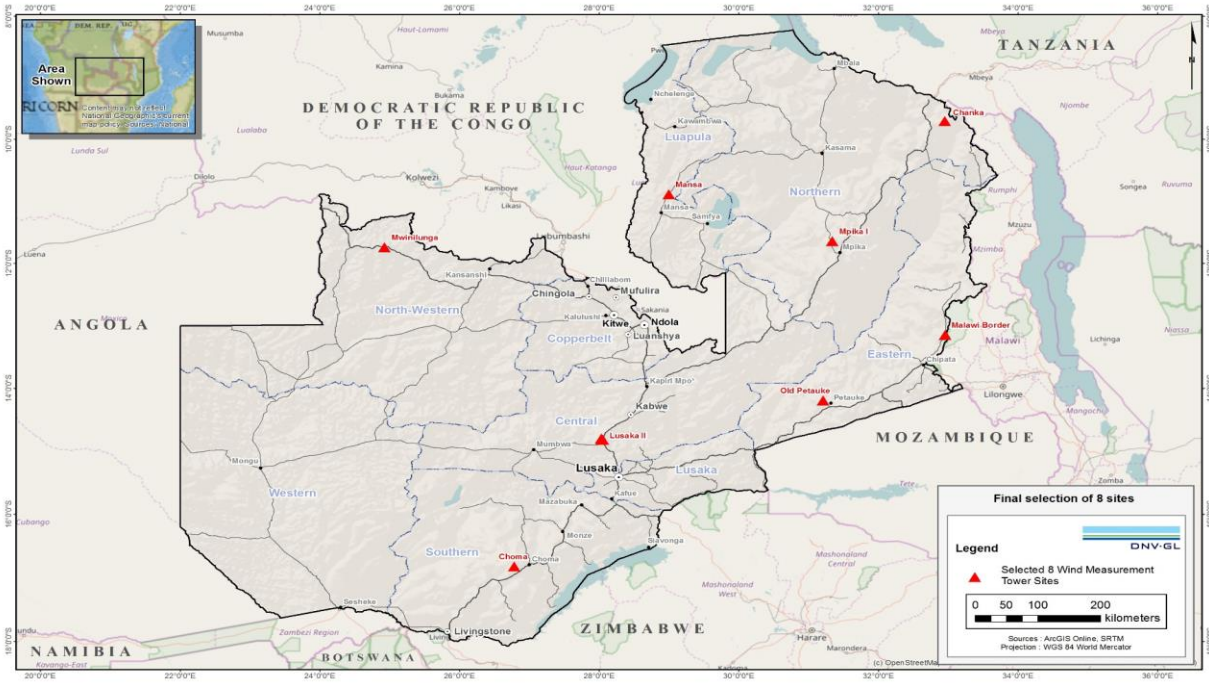


Figure 12.3 Approved sites for the installation of the wind masts (ESMAP, 2015).

Two local engineering firms were contracted to install the masts, Ranking Engineerig and CC systems. Rankin Engineering worked on the Environment Project Briefs (EPB) which was approved by ZEMA. Another company was CCsystems which was contracted to erect the masts.

3.4. Data Measuring Instruments Installed on the Wind Mast

The masts are installed with 14 data measuring instruments or sensors at the heights of 20m, 40m, 60m and 80m. The numbers of the sensors are 8 anemometer, 2 wind vanes, 2 thermoemters, a barometer and a hydrometer. The sensors are installed at different heights and are explained in detail below:

- **Anemometer**, an instrument for measuring wind speeds. This is the main instrument installed on the masts and serves the purpose of the exercise which is to measure the wind speeds in the area. The anemometers are installed in pairs and the different heights mentioned just in case one is not working and to ensure wind speed is measured at all times. Each wind mast therefore is installed with eight anemometers.
- **Wind vane**, an instrument for determining wind direction. It is important to measure wind direction as it gives the idea how much wavering of the wind can be experienced during the day

and night. The wind profile can assist in wind turbine choice for maximum energy extraction. Each mast is installed with two wind vanes at 80m, and 60m. It is not necessary to install many wind vanes because the two at the heights mentioned are enough to give the wind direction.

- **Thermometer,** an instrument that measures temperature. Apart from density, temperature affects wind speeds in a great way that is the reason why the day wind speeds differ with the night speeds. The difference in temperatures between two points is the reason there is wind from which we can tap energy. There are two thermometers installed on the mast, one at 80m and another at 20m.
- **Barometer**, an instrument that measures air pressure. Temperature affects the air pressure as it changes the density of the air and hence the pressure. There is only one barometer installed at 3m from the ground.
- **Hygrometer:** an instrument used to measure humidity in the air. Humidity also affects the wind speeds because humid air is denser. It also influences the turbine performance in terms of the water condensation effect on the wind turbine blades. There are separate research papers which have been written concerning the effect of humidity on the wind speeds and turbine performance especially when it concerns offshore winds.

The instruments described above are shown in Figure 3.4.

	Intsrument	**Name of the instrument**
1		Anemometer
2		The temperature sensor (Thermometer)

3		Hygrometer
4		Barometer
5		Wind vane

Figure 12.4 Equipment stalled on the wind mast

Apart from sensors, there are two solar panels which charge a battery that supplies power to the tower light at the summit of the tower and the data logger. The light is important to show those in the avaiation industry that there is a tower standing at that height. The schematic vies of the mast is shown in Figure 3.5 and the picture of the tower is in Figure 3.6.

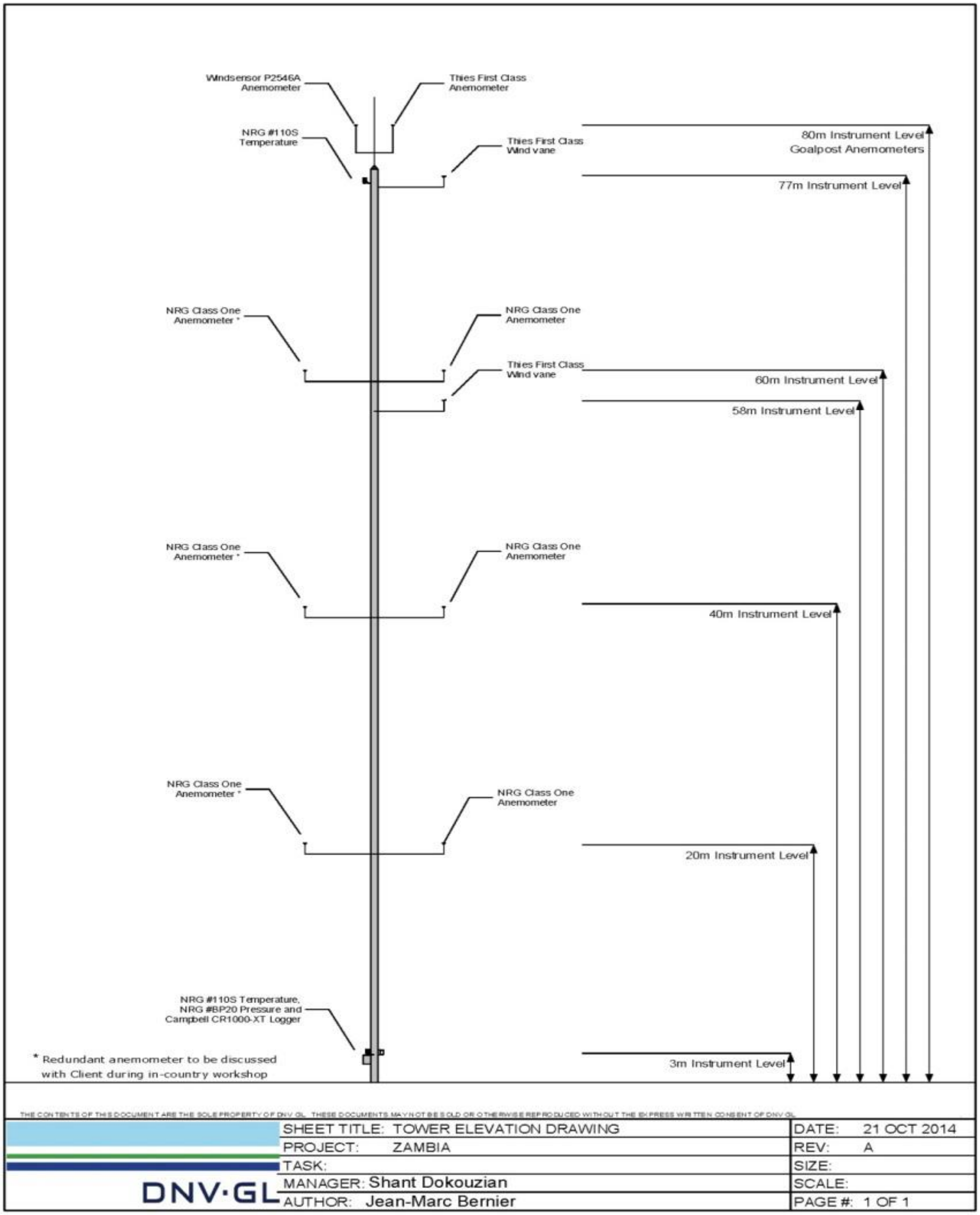


Figure 12.5 A schematic drawing of the wind mast (ESMAP, 2015).

Figure 12.6 The 80m wind mast installed in Chisamba area at Kambwese farm.

For the automatic acquisition of data, the tower is also installed with a data logger shown in Figure 3.7 and a back up memory.

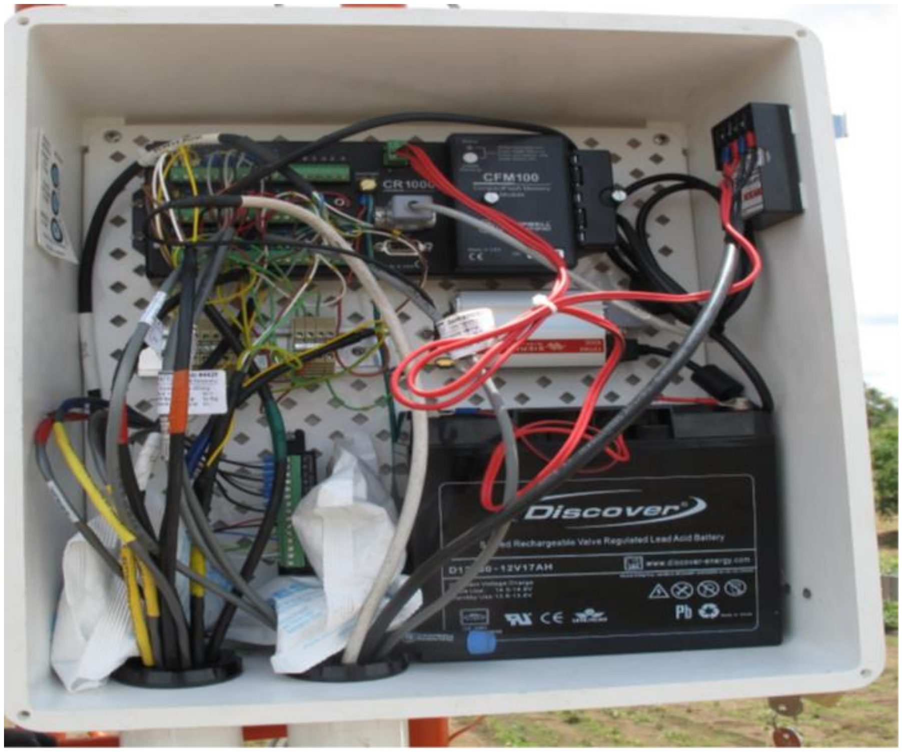


Figure 12.7 The data logger

It is powered with a solar panel and a battery which would last for a week without extra charging in case of cloud cover and pesistent rainfall. There is also internet loaded through a SIM card from MTN and Airtel to automatically deposite the raw data to the ESMAP website.

The raw data from the sites is deposited on the World Bank ESMAP website. The interest is to analyse the monthly data set and see how the wind speeds change each month of the year i.e the cold and dry, hot and wet seasons. It is this source of data that will be analysed, summarised and cleaned up with the interpretations that will make sence to the project developers.

A second data set is the monthly power generation profile which was obtained from the power utility company ZESCO Ltd. The company records the total power generated from each power station monthly. The monthly data is important to compare how it differs with that of the wind data.

The data that has been obtained from the project is as shown in Table 3.1.

Table 12.1 Wind Speeds for one year of data collected for 2017 (ESMAP, 2015).

		Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
1	Choma	5.0	5.1	5.6	6.8	6.5	6.9	6.5	6.6	7.9	7.0	6.0	5.5
2	Mwinilunga	4.8	4.5	5.0	6.4	7.3	7.7	7.7	7.5	7.0	5.5	4.9	4.1
3	Lusaka	4.4	4.3	5.6	6.8	6.9	7.6	6.9	7.2	7.9	6.7	5.3	4.7
4	Mpika	3.9	4.2	5.5	6.9	7.0	7.2	7.3	7.5	7.9	6.7	5.4	4.3
5	Chanka	4.0	4.3	4.6	7.0	7.7	7.7	7.6	8.1	8.8	7.4	6.0	4.7
6	Petauke	4.0	3.8	5.5	5.8	5.6	6.2	6.4	6.7	7.1	6.8	5.3	4.7
7	Mansa	4.1	4.2	4.9	6.5	7.0	7.0	7.1	7.1	7.2	5.6	4.8	3.9
8	Lundazi	4.0	3.8	4.8	5.8	6.1	6.2	6.2	6.9	7.4	7.3	5.7	4.5

To calculate the total annual energy produced is calculated using the formular, an assumption is made that the turbine being used is the standard 500kW turbine with a rotor size of 40m.

The total power produced is found using the formular

$$P = \frac{1}{8}\rho\pi V^3 D^2$$

Where ρ is the density of the air taken as 1.225kg/m^3

V is thewind velocity at 80m and D is the diameter of the swept area for a rotor size of 40m.

The values so the wind speeds are multiplied by the Betz constant, and efficiency value of 59.3%, which is the maximum power that can be extracted from the wind , independent of the design of the wind turbine in open flow. For a wind speed value of 5.0m/s, the total power produced is

$$P = \frac{1}{8} * 1.225 * \pi * 40 * 40 * 125 * 0.593 = 57053.28\text{W}$$

And the average annual energy produced is 57053.28/1000*24*365=499786.78 kWh=499.786 GWh.

The values for the other average energy produced monthly for each site are calcolated the same way with the following assupmtions:

The average energy produced assumes the maximum efficiency of Betz constant. While the actual efficiency is supposed to be less than the Betz limit, the maximum value is however being used for calculations. The air density used is 1.225kg/m^3.

Another assumption used is the generic turbine of 500kW with a rotor size of 40m and Figure 3.8 indicates scientifically generated information recommending the ideal rotor size for wind power generation of the magnitude indicated.

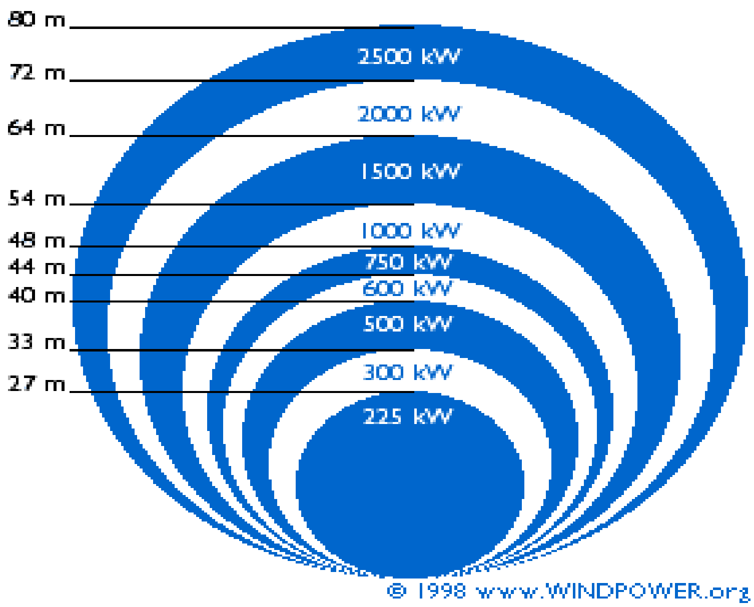


Figure 12.8 Generic turbine guide

3.5. Hydro power calculations

The values for hydro power were collected as recorded from the power plant as power was being generated. The power values were then converted to energy in gigawatts –hours (GWh) by calculating the product power produced, hours of production and days of the year.

That is:

Energy in Gigawatt-hours = power produced (GW) x hours of production x 365days.

The capacity factor of the plant does not apply in this case because the calculation is taking into consideration of the actual power produced and the actual hours of production by the plant and not its capacity. The values of the energy are categorized in monthly and yearly production for seven years. This was done for the data from ZESCO Ltd managed power plant and for the Zengamina private power plant though the Zengamina values were left in Kilowatt-hours for easy of graphing.

The data obtained was used to formulate graphs for easier visibility of the trend and variations of the power produced in each month for all the seven years under consideration.

3.6. Determination of the required power from wind to cover for the reduction in power production

There are two considerations which have been taken in determining the reduced hydro power which should be compensated by wind energy. The first is the total deficit for all the months in a year compared to a hypothetical situation where the power production does not vary in a year, i.e., in a theoretical situation of the straight horizontal trend line of power production in a year. Secondly, the power demand that is required from wind to cover the deficit from hydro power was determined from difference of averages of the highest mini-hydro power produced in the seven years and the minimum. This indicates the general gap that should be covered from the maximum to the minimum average power production over a period of 12 months.

This has been diagrammatically represented in Figure 3.9 and Figure 3.10. Figure 3.9 shows the general outlook of the power deficit within a year and Figure 3.10 gives the amount of power deficit that should advise how much the minimum installed capacity of wind should be in order to cover the deficit at the lowest hydro power production point in a year.

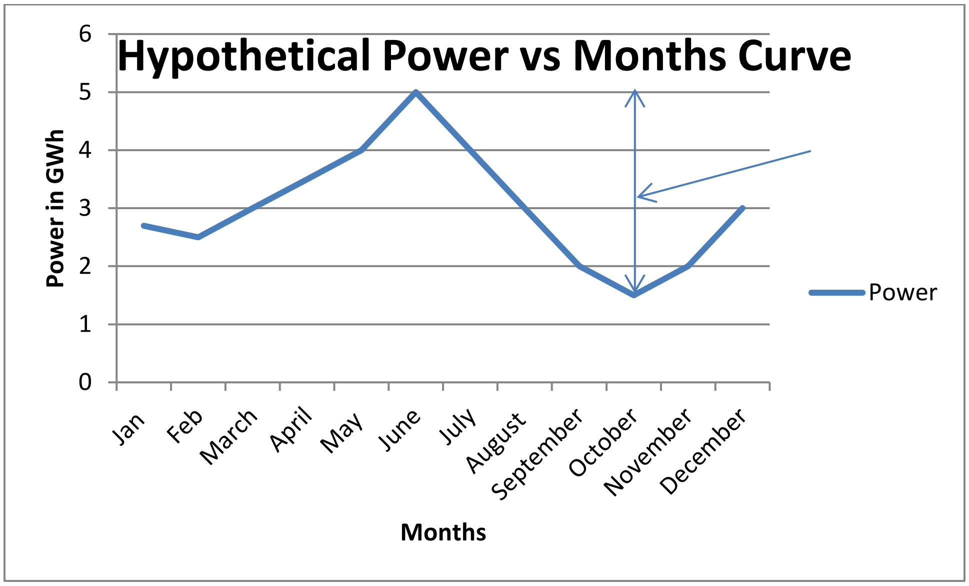


Figure 12.9 Hypothetical Power Vs Months Curve

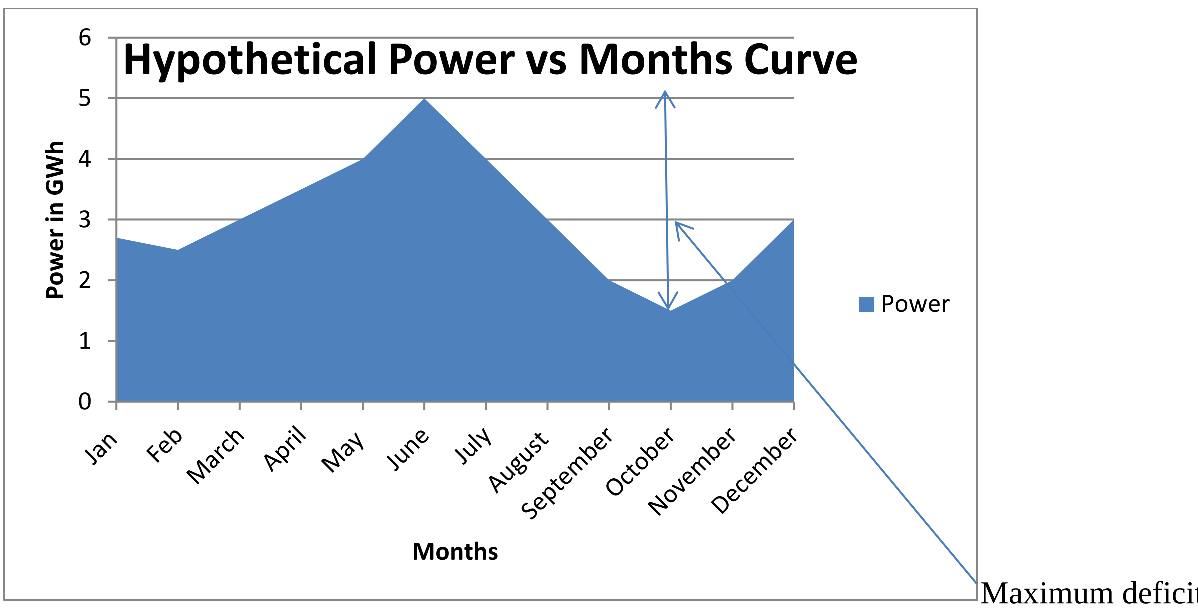


Figure 12.10 Hypothetical graph of Power Vs Months for calculation area under the graph.

To calculate the area under the graph, an equation for the graph would need to be generated using Microsoft Excel spreadsheet. The equation will be produced for a curve indicating the average of the points the Figure 3.7 for example. Calculus (integration) will be used to find the area under a curve which is the total power produced for mini hydro's in a year. For the area under a graph of the function

$$y = f(x),$$

The area is calculated as

$$\int_{x1}^{x2} f(x)dx.$$

The resulting value of the area is subtracted from the total possible production assuming that there is no intermittence or in other words, assuming that the power production is depicted by a straight horizontal line starting from zero on the x-axis but at the maximum power produced in a year for the y-axis. This calculation gives the total deficit that needs to be covered throughout the year.

CHAPTER FOUR

4.0. RESULTS

4.1. Introduction

This chapter explains the results of the calculatons of the power that can be generated from wind speeds tabulated in Table 3.1. The calculations have been done with respect to the assumptions stated in Chapter 3 and the actual wind speeds at 80m above the ground were used as opposed to projections of the hub height which would otherwise indicate a higher energy production.

The second part of this chapter reveals the results of the 7 year data of the hydro power production and how it varies monthly in each year. The data is separated between large and small hydro power produced to compare the similarities and differences across the seasons of the year and possibly determine the factors that could be the cause of the behaviour.

There are two main Zambian seasons that affect the weather in Zambia, the rainy season (November to April) which is equivalent to summer, and the dry season (May or June to October or November) which corresponds to winter. The dry season is subdivided into the cool dry season (May/June to August), and the hot dry season (September to October/November).

Most of Zambia sits on a plateau that is 900 m above sea level in the south, rising imperceptibly to 1,800 m in the north near Lake Tanganyika 800 miles away. This altitude has a modifying influence on the climate and makes it sub-tropical rather than tropical. Nonetheless, average monthly temperatures remain above 20 °C (68 °F) for 8 months of the year or more (ZTB, 2015).

4.2. Wind Energy Results

The results obtained from the calculations of the energy that can be produced using the wind speeds (in Table 3.1) in kWh are tabulated in Table 4.1. The data has been used to come up with a graph in Figure 4.1 that indicates how wind energy produced changes with reference to the seasons of the year or how is varies monthly.

Table 13.1 Calculated Energy production in GWh for the year 2017 from wind speed

	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Choma	499.7581	530.347	702.124	1257.12	1097.969	1313.4	1097.969	1149.428	1971.202	1371.336	863.582	665.178
Mwinilunga	442.154	364.324	499.758	1048.069	1555.315	1825.249	1825.249	1686.684	1371.336	665.178	470.368	275.551
Lusaka	340.5712	317.874	702.124	1257.12	1313.4	1755.055	1313.4	1492.27	1971.202	1202.47	595.22	415.091
Mpika	237.1612	296.209	665.178	1313.4	1371.336	1492.27	1555.315	1686.684	1971.202	1202.47	629.551	317.874
Chanka	255.8762	317.874	389.156	1371.336	1825.249	1825.249	1755.055	2124.736	2724.569	1620.112	863.582	415.091
Petauke	255.8762	219.382	665.178	780.07	702.1242	952.851	1048.069	1202.47	1430.951	1257.12	595.22	415.091
Mansa	275.5506	296.209	470.368	1097.969	1371.336	1371.336	1430.951	1430.951	1492.27	702.124	442.154	237.161
Lundazi	255.8762	219.382	442.154	780.07	907.4848	952.851	952.851	1313.4	1620.112	1555.315	740.414	364.324

Out of the data in Table 4.1, the graph in Figure 4.1 has been generated to interpret the data.

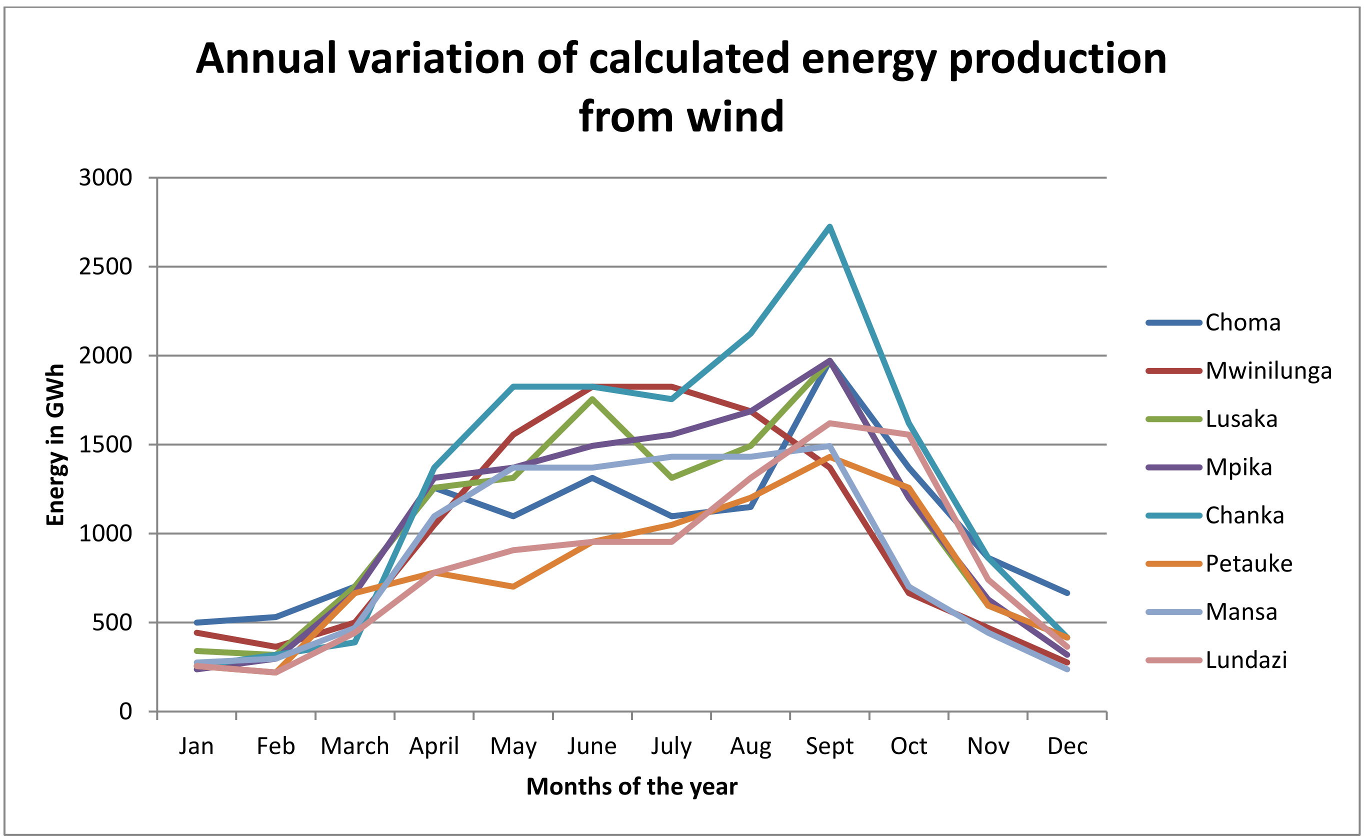


Figure 13.1 Monthly energy production from wind in Megawatts

Figure 4.1 indicates that the year begins with the wind energy production on a decrease and begins to rise in late February to March when the rainy season is almost over. The wind energy production keeps increasing in the dry season between April and September when it reaches its peak. The wind speeds start reducing gain in October as the rainy season begins. The graph therefore indicates that the wind speeds are high in the dry season and low in the rainy season. In addition, the real time data shows that wind speeds are larger during the night as compared to the values during the day.

4.3. Hydro Power Analysis

Data for the total energy production in GWhs from 2010 to 2017 from all the hydro power plants in Zambia was obtained (Annex1). The Hydro power plants under consideration are listed in Table 4.2. The power stations being considered are those owned by ZESCO Ltd because it was easy to get information on them. There are other players in the hydro energy space who are private and are not being considered in this research except for Zengamina mini-hydro Ltd. Leaving them out of the analysis has no significant effect on the results of the research. By conversion in Zambia, any power plant producing power less that 20MW is regarded a mini-hydro power plant.

Table 13.2 Power Stations owned by ZESCO Ltd and their capacities (MOE, 2017)

	Power Station	Category	Installed Capacity (MW)
1	Kafue Gorge Power Station	Large hydro	990
2	Kariba North Bank	Large hydro	720
3	Kariba North Bank Extension	Large hydro	360
4	Victoria Falls	Large hydro	108
5	Lusiwasi hydro Power	Mini hydro	12
6	Musonda Falls hydro power	Mini hydro	10
7	Shiwang'andu hydro Power	Mini hydro	1
8	Chishimba Falls hydro power	Mini hydro	10
9	Lunzua hydro power	Mini hydro	14.8

The total annual hydro production obtained from ZESCO Ltd for the power plants in Table 4.2 for the last seven years since 2010 is listed in Table 4.3. There are other two or three hydro power plants in Zambia which are not on the list and are operated by private companies but the ones being analysed will give a good representation of the data and serve the intended objectives. In addition, the analysis for large hydro included data for mini hydro as it is too insignicant to effect any change when extracted as can be seen from Table 4.2.

Table 13.3 Large hydro generated power from 2010-2017 in GWh.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
2010	868,618	770,485	904,390	935,462	929,283	925,027	1,018,237	993,844	940,897	947,493	917,473	976,070
2011	978,343	840,542	979,192	933,352	980,512	1,012,582	1,068,694	1,082,669	1,042,112	1,023,562	931,168	924,596
2012	947,425	928,119	980,056	1,083,962	1,092,340	1,062,110	1,094,613	1,083,243	1,030,437	1,045,782	1,022,543	1,056,185
2013	1,101,912	990,458	1,115,992	1,070,033	1,138,977	1,123,243	1,179,304	1,128,295	1,087,329	1,113,750	1,091,741	1,122,601
2014	1,086,201	1,070,647	1,172,831	1,112,691	1,128,198	1,146,099	1,189,344	1,175,827	1,130,213	1,124,031	1,136,128	1,165,349
2015	1,168,830	1,079,930	1,244,839	1,107,432	1,217,883	1,187,642	1,130,280	1,107,143	954,033	904,586	825,727	823,131
2016	805,516	757,484	857,269	859,109	936,504	951,216	1,015,556	939,575	936,805	936,391	872,791	912,403
2017	900,760	904,644	1,003,199	1,058,171	1,034,806	968,239	1,076,831	991,674	1,033,815	1,088,410	1,027,763	1,018,483

From the data in the Table 4.3, the graph of the total (Large and Mini hydro) hydro power variations monthly in the several years under consideration is shown in the Figure 4.2.

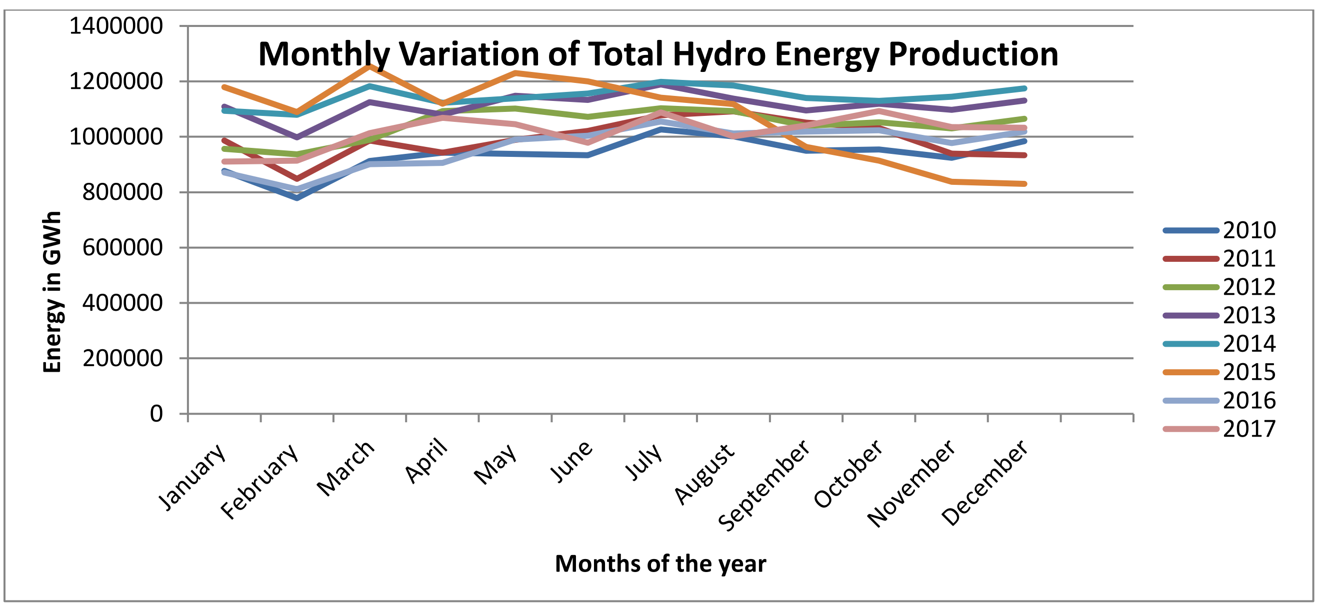


Figure 13.2 The total energy generation from all power plants from 2010 to 2017 over the seasons of the year.

Figure 4.2 indicates that there though there is minimal variations in the total energy produced by all hydro power stations over the seasons on the year, there is an increase of production after February. The increase reaches its maximum at in July after which it begins reducing. The reduction continues gradually until after November when the prodiction begins to rise. This is in direct colleration with the rain season of the year. More water means more hydro power generation. The variations are not pronounced because the large hydro power plants have dams which store water and its use is regulated over the seasons of the year. The wind-hydro complement does not make much difference in this case.

NOTE: Note that the graph of the large hydro only, i.e, the mini hydro values subtracted from the total hydro power values is the same as in Figure 4.2. This is because the values for mini –hydro are not large enough to make any significant or notiable difference in the graph. Figure 4.2 therefore represents a trend observed both for total and for large hydro.

The mini hydro power generation data is extracted from the combined data with the large hydro to observe if there is any differences between the two in terms of the variations in the seasons of the year. The data in Table 4.4 is the total mini hydro energy production extracted from Table 4.3 with reference to Table 4.2 which shows the separation between the large and mini hydros.

Table 13.4 The mini-hydro power production for the years 2010-2017in GWh

	January	Feb	March	April	May	June	July	August	Sept	October	Nov	Dec
2010	877070	778468	912068	942502	937843	933380	1026470	1001663	948962	954495	924098	983965
2011	986867	848092	986785	942297	988767	1020794	1078200	1091786	1051228	1031080	939188	933930
2012	956562	936655	988686	1092915	1102357	1072230	1102879	1092888	1039681	1052486	1030539	1064399
2013	1109198	997805	1125063	1079869	1148116	1132592	1188875	1137253	1095365	1119255	1097469	1130270
2014	1093819	1079239	1182440	1122541	1138545	1155964	1198184	1185284	1139620	1129700	1144570	1174729
2015	1178732	1088792	1254833	1119353	1230101	1199645	1141262	1117809	963545	913433	837022	829954
2016	870605	810788	901526	905569	989899	1004118	1055004	1011598	1018646	1023378	977594	1018201
2017	910488	913222	1012928	1068097	1045783	978009	1088119	1001664	1040167	1092897	1034496	1032979

The graphical interpretation for the information in Table 4.4 for mini hydro is as indicated in Figure 4.3.

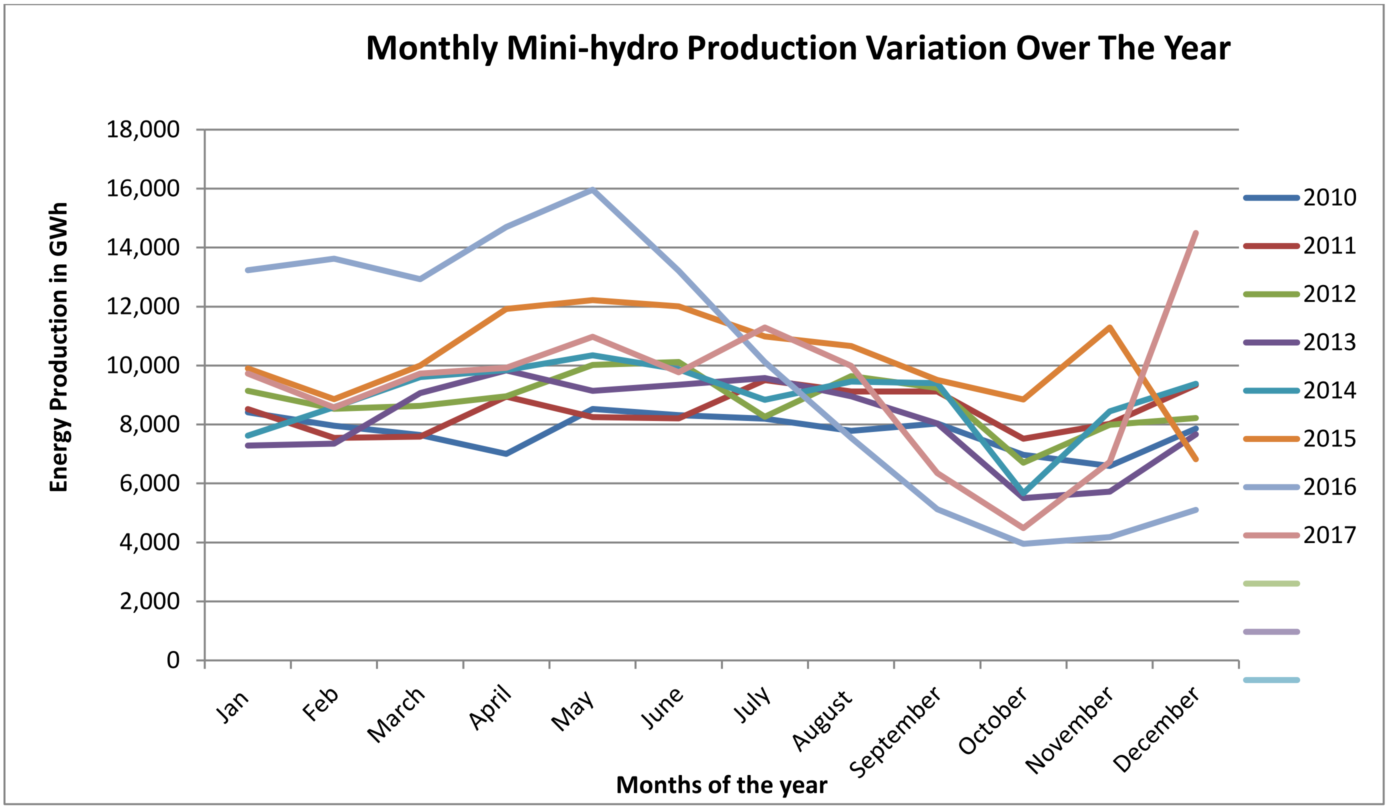


Figure 13.3 Variation of mini hydro energy production over the seasons of the year

4.4. Mini-Hydro Deficiencies and Compesation From Wind Energy

Mini-hydro variations over the seasons of the year indicate a slight increase in the power production after February (Rainy season). The energy production increases only up to May and June (cool dry season) after which it begines to reduce after July (hot dry season) until it reaches its lowest in October as shown by all the years under analysis. After October, there is a sharp rise in the production as the rain season sets in, and remains the same for the rest of the rainy season except for a slight reduction in February and the process repeats.

Comparing Figure 4.1, the graph of wind variations through the seasons and Figure 4.3, the graph of mini-hydro production through the seasons of the year, the peak production of wind (highest wind speeds) occurs in October in the hot dry season which is the lowest power production point for mini-hydros. The wind energy production sharply reduces after October while the mini-hydro begins to rise.The wind energy production begins to rise again in March and continues to until October while the mini-hydro reduces until it reaches its lowest in the same month.

It can be seen from the graphs in Figures 4.2 and 4.3 that minihydros are more affected by seasonal changes as compared to large hydros considering their more pronounced variations of poduction across the year. In addition, highest wind speeds occur in the dry season while the lowest wind speeds occur in the rainy season. This indicates a complementarity between wind and hydro power for Zambia through out the year.

To augment this result, a Zengamina hydro power project located in Ikelenge District of North-Western province was studied in relation to the wind speeds results in the area.

4.5. Zengamina Mini Hydro Project

Zengamina mini-hydro project is one of the private owned mini-hydro plants located in the Northwestern province and has a capacity of 0.75 MW. Daily data for the power generated in MWhs since its commencement in 2010 and upto 2017 was obtained and compiled as in Table 4.5. The Table 4.5, has started with July and ending with June. This has been done to make visible the variations that take place in the year as starting with January doesn't seem to bring out the changes clearly

Table 13.5 0.75MW Hydro power project power production from 2010 to 2017

	JULY	AUGUST	SEPTEMBE	OCTOBER	NOVEMBE	DECEMBEI	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE
2010	21706.96	23876.29	25164.73	28502.83	29854.77	33141.1	6016.62	11646.79	14530.48	15640.44	17846.06	19081.37
2011	53242.98	57422.46	59450.69	64286.83	64827.1	69641.45	35513.84	34252.97	40452.96	41657.81	45797.8	47674.64
2012	85302.73	97475.66	98476.71	105439.6	105583.5	112685.8	72414.7	70466.23	78364.42	78748.79	84427.25	85302.73
2013	141108.6	145789.7	144296.1	152043.6	150214	159198.8	116336.5	108348.6	123619.6	123424.3	131716.4	131965.3
2014	189874.8	195208	193937.2	171887.1	202608.6	213818.7	163336.1	151339.2	171905.9	141933	180008.4	178708.3
2015	246896.6	252824.4	241761.8	246000.2	258692.3	272619.3	218069.8	200913.4	226736	224069.1	236344.2	233674.5
2016	312401.6	318686.5	313704	328645.4	322088.9	338345.5	278119.5	265573.8	289479.1	285424.3	300436	296472.3
2017	380251.4	385691.8	376958.5	392367.1	383225.5	401653.3	344084.5	316159.5	355912.3	350081	367497.8	361664.8

Table 4.5 is interpreted by a graph in Figure 4.4 .

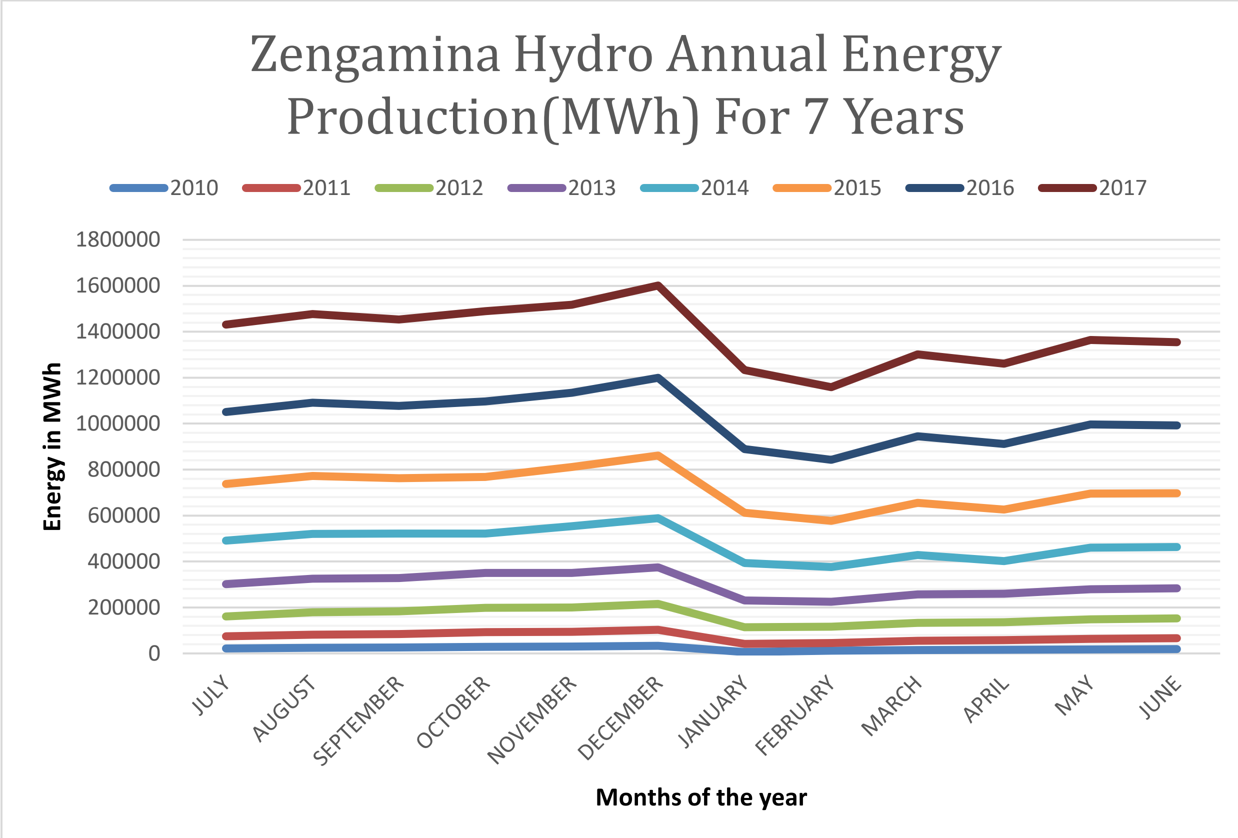


Figure 13.4 Power Production of Zengamina Hydro Power For 7 Years.

The variations of power production of the Zengamina Power project over the seasons of the year are compared with the wind regime in the area where it is located. The nearest wind mast to the mini hydro is the mast located in Mwinilunga, Northwestern Province. The distance between Inkelenge and Mwinilunga districts is 65km and therefore within the area of influence of the wind being recorded. The data from the Mwinilunga wind masts extrated from Table 3.1 is as shown in Table 4.6.

Table 13.6 MWh of Power generated from the Mwinilunga Mast

Mwini	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June
	1825249	1686684	1371336	665178	470368	275551	442154	364324	499758	1048069	1555315	1825249

The interpretation of the variations in Table 4.6 are shown in the graph in Figure 4.5. The graph has also been changed to start with July to show clearly the monthly, seasonal variations and to match with what has been done for Zengamina hydro data.

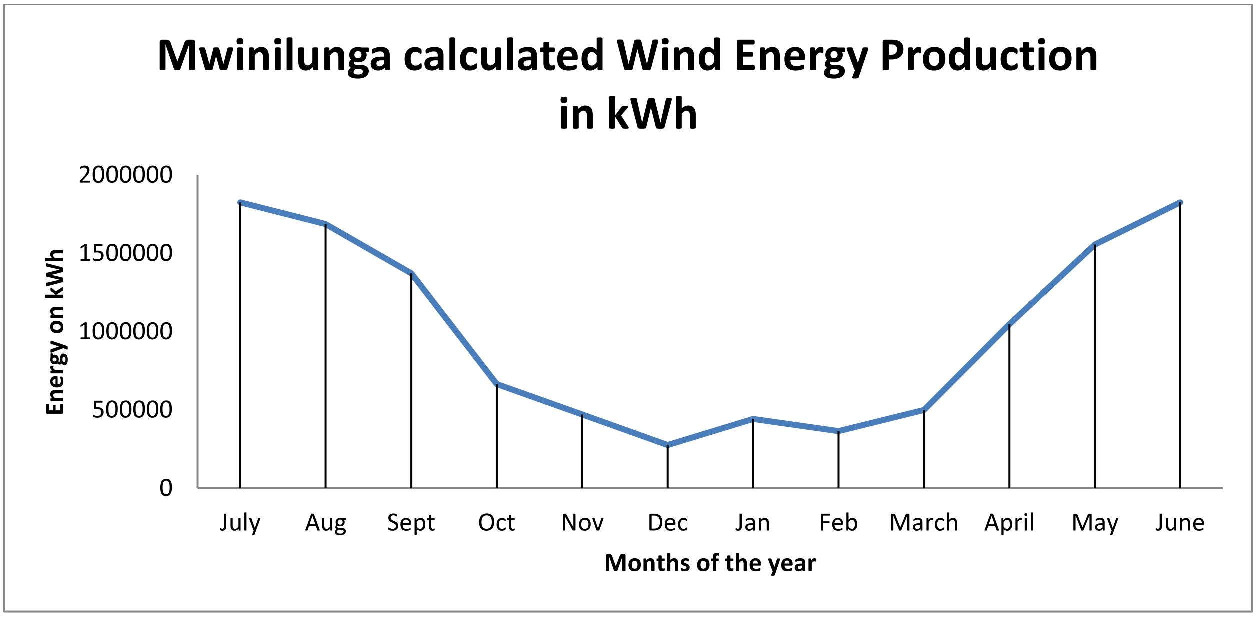


Figure 13.5 Potential wind Power production per month in Mwinilunga

The changes on the graph appear more at the beginning and the end of the year and the months where swapped so that the monthly vatriations are shown in a more pronounced manner.

Comparing Figure 4.4 and 4.5, it can be seen that in Figure 4.4, the power generated increases until it reaches its peak value in December after which it begins to reduce until March. After March, the power generation remains low and begins to rise in July. In Figure 4.5, for wind energy production, the reduces from July and reaches its lowest in December after which it begines to rise. This is exactly the opposite to Figure 4.4.

4.6. Approximate Energy to Compensate for the Reduction in Electricity production

Now that it has been established that there is a reduction in the annual power production of mini-hydro power plants due to factors expalined, there is need to establish the amount of wind energy that would be required to compensate for the reduction. The minimum installed capacity of wind should atleast be equal to the maximum reduction experienced in a year for it to be succesful. There must be a consideration also that wind is intermittend and has a lower power factor as compared to hydro.

As stated under subheading 3.6 with specific forcus to the table 3.7, Figure 4.6 is extracted from Figure 4.3. Its the average of all the energy from mini hydros produced for seven years. The graph still indicates the same charateristics from the original graph, that is the maximum production around the months after the rain season and the minimum just before the next rain season. The Figure 4.6 shows a curve which indicates the average of the graph in as much the same way we deal with the best fit lines in linear graphs.

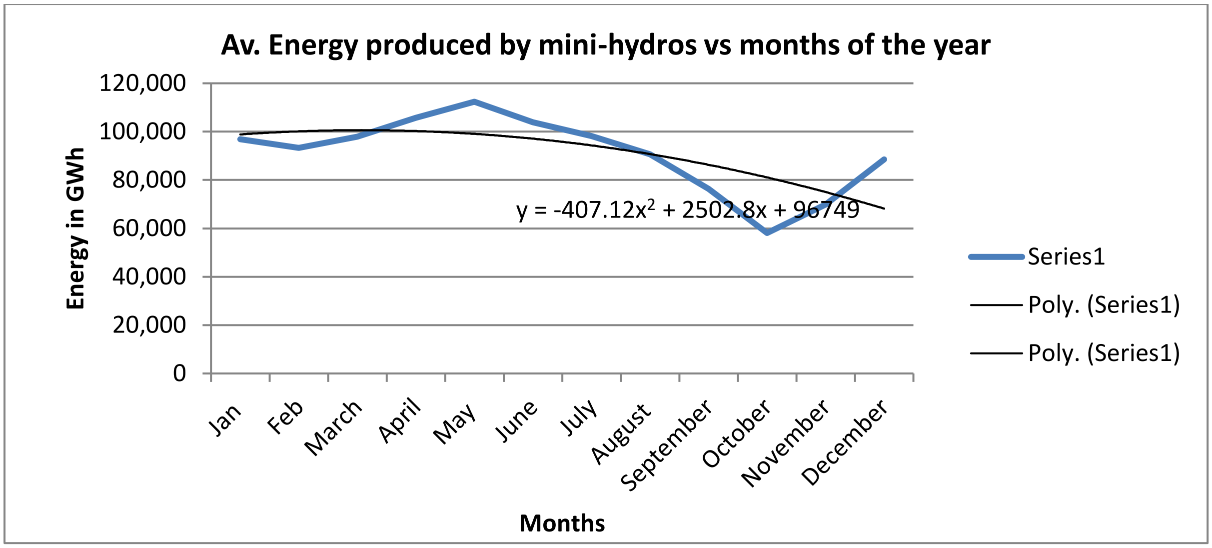


Figure 13.6 Annual average energy produced from mini hydro’s for seven years

Considering the simpler method of getting the power production reduction value, that is by getting a difference of the highest possible value and the lowest possible value, the maximum reduction that can be experience is as follows:

Maximum value (tip of the graph) =112,383 GWh and the Minimum value=58,091 GWh.

The difference therefore is 54, 292 GWh. This is an approximate highest possible drop in the energy production of mini hydro’s in the country and represents 48% of the power deficit. However, this maximum reduction only happens in October.

The actual annual reduction however can be calculated by getting the area under the graph

$$y= f(x) = -407.12x^2 +2502.8x+96749 \text{ with the limits being 12 and 0 months.}$$

The function inserted in the formula

$\int_{x1}^{x2} f\ (x)dx$ Such that it is

$$\int_0^{12} (-407.12x^2 + 2502.8x + 96749)dx$$

The resulting solution is 1,106,688.48 GWh.

This is the area under the graph which is the maximum energy produced from all mini hydro's in a year.

To find the maximum possible value of the energy assuming no variations, we calculate the value of a square. This was done by calculation the maximum value of the curve by the months. The maximum value of the curve is where the differential of the curve is equal to zero that is, $\frac{dy}{dx} = 0$.

The resulting answer is

$\frac{d(}{dx} - 407.12\text{x}2\ + 2502.8\text{x} + 96749\ )$=0:

Value of x=3.074.

The maximum value of the curve inserting the value of x in the equation gives=100595.536 GWh.

The maximum possible value of the energy produced assuming no variations is 100595.536 x 12= 1207146.43 GWh.

The percentage deficit is energy produced over maximum possible, that is (1207146.43-1,106,688.48) /1207146.43 GWh=8%

The reduction of the power production usually results in power deficits for the period of the reduction. The power deficit in turn results in blackouts aimed at impelementing a load management in order not to strain the elctrical transmission and distribution network.

CHAPTER FIVE

5.0. DISCUSSION

5.1. Introduction

This research paper forcusses on the wind-hydro energy mix particularly for Zambia. It basically explains how wind and hydro power varies in terms of power that can be produced throughout the year. It forcusses on the seasonal differences of power production between wind and hydro which can be exploited to achieve the objectives stated in chapter one.

This chapter discusses the results obtained from the calculation of wind speeds in accordance to the process discusssed in the Methodology taking into consideration factors such as the Betz constant and assuming the capacity of the turbine that can be used to achieve the objective. The values were analysed using graphs to clearly indicate the variations of wind energy production that can possibly be produced from the recorded wind speeds in the resource mapping exercise. It also elucidates the hydro power plant graphs that have been obtained from the data of the power produced from 2010 to 2017 from large and small hydro and interpret what the results mean.

It must be noted and as stated in the preceding chapter that Zambia has two main seasons, the rainy or wet season (Novermber to April) corresponding to summer, and the dry season (May to October/November), corresponding to winter. The dry season is subdivided into the cool dry season (May to August), and the hot dry season (September to October/ November), (Season in Zambia, ZMD).

5.2. Discussion of Results

As indicated on Figure 4.1, of the potential wind energy production from all the 8 sites, the wind energy starts increasing from the month of February and March. The wind speeds and hence potential power production keeps increasing until it reaches its peak in September/October. It then begins to drop in October as the rains commence. The winds speeds continue reducing until it reaches its lowest in February and March after which it begins to rise again. As stated, the rainy season starts in November and ends in April. This is the period in which there is low wind speeds. This means that the wind speeds are high during the dry season and low during the rainy season. This is in line with the wind speed regime as received from the ZMD for low elevation wind speeds and indicated in Figure 2.3 in the Literature Review.

As stated, the main purpose of this study is to analyse the interlink between the wind and hydro power and having discussed the graph for wind monthly or seasonal variation over the year, the graphs that follow therefore are for the analysis of the hydro aspects in order to observe variations and compare them with that of the wind energy variation graph in Figure 4.1. Figure 4.2 shows a graph that indicates the power generated in total from all power plants run by the utility company ZESCO Ltd in Zambia. The graph shows little variation but the lowest production occurs in February and then there is an increase in the production for the rest of the dry season until the month of October when the rainy season starts. The production is the lowest in October because it's the last month of the dry season. After October, as the rains begin, there is an increase in the water levels and hence the electricity production ,as can be seen from Figure 4.2. The variation is not so pronounced for large hydro as they have storage dams and the release of water for electricity production is regulated. Though the variations are not so pronounced, the maximum power produced is in the rainy season. It must also be indicated that the flow of water is slow and can take months depending from the river sources to reach the dams and therefore the power plants. An example is for the Kafue Gorge power plant whose main reservoiur is in Itezhi tezhi. The water takes 3 months to reach the Kafue Gorge Power plant from the main reservour in Itezhi Tezhi. The variations of the power production can be linked to the reseviour levels in the dams as can be seen from the Kariba Dam variations in the reservour levels in Figure 2.5.

Figure 4.3 indicates the power production annual variations from Mini hydros. As can be seen from the graph, the mini hydro power production profile is such that from February, the power production increases slightly through the months of March, April, May and June. In July, the production begins to lower down until it reaches the its lowest in the month of October and Novermber after which it begins to rise. The production begins to rise as the rain season begins and lowers down in the dry hot season.

The monthly or seasonal power production variations are more pronounced in the mini hydro case as compared to the large hydro scenario. The Figure 4.3 clearly shows that the increase in water levels during the rainy season and the reduction during the dry season has a profound effect on the power production. This is because most of the mini hydro do not have storage dams and the production of electricity depends on the water levels. Most of the mini hydros have weirs to assist in channelling water to the penstocks and some of them are run off rivers and no big dams to store water and regulate the power generation. This means the shortages of power from mini hydros during the dry season is more drastic than from big hydro power plants. Examples of large hydro power plants with dams and mini hydro with weirs and run-off river are shown in Figure 5.1 and 5.2 respectively.

Figure 14.1 Large hydro dam at Kariba Dam

The weirs for the small and mini-hydro's are shown in Figure 5.2.

Figure 14.2 A weir at Chishimba falls (on the left) and a run off river Zengamina mini hydro (on the right).

Figure 4.3 also shows that the months of the lowest production of wind are the months or seasons for largest production of hydro. As it can be seen from the graph, the highest potential wind energy production is in the months of October and November and they are the lowest hydro energy production months. Conversely, the lowest power production months for wind is the time when the hydro is the highest. In other words, wind is available in abundance when hydro power especially from minihydros is at the lowest and vice-versa. This shows a complement of wind-hydro energy mix. Literature on Figure 2.6 indicates that this kind of scenario will be sustained for a very long time.

A further analysis of the 0.75 MW off grid system Zengamina mini hydro project and the wind energy calculated from the wind mast in Mwinilunga shown in Figure 4.4 and 4.5 respectively indicates a similar complement of wind and hydro power. Mwinilunga has been paired with Zengamina for reasons explained in Chapter 4. The months on the graphs have been swapped so that the monthly variations are clearly seen since they are more pronounced at the beginning and end of the year. As can be seen from the mentioned figures, the peak for the hydro, which is in December, is the lowest for the wind energy production. The hydro production begins going down after December while the wind energy begins to increase. This indicates a perfect complement of the two sources of energy under investigation.

The analysis of the wind and hydro electricity production patterns indicates that wind energy production is high during the dry season and low during the rainy season. The hydro energy production is the exact opposite. This means wind energy is the perfect complement for hydro in Zambia and wind energy can be used to complement hydro during the dry season when the country has low energy production and when power cuts are prevalent.

One of the objectives of this research is to create a basis for governement priotisation of the energy resource for exploitation. Though not all energy sources have been studied for comparison, wind energy is one of the keys sources which should be considered for exploitation considering that it has the potential to reduce seasonal variations in power production for the country. This may mean arranging the mini hydros such that there is consideration of how wind energy may complement them, i.e, pairing the mini-hydros with the masts nearest to them.

It is therefore recommeded that the operators of the mini-hydros in the Country consider establishing wind farms in the specific areas to guarantee the availability of power throughout the year. The areas of the mini hydro locations should be connected to the same power lines within the areas of consideration for them to have a desirable influence in the power variations over the months of the year. Since the wind masts are the source of data to be used for the power plants and they are area specific, it can be recommended that the mini hydros in those areas consider the data from the wind masts to establish the wind farms. They can therefore be paired as in figure 5.1. The Victoria Falls hydro dam has been included in the list below because even if its not a small hydro, it has no dam for storage and hence the effect of low or high levels of water affect it to a large extent.

Table 14.1 Pairing of the mini-hydro and wind masts in the same areas

	Mini hydro Location			**Wind Masts Location**		**Recommended minimum Capacity of Wind Power (MW)**
	Name	Capacity(MW)	Location	Site	Location	
1	Musonda Fall	10	Mansa, Luapula	Mansa site	Mansa	4,8
2	Shiwang'andu	1	Chinsali, Muchinga	Mpika Site	Mpika	0.48
3	Lunzua Hydro power	14.8	Mbala, Northern Province	Chanka Site	Nakonde	7.1
4	Chishimba Falls	14	Kasama, Northern Province	Chanka Site	Nakonde	6.72
5	Lusiwasi	12	Muchinga	Mpika Site	Mpika	5.76
6	Victoria Falls	108	Southern Province	Choma Site	Southern Province	51.84

Considering that much of the large hydro power plants are located on the southern part of the Country, there are a lot of transmission losses in an effort to make power available in the Northern Region of the Country. The mini hydros therefore are important in supplementing power from the large hydros and providing stable power in the Northern region. But because of the susceptibility to water level variations during the year, wind farms would provide a perfect energy mix to counteract the deficit in certain months of the year.

5.2.1. Power Requirement to Counteract the Power Production Reduction

In Chapter Four, there is calculation of the power requirement, in this case from wind, that is required to counteract the power production reduction in certain months of the year. Two values have been determined, one which indicates the maximum variation from the maximum production to the minimum. This value gives the minimum capacity of wind power that must be installed to cover for the reduction. This was found to be 48% of the energy production which will translate in the installed capacity of the mini-hydros. This means 48% of the installed capacity of wind is sufficient to cover for the power reduction at a point when the wind is highest. The rest of the year the required wind energy will be lesser but still required.

The second calculation was done to detarmine the overall reduction as compared to the annual generated energy. The total annual reduction was found to be 8% of the annual power production. This is because of the high capacity factor of hydro power as compared to other intermittent renewable energies such as wind itself. The design of the wind farms therefore must ensure to put capacity factor considerations to ensure the energy output estimation are close to the actual values.

The values of the wind energy speeds used are average values and do not indicate the variations in a day. The real time data indicates that the wind speeds are more during the night time as compared to the time of the day. The most unfortunate aspect is that mini-hydros use weirs and run off rivers and therefore difficult to save water because of lack of storage. If storage is there, the recommendation would have been to reduce the power production of hydro power at night when a larger amount of wind power can be produced due to the increased wind speeds. This should be considered for networks with power from both hydro and wind energy. It must be noted that the values of the require power to counteract the reduction are estimates which can offer guidance during project modelling and may be different from the actual values that should be implemented. The recommendation of this research is to install a larger amount of wind energy because of its challenges of intermittence and lower power factor.

Given the increased interest from the Governement and private players in the energy sector to develop mini hydros for increasing access to rural electrification, it is prudent for the institutions participating to be aware of the wind-hydro energy mix to avoid power outages at certain times of the year and for increased utilisation of the renewable energy resource at our disposal.

CHAPTER SIX

6.0. CONCLUSION AND RECOMMENDATIONS

6.1. Introduction

This chapter summarises the findings of the research and checks them against all the objectives. It also clarifies the issue discussed in chapter 5 and those that augment the results of the findings. The second part of this chapter recommends further studies that can be done using the information in this research and also adds other recommendations.

6.2. Conclusion

The Wind-Hydro Energy Mix-A Case For Zambia research used the calculated total annual energy that can be produced if wind energy is produced at 80m height, making all the necessary assumptions. The monthly data for the hydro power produced from the ZESCO Ltd managed power stations for 7 years from 2010 to 2017 was used. With reference to the objectives of the research as stipulated in chapter 1, the research shows the following:

The research shows that wind and hydro power in Zambia complement each other. The research is able to demonstrate that the wind speeds are at a maximum when the hydro prower production is at the minimum and vice-versa across the seasons of the year.

The monthly variations of large hydro power production over a year is not pronounced though the graph indicates a similar behaviour of increased production during the rainy season and reduced production for the large part of the dry season because of reduced water levels. This is because of the storage dams that large hydro power has and the use of the water from the dams is rationed so that it is used through out the year. The variations of large hydro power therefore does not vary much as indicated in Figure 4.2.

The mini hydro power produced annually varies significantly with seasons of the year as shown in Figure 4.3. From the 7 years studied (2010-2017) the power production from mini hydros indicate a minimum production just before the rainy season begins in October. The variation is because the mini hydros do not have dams and instead weirs are constructed for directing water into penstocks and some are on run off rivers. Any change in the levels of water, because of lack of storage, shows significantly in the power produced. On the other hand, the months of minimum power production for mini hydros are the maximum power production months for wind power. This is because wind power in the rainy season is minimum (maximum production for minihydro) and maximum in the dry season (low production for mini hydros). This shows that wind energy and mini hydro power are complementary. Wind energy is a good energy mix to mini hydro as it complements it almost perfectly in Zambia.

6.3. Recommendations

The recommendations from the findings of the reseaerch are as follows:

The governement must priotise wind energy in an effort to diversify the national energy mix. Apart from advantages of wind stated, it is also a good complement of mini hydro. It therefore smoothens the variations of the two sources.

Companies running hydro power plants should consider installing wind farms along side mini hydro power plants to run together so that they can smoothen the variations in the power production and guarantee adquate power through out the year. It must be noted that wind is site specific and installing a wind farm along side a mini hydro might not always be possible but because they will be connected to the same grid, the effect of the smoothing the variations can be experienced. The minimum installation of the wind energy is supposed to be atleast 48% of the installed mini-hydro capacity. The grid study must be done in order to acertain if the grid can take the amount of the energy estimated. In addition, the capacity factor of the wind in the area can also help to determine the exact amount of the wind capacity that should be installed.

7.0. ANNEX

7.1. Partners of The Research Project

The partners in the research project are;

The Department of Energy, Lusaka

DNV GL Consultants in the United States of America

Rankin Engineering, Lusaka

CC systems, Lusaka

CEEEZ, Lusaka

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