A TECHNO-ECONOMIC FEASIBILITY STUDY OF A GRID-CONNECTED HYBRID SOLAR PV-WIND POWER GENERATION SYSTEM IN ZIMBABWE

SUSTAINABLE ENVIRONMENT AND ENERGY SYSTEMS

MIDDLE EAST TECHNICAL UNIVERSITY

NORTHERN CYPRUS CAMPUS

BY

REMEMBER SAMU

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR

THE DEGREE OF MASTER OF SCIENCE

IN

SUSTAINABLE ENVIRONMENT AND ENERGY SYSTEMS PROGRAM

JANUARY 2019

Approval of the Board of Graduate Programs

Prof. Dr. Gurkan Karakas

Chairperson

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science

Asst. Prof. Dr. Ceren Ince Derogar

Program Coordinator

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Assoc. Prof. Dr. Murat Fahrioglu

Supervisor

Examining Committee Members

Assoc. Prof. Dr. Murat Fahrioglu

Electrical and Electronics Engineering

METU NCC

Asst. Prof. Dr. Onur Taylan

Mechanical Engineering,

METU NCC

Prof. Dr. Serkan Abbasoglu

Energy Systems Engineering,

Cyprus International University

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last Name: Remember Samu

Signature:

ABSTRACT

A TECHNO-ECONOMIC FEASIBILITY STUDY OF A GRID-CONNECTED HYBRID SOLAR PV-WIND POWER GENERATION SYSTEM IN ZIMBABWE

Samu, Remember

M.Sc., Sustainable Environment and Energy Systems

Supervisor: Assoc. Prof. Dr Murat Fahrioglu

January 2019, 97 pages

The depletion of fossil fuel resources on a worldwide basis and an increase in greenhouse gas emissions and climate change as a whole have caused an urgent search for alternative sustainable energy sources to cater for the rising energy demands. The demand of energy is rapidly growing in both developing and developed nations thus making hybrid renewable energy power systems (RES), comprising Solar Photovoltaic (PV) and wind energy to be chosen as one of the best alternatives. However, on the downside, these resources are unpredictable and intermittent, even though to a certain extent they complement each other to fix this problem. Batteries, fuel cells or other storage systems could also be proposed but they increase the cost and some options may not be environmentally friendly. The renewable energy sources can partially or fully meet the deficit in Zimbabwe's demand with minimal disturbance on the stability of the country. The main objective of this present study is to convert the solar and wind resources in different locations in Zimbabwe into electrical energy so as to meet the demand that is significantly growing. This kind of hybrid system ensures efficient utilization of the available renewable energy resources thus making them more efficient than their separate modes of generation. The system's annual generated energy, annual excess energy and energy deficit, are amongst other energy parameters analyzed in this study. The goal of this thesis is to model a hybrid PV-Wind system using Microsoft Excel, so as to maximize the renewable energy sources (RES) fraction for Zimbabwe's grid. An electricity demand forecast analysis was done up to 2030.

An analysis of the levelized cost of electricity (LCOE) is also performed so as to examine the economic impact of this addition. In addition, Environmental costs were analyzed to point out the importance of this system to the environment. Four different scenarios were examined for in this study; (1-2) individual solar PV and wind resources were examined, (3) a hybrid solar PV/Wind with the energy storage system (ESS), (4) hybrid solar PV/Wind energy systems without energy storage systems. The obtained results show that there will be an increase in primary energy consumption from 0.17 quadrillion Btu to 0.183 quadrillion Btu by 2030 which then corresponds to an expected to increase in power consumption from 2200 MW to 2368.19 MW by 2030. Furthermore, the integration of ESSs to a hybrid PV/Wind system increases the capital cost of the system without significantly increasing the RES fraction. Only Gwanda location was studied for this scenario, by integrating Zinc Bromine and Lithium-Ion batteries and this system only had RES fraction of 60.47% compared to 60.42% where there was no ESS. The NPV of this system was US$39,130 and a capacity factor of 30.82% against a capacity factor of 30.58% for the system with no ESS. This system consisted of 157 kWh of Zinc Bromine batteries, a wind capacity of 2 MW and a PV capacity of 503 kW. The addition of ESSs, therefore, increased the system's capital cost without significantly increasing the RES fraction. A grid connected hybrid system consisting of 4 MW wind capacity and 1328.76 kW PV capacity has the highest RES fraction of 74.03%, highest capacity factor of 30.84 %, the highest NPV of US$ 9.41 million and the highest yearly avoided carbon dioxide emissions of 19042.64 tons which gave a total yearly avoided cost of US$ 760000. This system was located at Victoria Falls and it is, therefore, considered the most favourable location for investment whilst the least favourable of the 16 locations under study is Harare. Overall the hybrid system gave rise in RES fraction, capacity factor and annual energy production compared to the individual PV only or wind only configurations.

Keywords: Grid-connected, renewable energy, solar photovoltaic energy systems, techno-economic feasibility analysis, wind energy systems, energy storage systems, Zimbabwe.

ÖZ

Zimbabwe'de Şebekeye Bağlı Hibrit Solar Fotovoltaik-Rüzgar Gücü Sistemlerinin Tekno-Ekonomik Fizibilite Analizi

Samu, Remember

Yüksek Lisans, Sürdürülebilir Çevre ve Enerji Sistemleri Programı

Tez Yöneticisi: Doç. Dr Murat Fahrioglu

Aralık 2018, 97 sayfa

Fosil yakıtların dünya çapında tükenmesi, sera gazı emisyonundaki artış ve iklim değişikliği bir bütün olarak enerjiye olan talebi sağlamak amacıyla acil olarak alternatif yenilenebilir enerji kaynakları arayışına neden olmuştur. Enerjiye olan talep gelişmiş ve gelişmekte olan ülkelerde hızla artmaktadır ve bunun sonucunda fotovoltaik güneş enerjisi ve rüzgar enerjisi içeren hibrit yenilenebilir rüzgar enerji sistemleri en iyi alternatiflerden biri olmuştur. Ancak, bu kaynaklar birbirleri yerine kullanılabilmesine rağmen tahmin edilemez ve aralıklıdır. Buna çözüm olarak bataryalar, yakıt hücreleri veya başka depolama sistemleri önerilse de bu çözümler maliyeti arttırmaktadır ve bazıları doğa dostu olmayabilir. Yenilenebilir enerji kaynakları Zimbabwe'nin enerji talebindeki açığı tamamen veya kısmen ülkedeki dengeyi minimum etki ile karşılayabilir. Bu çalışmanın amacı, güneş ve rüzgar enerjisini Zimbabwe'nin değişik yerlerinde elektrik enerjisine çevirerek gittikçe artan talebi karşılamaktır. Bu tarz hibrit sistemler elde olan yenilenebilir enerji kaynaklarının etkili bir biçimde kullanımını sağlayarak bu kaynakların ayrı ayrı kullanımına kıyasla daha etkili olmaktadır. Sistemin yıllık ürettiği enerji, yıllık fazla enerji ve enerji açığı bu çalışmanın enerji parametrelerindendir. Bu tezin amacı, modellenen hibrit fotovoltaik rüzgar sistemi ile Zimbabwe şebekesindeki yenilenebilir enerji kaynakları payını maksimum şekilde arttırmaktır. Elektrik seviyesinin maliyetlendirilme analizi ile de bu çalışmanın ekonomik etkisi incelenmiştir. Bunun dışında, çevresel maliyet analiz edilerek önerilen sistemin çevreye olan katkısına dikkat çekilmiştir. Bu çalışmada dört ayrı senaryo incelenmiştir: (1-2) ayrı olarak güneş ve rüzgar kaynakları incelemesi, (3) enerji depolama sistemi ile birlikte hibrit solar fotovoltaik rüzgar ve (4) enerji depolama sistemi olmaksızın hibrit solar fotovoltaik rüzgar incelemesi. Elde edilen sonuçlar

birincil enerji tüketiminin 2030 itibariyle 0.17 katrilyon Btu'dan 0.183 katrilyon BTU'ya ve bunun sonucunda elektriğin 2200 MW'dan 2368.19 MW'a çıkacağı beklenmektedir. Enerji depolama sistemlerinin hibrit fotovoltaik rüzgar sistemlerine entegrasyonu maliyeti arttırmasına rağmen yenilenebilir enerji sistemlerinin payını önemli bir derecede arttıramamaktadır. Bu senaryo sadece Gwanda lokasyonunda çalışılmış olup, Çinko-brom ve lityum-ion bataryaların sisteme entegre edilmesi yenilenebilir enerji kaynaklarının payını %60.5, bugünkü değer ile 39,130 Dolar maliyet ve %30.82 kapasite faktörü olarak sağlamıştır. Bu sistem, 157 kWh çinko-brom bataryalardan, 2 MW rüzgar ve 503 kW fotovoltaik kapasiteden oluşmaktadır. Şebekeye bağlı olan 4 MW rüzgar ve 1328.76 kW fotovoltaik kapasite maksimum %74.03 yenilenebilir enerji kaynakları payı, bugünkü değer ile 9.41 milyon Dolar maliyet ve karbon emisyonunda 19042.64 ton azalma sağlamıştır. Karbon emisyonundaki bu azalmanın maliyeti 760000 Dolardır. Bu sistem Victoria Falls lokasyonunda kurulmuş olup yatırım için Harare'deki 16 lokasyondan en elverişli koşullara sahiptir. Bir bütün olarak hibrit sistem yenilenebilir enerji kaynakları payı, kapasite faktörü ve yıllık enerji üretiminde ayrı ayrı fotovoltaik ve rüzgar sistemlerine kıyasla yükselme kaydetmiştir.

Anahtar Kelimeler: Şebekeye bağlı, yenilenebilir enerji, solar fotovoltaik enerji sistemleri, tekno-ekonomik fizibilite analizleri, enerji depolama sistemleri, Zimbabwe.

DEDICATION

To Mom (*Lucy Aydini*) for her endless support, spiritually, mentally, emotionally and financially.

ACKNOWLEDGEMENTS

I would like to appreciate my advisor and mentor, Dr. Murat Fahrioglu for his endless support during my studies and time at METU NCC. Special thanks go to Dr. Onur Taylan who motivated in the initiation of this present study while I took a course, Design of Renewable Energy Systems, with him and Dr. Derek Beker for his assistance in obtaining the solar and wind resources data used throughout this study. Dr. Onur also provided the foundation of the model that I utilized for this present study. Working with Dr. Murat and Dr. Onur was an invaluable experience.

I would also want to extend my utmost gratitude to my mom, Lucy Aydin, for her priceless and endless support since the day I was born. Nothing would have been necessary if it wasn’t for you Mom. Together with the support of my siblings, Miriam, Tinei, Joyleen, Ieelue, Innocent and Chiedza, this study was made possible.

I would like to thank the whole of Electrical and Electronic Engineering Department and the administration of METU NCC for the teaching assistantship position which saw me through my studies without facing any financial difficulties at METU NCC. I would also like to thank my friends, who were more like family, Dr. Akeem, Marlon, Ishmael, Aswad, Merrline, Abdullah, Mohammed, Rafi, Vincent, Kathy, Loiy, Samuel, Hope, Phebe, Haroon, Zackria, Ahmad, Koray, Ahmet, Berkay, Khadija and Hamed and his wife Narges.

However, my greatest thanks go to my brothers Wicknell, Joseph and Rohat for their mentorship and support during my studies. I would not forget my spiritual mentor and brother Baba Johane Tasisiro for his utmost support and encouragement, letting me know that it's never easy but it's worth trying. Lastly for their support and seeing me through in almost every path of my life, I would thank Mr and Mrs Katsiru and the whole respected Katsiru family including but not limited to; Ignatius, Ospar, Refnise, Barnabas, Godfrey, Anesu and Panashe.

Finally, I give thanks and praise to God granting me the strength, hope and opportunity to undertake this amazing experience.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

A_{CO_2}(ton)	Yearly avoided CO_2 emissions
C_i (USD)	The capital cost of the renewable energy system
CF (%)	Annual capacity factor
COE(USD/kWh)	The Cost of Electricity of the renewable energy system
D(kWh)	The electrical energy demand
D_{excess}(kWh)	Excess electrical energy generated by the renewable energy system
D_{grid} (kWh)	The energy demand met by the electricity grid
D_{RES}(kWh)	Demand met by the renewable energy system
E_{gen} (MWh)	Yearly total energy generated by the renewable energy system
F_{RES}(%)	Annual renewable energy fraction,
$G_{S.C}$(W/m^2)	The solar constant
GT(USD/kWh)	Local grid tariff
H	The number of hours in a year that the RES totally met the demand
I(Wh m^{-2})	Global insolation on a horizontal surface
I_o(Wh m^{-2})	Extraterrestrial horizontal insolation
$I_{b,n}$(Wh m^{-2})	Hourly beam insolation
$I_{b,t}$(Wh m^{-2})	Hourly beam insolation on a tilted surface
I_d(Wh m^{-2})	Diffuse insolation on a horizontal surface
$I_{d,t}$(Wh m^{-2})	Diffuse insolation on a tilted surface
I_{Ref}(Wh m^{-2})	Reference insolation at nominal conditions
I_T(Wh m^{-2})	Global insolation on a tilted surface
K	Shape parameter of the Weibull distribution of the wind speeds
k_T	Clearness index
L(years)	System lifetime
L_{loc}(degree)	Longitude of the location
L_{st}(degree)	Standard meridian for the local time zone

$LCOE$(USD/kWh)	Levelized cost of electricity of the renewable energy system
M_t(USD)	Yearly fixed maintenance cost of the hybrid system
N	Number of wind turbines
$N_{modules}$	Number of PV modules in the power plant
$NOCT$(°C)	Nominal operating photovoltaic cell temperature
NPV($)	Net present value
P(kW)	Installed capacity of the PV power plant
P_e(kW)	Average electrical power generated at each hour from the wind turbine
$P_{e,R}$(kW)	Wind turbine rated electrical power
PR(%)	Performance ratio of the PV system
PBP(years)	Simple payback period
R_{CO_2}(kg/kWh)	CO_2 intensity of electricity
R_t(USD)	Annual net revenues from the system
R_{t1}(USD)	Annual net revenues for the first year
r (%)	Annual discount rate
T_{amb}(°C)	Ambient temperature
T_{PV}(°C)	Module temperature
$T_{Ref,NOC}$(°C)	Reference module temperature at nominal conditions
$T_{Ref,STC}$(°C)	Reference module temperature at standard test conditions
T_z(hour)	Local time zone
u_C(m/s)	Wind turbine cut-in wind speed
u_F(m/s)	Wind turbine cut-out wind speed
u_R(m/s)	Wind turbine rated wind speed
u_Z(m/s)	The speed at hub height
u_1(m/s)	Average wind speed at ground level
$\bar{u}$(m/s)	Average wind speed at hub height
Z(m)	Hub height
Z_1(m/s)	The height of the ground level

Greek Letters

α	Wind shear coefficient
α_s(degree)	Solar altitude angle
β(degree)	The tilt angle of the photovoltaic modules
β_{Ref}(1/°C)	The temperature coefficient of the photovoltaic module
γ(degree)	Surface azimuth angle
γ_s (degree)	Solar azimuth angle
δ(degree)	Declination angle
η_{PV}(%)	Photovoltaic module efficiency
$\eta_{PV,Ref}$(%)	Reference efficiency of the photovoltaic module
θ (degree)	Incident angle
θ_z (degree)	Zenith angle
σ (m/s)	Standard deviation of the wind speeds sample
ϕ(degree)	Latitude angle
ω (degree)	Hour angle

Acronyms and Abbreviations

COE	Cost of Electricity
DNI	Direct Normal Irradiation
GHGs	Greenhouse Gases
GHI	Global Horizontal Irradiation
LCOE	Levelized Cost of Electricity
LPSP	Loss of Power Supply Probability
NPV	Net Present Value
SPBP	Simple payback period
PV	Photovoltaic
RES	Renewable Energy System
ZESA	Zimbabwe Electricity Supply Authority
ZETDC	Zimbabwe Electricity Transmission and Distribution Company

CHAPTER 1

INTRODUCTION

It is very important for a society, community or country as a whole to have access to at least basic energy services. Modern lighting and cooking positively affect a nation's health sector, poverty alleviation and its economic development [6]–[8]. More than half a billion people in Sub-Saharan Africa still do not have access to basic electrical energy services [9]. Only 40% of Zimbabwe population has access to electricity and more than 81% of the rural population do not have access to basic electricity as well [10]. Fuelwood is still being commonly used in both urban and rural areas. In rural areas, they meet more than 80% of their energy requirements mainly from fuelwood and 15-30% of urban also rely on wood for cooking [10]. Due to unsustainable wood harvesting and clearing of lands for agriculture, the country now faces fuelwood shortages.

Zimbabwe's electricity power system relies heavily on 65% coal and 35% hydro, which leaves it endangered during these droughts that are recurring. A total of 12 billion metric tons of good quality coal reserves are available in Zimbabwe, with calorific values around 32 MJ/kg [11]. Zimbabwe has an installed capacity of 1900 MW though only 1150 MW were operational as of 16 October 2018 against a peak demand of 2200 MW [12]. 35% of the supplied energy deficit is currently met through imports from DRC, Zambia Mozambique, and South Africa, causing a foreign currency outflow thus worsening the currency situation in the country right now, therefore there is a need for a new generation planning. Zimbabwe imports petroleum fuels through a pipeline from Beira (Mozambique) to Harare and the southern part by the railway line from South Africa and the rest by a combination of both railway and road [13].

Zimbabwe lies in a sunny belt with average radiation of about 5.5 kWh/m^2/day with a total of around 4000 hours per year of solar radiation [3]. A hybrid grid-connected solar PV-Wind power system can partially or fully curb for the energy deficiency in the supplied electricity whilst capitalizing on the environmentally friendly methods of electricity generation and utilizing the vast solar resources in Zimbabwe that are currently not being harnessed. Harmonized operation of

Zimbabwe's extensive hydro and thermal systems can overcome the intermittency problems that are associated with these renewable energy sources.

1.1. Background

There exists an electricity supply deficit in Zimbabwe. The electricity that is being generated by the Independent Power Producers (IPPs) and from Harare, Kariba, Bulawayo, Hwange and Munyati power stations is failing to meet the current demands. The Zimbabwean power sector is facing the following challenges:

- Inability to meet demand
- Operational inefficiencies and poor financial performance
- Poor capital base and inadequate resources for infrastructure and equipment maintenance leading to supply disruption.
- No renewable energy feed-in tariffs (REFIT) have been set, thus resulting in low investment

1.2. Policy measures and strategies

1.2.1 Measures

- Encourage the generation of electricity from biomass cogeneration and mini-hydro projects
- Bagasse from sugar cane – Hippo Valley and Triangle sugar estates generate for their own consumption.

The policy does not suggest any large scale utilization of renewable energy resources such as solar and/ wind resources.

1.2.2 Strategies

- Extension of Kariba south by end of 2016, which was then completed in 2018
- 800 MW Batoka hydro by 2020
- Mandate the installation of solar geysers by 2013 which has not yet been done up to the time of the completion of this thesis
- To fix (REFIT) renewable feed-in tariffs which have not yet been done up to the time of the completion of this thesis

1.3. Problem Statement

To model an efficient grid-connected hybrid solar PV-wind energy system (maximize RES fraction, which should minimize GHG emissions) to be able to partially or fully meet the deficit in energy supply that Zimbabwe is currently facing.

1.4. Motivation of Study

My main motivation of this study is due to a rapid decrease in the market price of both photovoltaic and wind energy systems. Additionally, the following aspects of the Zimbabwean power system also contribute a lot to the motivation of this study:

- Zimbabwe has vast solar resources but this is only harnessed in small-scale solar home systems or for agricultural purposes.
- The heavy reliance of the country on coal makes the system unfriendly to the environment and also during dry seasons, water levels are decreasing in the main hydro generating dams leaving the generation sector vulnerable. Rainfall patterns have not been stable recently, floods have been prevailing frequently mostly due to climate change and uncontrolled rates of deforestation.
- There has been a rapid demand growth thus requiring an increase in the generation capacity. The decrease in the efficiencies and existing generators' problems also require an urgent search for alternative power generation technologies. By harnessing its own solar and wind resources, the country's imports of oil can be reduced thus reducing the dependence on continuously rising fuel prices.
- Since diurnal changes in the energy output from intermittent renewable resources such as solar and wind are highly possible, the existing hydro and thermal systems could be utilized to facilitate their integration into the system.
- Compared to solar thermal power plants, solar PV plants are not grid-friendly because of frequency fluctuations. However, on the other hand, solar thermal power plants need a larger land area and also for their integration into the grid, there might be a need for a grid and/ or transmission infrastructure upgrade which make them more expensive compared to PV plants.
- The economy consumes 3.5 million tons of coal per year for electricity generation normally but as of 2016, coal consumption reduced to 3 million tons per year. This is environmentally friendly as it results in reduced GHG emissions but at

the same time, it increased the deficit of electricity generation. As a result, new generation technologies are required.

1.5. Research Questions

The main objective of this present study is to determine if a hybrid solar PV-Wind system is able to provide an environmentally friendly solution for Zimbabwe's need for an increase in generation capacity and encourage the deployment of wind and solar resources on a large scale. The secondary investigation is to see if this can be done in an economically feasible way.

Below are the research questions in addressing this goal:

- How much PV and Wind can we integrate into the existing setup?
- Is it possible to include wind and / solar PV to the existing energy system without an increase in the average unit cost?
- How an addition of Wind and/ solar PV affect the forecasted energy demand growth?
- What is the suitable maximum renewable energy share that can be included in the system? This is a power system research question and is a topic for another thesis. However, some suggestions and recommendations from the power company in Zimbabwe will be considered.
- How are these outcomes affected by the unpredictabilities in demand growth and consumption patterns

This study is aimed at addressing the impacts of adding wind and solar PV to the Zimbabwean system. As such it does not address network optimization or dynamic expansion planning for the generation or transmission systems.

1.6. Step by step objectives

Due to the conflicting relationships among the objectives, there is no single optimal solution for all objectives as for a single objective problem, there are always trade-offs. The following are the proposed step by step objectives:

- Feasibility analysis of solar potential in Zimbabwe
- Feasibility analysis of wind potential in Zimbabwe
- To develop a renewable energy hybrid PV/Wind model, with or without ESSs so as to efficiently maximize RES fraction to partially or fully meet the demand

- To analyze the economic, environmental and technical aspects to configure the proposed hybrid system
- Demand forecasting up to 2030
- Propose this forecast to policymakers so as to optimize the Electricity installed capacity to meet the demand by 2030.
- Analyze to what extent is the hybrid system is more preferable to PV only or Wind only on grid connected systems.

1.7. Structure of the thesis

This thesis is divided into seven sections. Chapter 2 is an overview of the Zimbabwean energy sector. A detailed literature survey is given in Chapter 3. The literature review was categorized into thesis-based and article based (journal papers and conference papers). Chapter 4 outlines a detailed discussion of solar and wind resources. Technologies utilized in this thesis are explained in this chapter as well. A detailed outline of the developed model employed in this thesis is shown in Chapter 5 followed by the results and discussion in Chapter 6. Finally, Chapter 7 presents the concluding remarks as well as possible future studies that can be parented by this present study.

CHAPTER 2

ZIMBABWE: COUNTRY CONTEXT

In this section, background information on Zimbabwe's geography, climate and economy are outlined. Added information on this section also includes a comprehensive summary of Zimbabwe's energy sector, emphasizing the current status and future planning or vision of the nation's power sector.

2.1. Country overview

Zimbabwe used to serve as the breadbasket of the Southern African Development Community (SADC). Its main purpose was to ensure food security to countries such as Angola, Botswana, DRC, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Seychelles, South Africa, Swaziland, Unitede, Republic of Tanzania and Zambia [14]. Like the majority of Sub-Saharan countries, Zimbabwe has been facing many social, political and economic challenges such as a lack of modern energy services, outbreaks of diseases and political instability.

As of recent, there has been a ridiculous increase in the unemployment rate up to 95 per cent [15], which has seen a significant population living way below the poverty line. A plan which is very ambitious, Vision 2030, has been proposed by the government of Zimbabwe [16], [17]. The main objective of this plan is to raise the nation's status from low-income to a middle-income country by 2030. This is expected to be achieved through investments in environmental security, education, government transparency, health services and infrastructure [18]. In order to ascertain the feasibility of these goals, there is, therefore, a need for access to reliable, clean and sustainable energy sources. Because of this reason, it is therefore of paramount importance to integrate as much renewable energy resources available in Zimbabwe as possible to ensure a maximum if not 100% electrification by 2030.

The Vision 2030 plan does not give any comprehensive details about the exact projections on planned electricity infrastructure improvement. There are no targets as to how much improvement will be done to the rate of access to electricity against the current access to electricity rate which is as low as 38.15% [10]. This is access to electricity by population. Access to electricity in this context includes affordability and reachability to physical infrastructure. Due to the high unemployment rate, there is a significant low-income population in Zimbabwe, hence the urgent need for the government to increase the electricity connectivity without significantly increasing the tariffs such that the low-income consumers would not afford.

2.1.1 Economy and Demography

The population of Zimbabwe is close to 17 million, ranking 69th in the world countries by population and at the same time, it constitutes 0.22% of the total world's population [19]. Urban area constitutes 31.1% of the total population in Zimbabwe. Zimbabwe is furnished with numerous natural resources including vast fertile farmlands, precious minerals including gold and diamond, asbestos, coal and extensive hydropower sources. The tourism industry is very robust as it is fueled by diverse wildlife and secured national parks and some beautiful tourist attractions including the famous largest waterfall in the world called Victoria Falls which is said to be amongst wonders of the world [20]. Despite the nation's prevailing political instability and deterioration, domestic and international firms' investments, trade and tourism have helped drive the GDP of Zimbabwe to reach its recorded all-time high of 17.85 million United States dollars in the year 2017 [21]. The tourism industry only had a total contribution of 7.1% of this achieved all-time high GDP [22]. The central, eastern and north-eastern regions are the most populated areas in Zimbabwe. Agriculture still remains the major driving factor of Zimbabwe's economy and those most populated regions are the regions that are most suitable for farming [23], which can also be seen in Figure 2.1.

Figure 2.1. Map of population density distribution [1].

2.1.2 Geography and Climate

Zimbabwe derived its name from Dzimbadzemabwe meaning houses of stones. This name originates from the famous Great Zimbabwe structures in Masvingo city; which are very tall structures built of only stones without any mortar binding them together. Zimbabwe is a landlocked country with an estimated area of 390,760 km^2 situated and an average latitude of 19.0154°S and 29.1549°E longitude. The country straddles the high plateau between the Limpopo and the Zambezi rivers to the south and to the north, respectively with a tropical climate [24]. The Udizi and Nyanga Mountains stretch along the border to the east with Mozambique, also Zimbabwe’s highest and lowest points are found here [25]. The highest point is 2592 m above sea level which is found at Nyanga mountains and the lowest is at the intersection of Save and Runde rivers which is at 162 m. The Nyanga mountain is a source of three rivers namely the Pungwe River which flows due east into Mozambique, the Gairezi River, and the Nyamuziwa River.

The largest water bodies in Zimbabwe are the Victoria Falls and the Zambezi River on which both are located at the border with Zambia to the west. The Victoria Falls is claimed the largest in the world basing the argument on its height of 108 m and a width of 1708 m [25]. The water bodies constitute 26,572 km^2, and this is around 6.8% of the whole geographic area of Zimbabwe. Zimbabwe receives 266,666 million m^3 as an annual mean rainfall of which 7.5% of it is carried by rivers.

However, the mean annual evaporation of 1200 mm to 1800 mm is quite high thus creating a deficit in the water balance throughout the year. Highest rainfalls of 2000 mm are recorded in the eastern highlands whilst over one-quarter of the land area in the country receives precipitation which is less than 600 mm [26]. The dry season in the country is seven months in a year hence temporary water shortages have been observed over the recent years.

The hydrography of Zimbabwe comprises 6 basins in which the largest ones are the Limpopo river basin and the Zambezi basin. Parts of Masvingo drain into the Save river basin and the Indian Ocean. There is an inland drainage basin of Okavango which goes through the Nata River to which the Matabeleland western parts connect. The Buzi river drainage basin and the Pungwe River cover the southern and the northern parts of Manicaland and both drain into the Indian Ocean through Mozambique. In summary, Zimbabwe shares borders with South Africa to the South, Zambia to the north and Botswana and Mozambique to the west and south respectively.

Zimbabwe lies at the north of the tropic of Capricorn and observes a temperate climate with vast solar resources [27]–[29], to be further discussed in the literature review and methodology chapters. There are two main seasons; cool dry winters, which are observed from May to August and warm wet summers, observed from November to March [14].

2.2. Energy sector

The energy sector of Zimbabwe has experienced a gradual growth in recent years. Feasibility studies of renewable energy resources especially solar PV have been contacted recently and it has been concluded that such systems are feasible in almost the whole of Zimbabwe [27], [30]. Unfortunately, efforts to harness solar and wind resources on a large scale are still at an early stage. Zimbabwe relies heavily on hydroelectric power. However, the majority, around 90% of the rural population as well as peri-urban areas still depend on kerosene and wood fuel for heating, lighting and cooking, while diesel power systems are utilized for other tasks like grain milling due to the absence of electricity in the rural areas [10]. Biomass, therefore, still remains the popular utilized energy source as it still accounts for around 66% of the used energy.

Agricultural activities, both on large and small scales, the generation, transmission, distribution and consumption of energy and many other human-influenced activities have been reported to be the major causes of high carbon dioxide emissions globally. Zimbabwe has suffered a rapid increase in energy demand mainly due to economic growth and population growth. There has been an insufficient supply of electrical energy, as of 2014, around 7.25 million out of 14.6 million [31] that is almost 50% of Zimbabwe's population did not have access to basic electrical energy services. This deficit in meeting the electrical energy demand saw Zimbabwe importing almost 35% of its demand [30], [32]. The consumption rate has been growing rapidly and the current generation technologies are unable to meet this increasing demand. Due to this fact, there is an urgent need to exhaust all the possible electricity generation technologies so as to achieve 100% electrification.

Due to the relationship between human development and access to energy, Zimbabwe is currently categorized in countries with a low human development index (HDI) of 0.49 [33]. With a very low life expectancy at birth of 33.5 years as of 2002, Zimbabwe has a low GDP per capita of US$ 2,400 [33] and 0.92 metric tons as the value for the carbon dioxide emissions per capita [34].

2.2.1 Electricity sector structure

The Zimbabwe electricity sector is overshadowed by the Zimbabwe Electricity Supply Authority (ZESA) Holdings which is a utility that is government owned. The subsidiaries are the Zimbabwe Electricity Transmission and Distribution Company (ZETDC) which is the company that runs the transmission and distribution services and networks. The ZETDC also handles regional trading through that Southern African Power Pool (SAPP). Another subsidiary for ZESA Holdings is the Zimbabwe Power Company which manages the five major power stations in Zimbabwe namely; the Kariba South hydropower station, Hwange thermal power station, Harare thermal power station, Munyati thermal power station and the Bulawayo thermal power station [35]. Additionally, some Independent Power Producers (IPPs) are also available for the generation of electricity in Zimbabwe. These include the Charter IPP which is a 500 MW co-generation power plant and the Nyamigura IPP which is a 1.1 MW hydroelectric plant. Both of these entities sell their electricity to the national grid, though some small IPPs exists as well but independently dispose of their generated electricity. Figure 2.2 shows the institutional arrangements in the Power sector in Zimbabwe.

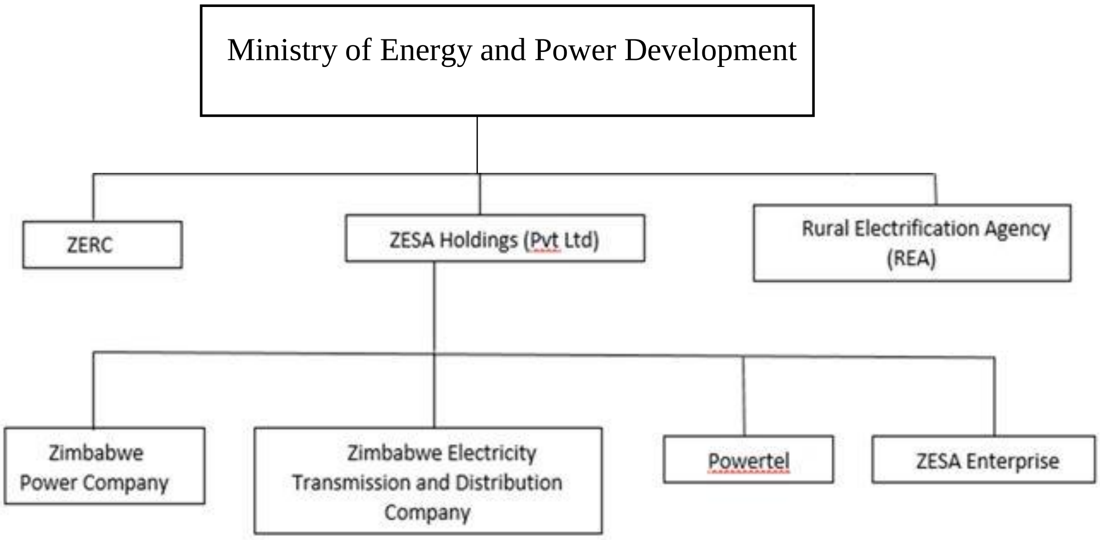

Figure 2.2. The institutional arrangements in the power sector in Zimbabwe.

The following are detailed operations of the institutions in the power sector of Zimbabwe:

- **The Ministry of Energy and Power Development (MEPD)**

The function of the ministry is to formulate the energy policy, monitor the performance and regulation of the energy sector as well as promoting new and renewable energy sources. The ministry supervises all the other institutes in Figure 2.2 with responsibilities in the energy sector.

- **Zimbabwe Power Company (ZPC),**

The Zimbabwe Power Company is responsible for all generating stations and for the supply of power to the transmission grid.

- **Powertel**

These are responsible for providing communication services to the power companies, and offer data services to the public.

- **Rural Electrification Agency (REA)**

The Rural Electrification Agency (REA) is responsible for grid extension in rural areas and for supplying specific institutions, such as schools, clinics, government offices, and community-initiated projects.

- **Zimbabwe Electricity Regulatory Commission (ZERC)**

The ZERC reports to the Minister of Energy and Power Development. The mandate of ZERC includes promotion of competition and private sector participation in the power sector, licensing and regulation of businesses engaged in the generation, transmission, distribution, and supply of electricity, arbitration and mediation of disputes, establishing operating codes and standards for the sector and issuing guidelines, and advising stakeholders about electricity services.

- **Zimbabwe Electricity Transmission and Distribution Company (ZETDC)**

ZETDC is responsible for transmitting and distributing electric power and for its sale, including meter reading, billing, cash collection, and credit control of the retail business. It is also responsible for regional trade in power.

The total installed generation capacity in Zimbabwe is 1,960 MW. The installed fossil fuel capacity is 1,220 MW and the hydro capacity is 750 MW. In terms of percentage, Coal constitutes 62% and the rest 38% is Hydro [36]. Zimbabwe is furnished with vast conventional energy sources for electricity generation, with main ones being hydro, coal-bed methane and coal. As of June 30, 2015, the total annual energy consumption of Zimbabwe is 12.57 billion kWh [37]. This entry consists of total electricity generated annually plus imports and minus exports, expressed in kilowatt-hours. The discrepancy between the amount of electricity generated and/or imported and the amount consumed and/or exported is accounted for as loss in transmission and distribution**.** Zimbabwe has been suffering a huge electricity deficit since it only generates a total of 1300 MW against a peak demand of 2200 MW [30] which results in a national electrification rate of about 40 per cent with the electrification rate of rural areas around 19 per cent.

2.2.2 Key Challenges in the Electricity Sector

The major problem in Zimbabwe is capacity. The Hwange Coal Plant which is one of the major power plants in the country was commissioned in 1987 and since then no new developments have been made to the country's generation sector. Additionally, there is an urgent need for upgrades of almost all coal-fired power stations in Zimbabwe since the majority of these plants have stopped production. These problems are therefore leading to lengthy blackouts throughout the whole country. To try and curb for the deficit, Zimbabwe now imports energy from neighbouring countries as well as encourage the utilization of small-scale generators, though these solutions are still not enough to overcome the problem of under capacity.

2.2.2.1 Reasons for the Prevailing Challenges

The electricity industry has suffered mainly due to operations that are unsustainable. These are as a result of having the distribution infrastructure vandalized. Due to the depreciation of the economy in the last 2 decades, skilled staff are fleeing the country hence the country is short of skilled staff. The country itself is suffering from the availability of capital thus resulting in less infrastructural investments. Additionally, due to the economic crisis as well as policy inconsistencies, the country has failed to attract new investors because they feel it's too risky to invest. Zimbabwe has a very high tariff compared to other countries in the SADC region thus resulting in financial constraints due to non-cost reflective tariffs [38].

2.2.3 Generation technologies

The electricity supply in Zimbabwe comprises both imports and local generation. The main local electricity generation plants are the Hwange power station, Kariba South power station, Harare power station, Bulawayo power station and Munyati power station [12]. Only Kariba is a hydropower plant all the others are thermal power stations with Hwange coal-fired power station being the largest of all the thermal power stations. Imports are from neighbouring Zambia, Mozambique, South Africa and from the Democratic Republic of Congo as well.

The combined total installed capacity in Zimbabwe is 1900 MW against a peak demand of 2200 MW [39]. Additionally, both the thermal and hydropower stations are old as the Kariba hydropower station was commissioned in 1962, the Hwange thermal in 1987 and the other 3 small thermal power plants in 1957 [38]. Kariba power station has been the most reliable one until the water in the dam was significantly decreased thus reducing the generation capacity in 2015. The lack of maintenance of the Hwange thermal power station has resulted in the intermittency of electricity production from this plant which is as well the same case with the other 3 small thermal power stations. Table 2.1 shows the total installed capacity by plant against the actually generated capacity on 16 October 2018. ZPC's total generation on this day was 1150 MW against a peak demand of 2200 MW thus leaving a 47.7% deficit of 1050 MW.

Table 2.1. Power Generation Statistics as of 16/10/2018. [12]

Power Station	Installed Capacity MW	Actual Generation MW	% generation of Installed Capacity
Hwange Thermal	920	376	19.58
Kariba South Hydro	750	774	40.31
Bulawayo Thermal	90	0	0
Harare Thermal	80	0	0
Munyati Thermal	80	0	0
Total	1920	1150	59.89

2.2.3.1. Generation Opportunities in Zimbabwe

- **Coal-** Zimbabwe is furnished with diverse conventional energy sources that can be utilized for the generation of electricity. The main sources comprise coal-bed methane, coal and hydro. An estimated total of about 26 billion tons of coal reserves is available in 21 deposits. 2 billion tons of the total amount of coal can be mineable by employing opencast methods [38]. At the current rate of usage, the Hwange, Munyati, Harare and Bulawayo thermal power plants use 300 million tons per annum for electricity generation.
- **Coalbed methane-** An estimated total of about 600 billion cubic meters is found in the deposits of coal bed methane located in Beitbridge, Chiredzi, Hwange and Lupane.
- **Renewable energy sources-** Renewable energy resources such as wind and solar which are not being harnessed in a commercial scale, are also available in Zimbabwe. More hydroelectricity potential is available on the Zambezi River which is expected to be equally shared between Zambia and Zimbabwe. 10 TWh per annum is currently being harnessed against an estimated 37 TWh per annum. Solar resources have proved feasible in almost the whole of Zimbabwe [30] since an average total of 2000 kW/h/km^2/year of solar radiation is available. This radiation is available for about 4000 hours per year [27]. At this radiation and resource availability, solar photovoltaic could be utilized to generate a total of 10000 GWh of energy.

2.3. The Current and Future Projects

In 2016, a total amount of US$ 482 million had been directed by the government of Zimbabwe to rural electrification projects as well as to improving the power network of the country. This provided amount was to be financed through:

- ZETDC's own resources with a total amount of US$ 89 million;
- Statutory funds amounting to US$ 27.1 million;
- Loan financing of US$ 351.3 million;
- Tax revenues contributing a total amount of US$ 5.5 million; and
- Through development partners with a total of US$9.1 million

The projects which were then supposed to be worked on are;

1. **Kariba South Extension-** Which was supposed to be completed by March 2016 and add a total electricity generation of 300 MW to the national grid, but was only finished in 2018
2. **Hwange Expansion-** This project is estimated to generate an additional 600 MW [12]. The tender has been granted but the projected is yet to be executed with financial closure activities still underway. It is expected to be finished in 42 months after the day of the financial closure.
3. **Emergency or Diesel Generator Power Plants-** The government of Zimbabwe is considering to rented diesel power plants to generate a total of 200 MW at a short notice to try and curb for the current energy deficits. These deficits are mainly arising from the reduced reliability of the Hwange Power station and due to a reduction in the generated electricity by the Kariba Power station. The tender was already awarded and the station was to be constructed at Dema Growth point and start feeding to the national grid by February 2016. The project is still not operational as of October 2018 due to tariff disputes.
4. **Batoka Gorge Hydro Plant-** A total of 2400 MW was supposed to have been generated from this project. Conceived in 1993, the project was never finished up the time of completion of this thesis, of which feasibility studies were supposed to be done by July 2016. Again, up to the completion of this thesis, feasibility studies were still undone.
5. **Biogas Energy-** Still no progress has been made on rural electrification. The government is, therefore, encouraging the use of biogas for rural electrification. A

total of 18 biogas digesters were commissioned and constructed at mission hospitals and rural schools in 2015 [12].

6. Solar Power- As of the end of 2015, Zimbabwe Power Company (ZPC) had awarded the tenders for the construction of three solar photovoltaic plants at Gwanda, Insukamini and Munyati with a size of 100MW each. Feasibility studies of these project are yet to be done, and the projects were supposed to be completed in 24 months but unfortunately, they have not yet started. As of 17 October 2018, the ZPC reports on their website that the status of these projects is still 'Not yet applied for.' This might be due to the fact that there have been arguments about the clarity of the tender awarding procedure which was suspected to be corrupt [12].

Another project which is yet to be completed and as well lagging way behind their forecasted deadline dates include; the Lupane Coalbed Methane, Gairezi Hydroelectric Scheme and the Hwange Power Station Plant Improvement and Life Extension. These projects are yet to be completed as well thus the country still has a huge deficit still being partially met by imports. Not only is this method unsustainable, but also costly especially to a nation facing economic and foreign currency crisis like Zimbabwe.

Significantly for this research, construction of many hybrid solar PV/Wind large-scale power systems does not play any role in Zimbabwe's expansion plans for electricity generation despite the availability of these renewable resources in abundance [30]. Even though solar photovoltaic has been mentioned, according to [30], the chosen location by the government are not the best sites for harnessing the resource. In their study, they already reported the feasibility of the solar PV systems, which are still not yet done by the government. Additionally, the government does not mention anything about harnessing the wind resources, be it harnessing in a small or a large scale. In a country facing such a huge energy deficit, deteriorating power network and rich in renewable energy resources, frantic efforts to harness as much as possible from the available resources is not only important but sustainable as well.

Additionally, Zimbabwe should also take advantage of the rapid decrease in solar and wind energy systems' prices and harness as much as possible from these resources. The recent increase in worldwide fuel price should definitely discourage the government from including much generators into the electricity expansion generation mix. There is, therefore, an unquestioned need for a sustainable electricity generation mix which is not only important for Zimbabwe's economic recovery but for the prevention of the degradation of the environment as well. There is also a need for renewable energy policy and gazetted renewable energy tariffs which are attractive to investors because as a country, Zimbabwe needs these private as well as foreign investors. The following chapter gives a detailed outline of the literature review.

CHAPTER 3

LITERATURE SURVEY

There have been a lot of published hybrid feasibility study papers and a couple noteworthy ones are mentioned here. Yousif, Sahal and Sandro highlighted the importance of renewable energy paying attention to the one harnessed from solar-wind hybrid systems. After obtaining data available in Jordan, they chose Al-Tafila district 2 as the best location of their study. They modelled a system using HOMER software in which they determined the capital cost as well as the cost of energy (COE) of their proposed system [7]. Hussein and Fathi modelled a system to determine the net present cost (NPC), cost of energy (COE) and the renewable energy fraction (RES). They chose Ras Elnaqab area 2 in Jordan as well and used MATLAB and HOMER software to size and economically analyze their system [8].

Sonali and Sayed determined the demand, capital cost and cost of energy for different types of resources [9]. Said and Mahmoud analyzed different PV-Wind hybrid configurations using a diesel generator as a backup system for a stand-alone system in a village in Algeria, and they also determined the cost of energy (COE) [10]. Chedid developed his own software that determined the operational cost of a WIND/PV/DIESEL system [11]. He found out that the operational cost of a diesel power plant will be reduced after the renewable energy resources are included. Using a Quasi-Newtonian method; Ashok determined a system that provided the lowest cost of electricity in a village in India. He found out that a hybrid system consisting of PV/WIND/DIESEL/Micro hydro would provide electricity for a complete 24 hours at 0.14 USD/kWh [12]. Furthermore, there are studies to determine optimization techniques for hybrid PV/Wind systems but mostly employing HOMER software [40]–[48].

Almost all the papers reviewed for this present study determined the cost of electricity but never included externalities in their determination of the LCOE so as to effectively argue the feasibility of their designs. Frank, Victor P, Irah, and Victor M, studied 11 locations in Sweden. They determined the cost of electricity of a hybrid PV-wind system and compared it to that of PV alone. They also determined the effect of the size of the load on the proposed system [13]. They did not mention how their proposed system's cost of energy compares with the current grid tariff in Sweden. The contribution of this study is to carry out a feasibility study of a grid connected hybrid PV-Wind system, maximize RES fraction, outline the amount of annual carbon dioxide emissions reduced from the atmosphere and determine a suitable LCOE for the hybrid systems. Table 3.1 is a summary of the hybrid Solar PV-Wind Literature Review (Thesis-Based).

Table 3.1. Solar PV-Wind Literature Review (Thesis-Based).

Study	Country	System type	System design	Model	Conclusion
Zhou Wei (2007) The Hong Kong Polytechnic University	Hong Kong and remote area of Guangdong province	Stand-alone with a battery bank	Techno-Economic	Generic Algorithm (GA)	The system proved feasible. Investment cost minimized
Headley Stewart Jacobus (2010) University of Maryland, College Park	quantifying the measurable Operational Costs for an experimental hybrid power system in Sierra Leone	Stand-alone	Economic	Hybrid 2 and HOMER	System cost was minimized
Mehdi Vafaei (2011) University of Waterloo	developed a microgrid for a remote community in northern Ontario (Canada)	Stand-alone microgrid (hydrogen energy storage)	Economic	GAMS and MATLAB	LCOE was minimized and demand was met
Umarin Sangparich (2013) University of Strathclyde	Rural electrification in Thailand Two case studies;30kW peak and 1MW peak (assumed Load)	Off-grid (Battery bank)	Economic	Sum Component Cost Model and Total Cost Model	The cost models are feasible for system analysis and design
K M Iromi Udumbara Ranaweera (2013) University of Adger	Rural electrification in Sri Lanka (Siyambalanduwa village)	Off-grid (diesel back up)	Economic	HOMER	The system can meet demand at 0.3 $/kWh
George N Prodromidis (2014) University of Patras	a based stand-alone system that is already installed in Leicestershire, UK.Use the same methods for 3 Greek islands	Stand-alone (Electromechanical Storage Bank)	Economic	HOMER	System feasible with low wind speed turbines

Berino Francisco Silinto and Nelson Alberto Bila *(2015* Unversity of Eduardo Mondlane Maputo	feasibility study of a hybrid PV-Wind System for rural electrification at the Estatuene Locality in southern Mozambique	Stand-alone Battery Bank	Technical And economical	HOMER	LCOE of 0.34$/kWh Greater than 0.1$/kWh of Mozambique
Collen Zalengera (2015) Loughborough University	techno-economic feasibility of increasing hours of electricity services on Likoma Island in Malawi	Island-grid connected to diesel generators	Techno-economic	HOMER	24 hours supply of electricity whilst connected to the grid. LCOE of diesel alone was 0.88$/kWh and was reduced to 0.44$/kWh
Pappas Konstantitos (2016) Technological Educational Institute of Western Greece	A house at Rhodos Island in Greece	Stand-alone with battery storage	Economic	MATLAB	System feasibility is proven based on LCE and NPV
Remember Samu (2018) METU NCC	The Whole of Zimbabwe 16 locations	Grid-connected	Environmental, Social and Techno-economic	Excel-based	The Goal is to maximize RES Fraction and reduce GHG emissions significantly. Electricity energy demand forecast up to 2030 and Analyze power quality.

3.1. Utilized Models

A wide range of software and models exist in literature to meet different goals. The common types are production cost models, optimal power flow, expansion planning, economic dispatch, network stability unit commitment and hydrothermal coordination. In expansion planning, models make use of multi-decade time scale in the optimization of investment decisions in transmission, generation or both.

Transient stability analysis models make use of sub-second time scales in monitoring network flows. Unit commitment, production cost, economic dispatch and hydrothermal coordination models pursue to optimise the generation output in the medium-term. All these models have a common objective which is to minimise costs but constraints on plant start-ups and shutdowns, water conservation, carbon dioxide emissions and environmental friendliness are not considered.

Whilst previous works have provided quite an overview of decision support tools and models; I would like to point out 3 specific models; WASP, VALORAGUA, and ReEDS. ReEDS are mostly used by US researchers in the evaluation of the renewable energy technology integration to the existing system whilst WASP and VALORAGUA are used internationally. NREL developed the Regional Energy Development System (ReEDS) which is a cost-minimizing model that is designed for transmission expansion planning, storage, and long-term generation. ReEDS is a very powerful expansion tool but it is only designed for US power systems. VALORAGUA is internationally designed for hydro-thermal coordination representing uncertainties in hydro-inflows through the following hydrological conditions; wet, dry and average. Wein Automatic Simulation Planning package (WASP) is a probabilistic planning tool used to determine the lowest cost expansion plan for a generation for different input conditions.

HOMER software has been the most utilized software which is capable of techno-economic analyses and well as optimization of renewable energy systems' configurations. However, there are also limitations to this software. HOMER software does not make an analysis of the externalities such as the annual avoided cost of carbon. Also when determining technical feasibility analysis of the RES, it bases the evaluation on RES fraction thus neglecting other important parameters such as the demand-supply fraction [49]. Finally, a comparative analysis between HOMER and RETScreen software conducted by [50] showed that the majority of costs determined by RETScreen software were less than those obtained from HOMER.

As observed, there are there limitations accompanied by HOMER software. Against this backdrop, a new Microsoft Excel-based model was developed for this study. The model employs pre-defined mathematical equations to determine energy produced hourly from various RES configurations. In the case of this study, the model determines hourly generated wind, PV and hybrid PV/wind energy systems. A techno-economic, as well as environmental analysis of the systems, is then performed by the model. Output parameters such as COE, LCOE, Payback Period (PBP), NPV, LSPS and amount of CO_2 avoided into the atmosphere are then determined. Microsoft Excel-based models close to the one developed in this study were also utilized by [51], [52].

3.2. Assessment of wind and solar power in Zimbabwe

Currently solar is used for small-scale household solar lighting and irrigation purposes whilst a few wind turbines for water pumping purposes are still operating in some farming regions. Limited literature for solar PV and wind exists in Zimbabwe. The available studies were done by [27], [28] in which they did a feasibility study of a grid connected hybrid solar PV-Wind energy system in Gwanda. This study was a techno-economic one and their LCOE was greater than the current grid tariff. Another study by Samu and Fahrioglu on the potential of grid connected solar PV in the whole of Zimbabwe proved that it is feasible to have localized PV plants in 28 different locations [39]. A wind analysis study by [53] suggests that wind energy can only be harnessed for water pumping purposes even though a satellite study by International Renewable Energy Agency (IRENA), assumed a possibility of harnessing around 39 GW of electricity from wind resources in Zimbabwe [54].

Renewable energy resources utilization is still lagging behind in Zimbabwe. Plans to invest in solar PV technology are at an advanced stage as Zimbabwe is looking forward to the installation of 300 MW [30]. Zimbabwe as a landlocked country is not rich in wind energy resources [32], [67]. However, with the advances in technology leading to the development of wind turbine prototypes with a lower cut in speed, it can be possible to harness wind energy in Zimbabwe. Wind energy had been used for pumping water to meet farm requirements using windmills. A study on the wind potential in Zimbabwe estimated that it might be possible to generate electricity at a hub height of 80 m, resulting in the manufacturing of wind turbine prototypes rated at 4 kW and 1 kW, which tested well and were installed in Rusape [68], [69].

However, there is little scientific research on the wind energy potential in Zimbabwe. With annual average wind speeds around 3.2m/s, most parts of Zimbabwe have wind potential only viable for pumping purposes. The Eastern Highlands and some parts of Bulawayo have with higher wind speeds [70]. Another study in Gwanda, located in the Matabeleland province of Zimbabwe, confirmed a yearly average wind speed of 4.75 m/s [32].

Further related studies for wind potentials confirmed the feasibility of high yearly yields of wind energy in many African countries [71]. [72] Did a wind energy analysis along the coasts of Ghana in which they only took into account six stations. By employing different methodologies, wind potential assessments were carried out in many different parts of Africa [73], [74].

3.3. GAP

Missing from existing literature

- Addition of externalities into the techno-economic analysis and when comparing the LCOE with the grid tariff and basing feasibility of a system on power quality (LSPS), to avoid blind capital spending.
- Hybrid renewable energy studies for Zimbabwe.
- Wind energy potential for electricity generation in Zimbabwe
- Grid-connected solar PV feasibility analysis for electricity generation in Zimbabwe
- Electricity demand projection for Zimbabwe is missing.

3.4. Contribution

Efficient utilization of hybrid grid-connected renewable energy systems for 16 chosen locations in Zimbabwe by also considering externalities on determining the economic parameters was done in this study. Electricity demand forecasting and determination of the generated power quality by the RES in these locations in Zimbabwe make this thesis prominent. Considering all economic parameters to develop a new model that is close to a real system. A feasibility analysis of both wind and solar PV potentials for electricity generation in Zimbabwe was also performed in this study. A detailed comparison of the following system configurations as to efficiently determine the suitable system configuration was done;

- PV systems alone
- Wind turbine systems alone
- Hybrid solar PV/Wind/ESSs
- Hybrid solar PV/Wind without ESSs

The following chapter outlines Zimbabwe's wind and solar resources as well the potential of power generation from them.

CHAPTER 4

SOLAR AND WIND TECHNOLOGIES AND RESOURCES

4.1. Solar Technologies

The major mature enough solar technologies for large-scale deployments are the concentrating solar power (CSP) and the solar photovoltaic (PV) technologies. A brief overview of these major technologies is given below. For this study, solar PV technology is the one chosen and the reasons for this decision are also to be outlined in detail.

4.1.1 Solar PV

In 1839, Becquerel discovered what he termed the photovoltaic effect, which then enabled a possibility to generate electricity by utilizing incoming energy from the sun. This principle was then improved and employed to enable the production of the first photovoltaic solar cell in 1954 [55]. Ongoing research up to date is continuing so as to improve cell efficiency and performance in general. [56] Gave a more detailed explanation of the full physics behind the photovoltaics.

The semiconducting material used for the generation of the first solar material was crystalline silicon (c-Si). Due to their high efficiencies reaching greater than 17%, the crystalline silicon cells are still the most utilized in today's solar cell technology, thus amounting to a market share above 80% [57]. Thinner cells called thin-film PV developed using less expensive materials are still at an early stage of development. However, they have proved to be less efficient than crystalline Silicon as of the time this present study was performed. The most common cells in this group are copper indium gallium selenide (CIGS), cadmium telluride (CdTe) and amorphous silicon (a-Si).

Initially, the development of PV technology was though not to be feasible due to the performance limitations on balance of system (BOS), lack of manufacturing scale, challenges on the availability of the raw materials and most importantly the capital costs were significantly high. There has been a rapid decrease in the market prices of these PV systems, thus attracting more audience and investors resulting in an increase in the manufacturing industry. This has then resulted in an exponential increase on the global installed capacity of solar PV. Since 2006, an annual growth rate of 58% has been recorded in installed solar PV. The total world solar PV installed capacity by the last quarter of 2018 was above 104 GW [58].

4.1.2 Concentrating Solar Power

The concentrating solar power technology resembles traditional fossil fuel-based technologies that employ Stirling or Rankine cycles that convert heat energy to work as opposed to PV technologies where the photovoltaic effect is used for the generation of electricity. The incoming solar energy is focused onto a heat transfer fluid which then produces either steam in a Rankine cycle or results in an isothermal expansion in a Stirling cycle thus creating mechanical torque to drive a generator for electricity production. The methods employed on focusing the solar rays onto the fluid vary in CSP technologies with power towers, dish/engine systems and linear concentrators being the most popular designs. Due to their high initial costs compared to solar PV technologies, locations for potentials for CSP technologies are more limited. This is due to the fact that in CSP plants there is need for the availability of water to be used for cooling and they also require a large land area for the collection of the direct normal insolation (DNI), which is the solar radiation that strikes normal to the reflecting surface so that the working fluid can be heated for steam creation. On average solar tower designs and parabolic troughs which employ the Rankine cycle, on average, need 80 gallons of water per MWh and 750 gallons per MWh for dry and wet cooling respectively. The water requirements are decreased in dry cooling techniques, but so is the plant efficiency as well accompanied with costs that are slightly higher [59]. In engine/ dish systems which utilize the Stirling cycle, water is only used in the washing of the reflective surfaces and a total amount of about 20 gallons per MWh is required [60]. The total world CSP installed capacity by the last quarter of 2018 was around 1 GW [61].

4.1.3 Chosen Solar Technologies for this Study

Only Solar PV technology was chosen for this present study over CSP technology. The man reasons why CSP technology was excluded in this study are;

- CSP technologies require large quantities of water,

- Since CSP is a still-developing technology, the installations still need high capital costs, and
- A huge land area is required for CSP plant construction.

CSP technology can only use direct solar radiation, contrary to solar PV plants which can utilize both direct and indirect sunlight [62]. Areas that are close to water bodies, close to the electricity grid and a minimum of 6 $kWh/m^2/day$ of DNI are considered feasible for constructions of CSP plants. An area of around 250 000km^2 is suitable for the construction of CSP plants and only 10% of this suitable land area is utilized, the generated electricity will be around 892 GW [63]. The constraints accompanied with CSP technology should not, however, limit Zimbabwe to invest in such a technology in the future. South Africa has CSP projects which are already at advanced stages, and this will then increase the basic knowledge on the performance, financing and base costs of CSP plants in Africa.

4.1.4 Solar PV Potential in Zimbabwe

Zimbabwe receives abundant solar resources throughout the whole year. The average daily solar insolation in the country is in the 5.7-6.5$kWh/m^2/day$ [63]. Figure 4.1 shows the map for the global solar radiation in Zimbabwe. The western and northern regions of Zimbabwe receive the highest solar irradiation. It has been reported that the country if feasible to harness more than 300MW from solar PV systems [64]. Solar energy is not yet being harnessed on a large scale. The small-scale harnessing is done mainly in rural areas, some social institutions like hospitals, clinics, police stations and schools, and in private homesteads. The individual small home solar systems' demand is increasing thus attracting quite a number of companies for small solar water heaters and small PV installations. The national telecommunication company is also utilizing solar through solar-powered base stations. These base stations are mainly electrical appliance charging.

Real data for annual solar radiation levels are still unavailable therefore to ensure the possibility of this study, Meteonorm V7 software was employed for the generation of average hourly solar radiation as well as wind speeds data. This methodology might then be accompanied by some shortcomings then. These shortcomings might include uncertainty and variability in the radiation data. Variability accounts for the changes in the solar insolation over a certain period, whether minute-by-minute or hourly scale. Variability is directly related to the intermittency problem then, thus affecting the generated electricity output. This then raises voltage or system stability issues. The spatial variations in solar insolation levels are described by uncertainty. It is of paramount importance to have real locational solar radiation data when studies being conducted are considering a multimode system [62]. In summary, a detailed study on the techno-economic and environmental feasibility analysis of the solar energy potential in Zimbabwe was performed by [30]. In this study then confirmed the potential feasibility of solar PV technology in the whole of Zimbabwe with Chegutu being the most feasible and Chiredzi the least.

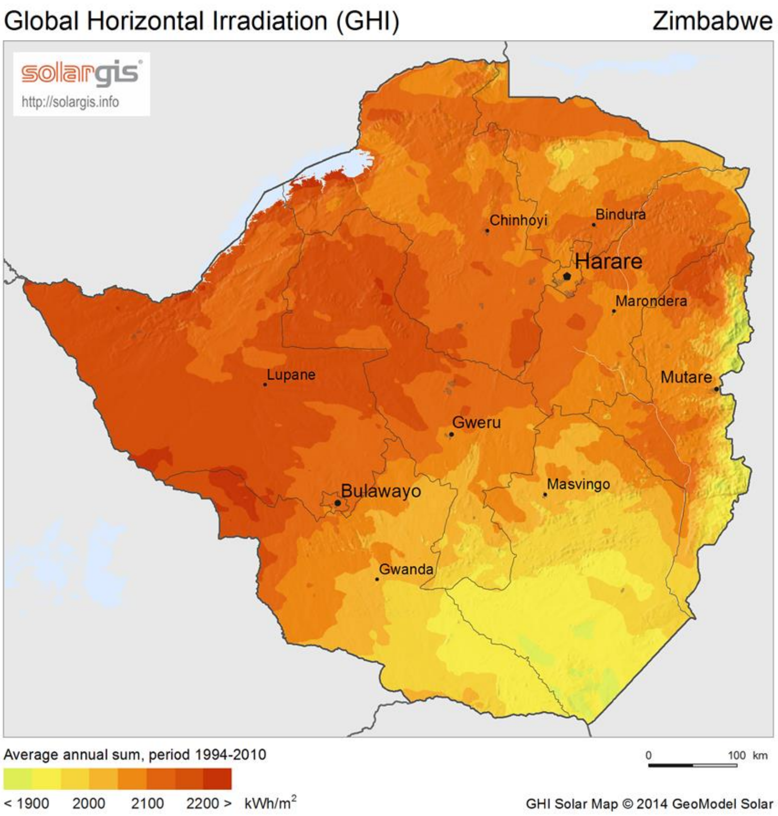

Figure 4.1. The Global Horizontal Solar Irradiation map of Zimbabwe [2].

4.2. Wind Turbine Technologies

There are two major categories of wind turbines namely the vertical axis wind turbines (VAWTs) and the horizontal axis wind turbines (HAWTs). However, the most dominating in the global market are the HAWTs [65]. These have been developed and improved over time and still more research is being done to further increase their efficiency and reduce their cost.

There is a wide variation in the size of the wind turbines. Normally, the blade length determines the electricity generation capacity of the wind turbine. The HAWTs are now commonly being equipped with three turbine blades with the largest ones having blade lengths of more than 100 feet and height taller than a 20-storey building [66]. Almost all large-scale wind farms generate electricity from horizontal axis wind turbines.

VAWTs are basically constructed by attaching the top and the bottom of a blade to a vertical rotor. The most common type of this type of wind turbine technology is the Darrieus wind turbine designed in 1931 [66]. Due to their low efficiency and performance compared to the HAWTs, only a few VAWTs are being used today even though more research is still being done to try and improve them. Figure 4.2 and Figure 4.3 show the two major types of wind turbines.

Figure 4.2. The horizontal axis wind turbine (HAWT) [3].

Figure 4.3. The Darrieus-Rotor vertical axis wind turbine (VAWT) [4].

4.2.1 Wind Technology Chosen for the Study

As outlined their studies, [27], [28], the horizontal axis wind turbine technology (HAWT) is the best choice of technology for this study. This claim comes with supporting evidence that globally this type of technology is the one being utilized the most. The reason being that the HAWTs have proved to have better performance and efficiency as well as less cost compared to the VAWTs.

4.2.2 The Cost of Wind and Solar PV Energy Production Compared to its Alternatives

As many competitors are emerging in the market and there have been many technological advances in wind energy harvesting, a 90% decrease in the cost of energy production from wind since 1980 has been observed. Yes, there has been a significant decrease in energy production from wind, but is it cheaper than the other alternative energy sources? In responding to this question, I will consider different factors related to wind energy harvesting and the corresponding Levelized Cost of Energy (LCOE). All energy generation types depend on economics, their feasibility and optimization is of paramount importance

Wind power market advanced in 2014, and as shown in Table 4.1, it has been considered as one of the power generating sources with the least cost and this has given rise to new markets in Latin America, Asia and Africa. The main disadvantage on wind turbines is their installation cost even though maintenance costs over a long-term are relatively cheap. As discussed before, land can also be a limiting factor since these machines are very huge and for more electricity production, more turbines should be installed hence more land is required. The other downside is the wind system insurance which can be relatively high. In comparing the cost of energy production from wind and solar PV with relative to other sources, equation (1) is used [6].

Levelized Cost of Electricity;

$$\text{LCOE} = \frac{C_i + \sum_{t=1}^{n} \frac{M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_{gen,t}}{(1+r)^t}} \quad (USD/kWh) \tag{1}$$

Where C_i is the initial cost of investment, M_t is the annual fixed Operation and Maintenance cost, F_t is the annual fuel cost , $E_{gen,t}$ is the annual energy generation, r is the annual discount rate and n is the lifetime of the system in years. The initial cost includes the cost of equipment, cost of land, transport cost, labor cost and the cost of connecting the system to the grid. A cost comparison of energy sources was carried out in the US in which they considered the life time of the systems as a period of 25 years and the results are summarized in Table 4.1 [7].

Table 4.1. A comparison of the average LCOE of most popular energy sources, where the cost is represented in US$/kWh.

Plant Type	Cost (USD/kWh)
Coal	$0.095-0.15
Natural Gas	$0.07-0.14
Nuclear	$0.095
Wind	$0.07-0.20
Solar Photovoltaic	$0.125
Solar Thermal	$0.24
Geothermal	$0.05
Biomass	$0.10
Hydro	$0.08

4.2.3 Wind Energy Generation in Zimbabwe

As part of the contribution of this study, an analysis of economic viability and potential of wind energy in Zimbabwe employing RETScreen modelling software is performed. As the energy situation in Zimbabwe is deteriorating, this analysis highlighted the feasibility of harnessing wind energy and how the country can help curb the current energy shortages in an environmentally friendly as well as sustainable manner.

There has not been any feasibility analysis of the wind potential for electricity generation for Zimbabwe and against this backdrop, this present study analyses the wind energy potential in Zimbabwe in terms of; energy production costs and savings, energy production, operation and maintenance costs, reduction in greenhouse gas emissions and financial feasibility of 10MW wind farms for 11 different stations scattered all over Zimbabwe was done. Following is a detailed study performed for the analysis of wind energy potential in Zimbabwe.

- **Methodology**

Meteonorm V7 software was used to generate Typical Meteorological Year 2 (TMY2) wind speed data for the 11 locations in Zimbabwe. RetScreen V4 modelling software was then employed to further analyse the wind energy potential. Typical Meteorological Year (TMY) data would have been more accurate for the present analysis because of the atmospheric losses due to changes in meteorological conditions [75]. However, it is difficult to access TMY data, and hence TMY2 data developed by NREL was instead used.

In this study, the mathematical details of the generation of TMY2 data were excluded due to their availability in already existing literature. The RETScreen software used in this study was developed by National Resource Canada. An assessment of the energy production costs and savings, energy production, operation and maintenance costs, life-cycle costs, reduction in greenhouse gas emissions and financial feasibility determination of the wind energy systems were done using the RETScreen modelling software.

The locations under study were chosen based on their accessibility to the grid, availability of their data set from Meteonorm V7 software and NASA global solar radiation database. The geographical locations of the locations as well as the respective average wind speeds are shown in Table 4.2. For the accurate analysis of wind potential, there is a need to take into account some losses and full consideration of some important coefficients.

Table 4.2. Coordinates of the 28 locations in Zimbabwe.

Location	Longitude (°E)	Latitude (°N)	Elevation (m)	Annual Average wind velocity (m/s)
Beitbridge	30.00	22.20	696	3.4
Bulawayo	28.60	20.20	1,344	3.2
Chegutu	30.10	18.10	1,261	3.4
Chikore	32.30	17.80	974	3.6
Chinhoyi	30.20	17.40	1,293	3.5
Chipinge	32.60	20.20	576	3.6
Chiredzi	31.70	21.10	425	3.5
Dorowa	31.80	19.10	1,106	3.5
Gokwe	28.90	18.20	1,078	3.5
Gwanda	29.00	20.90	1,096	3.2
Gweru	29.80	19.50	1,311	3.3
Gwetera	32.00	16.90	564	3.6
Harare	31.00	17.80	1,472	3.6
Kutsaga	31.10	17.90	1,480	3.5
Hwange	26.50	18.40	905	3.6

Inyati	28.90	19.70	1,192	3.3
Kamativi	27.10	18.30	967	3.6
Kariba	28.80	16.50	646	3.4
Karoi	29.70	16.80	939	3.5
Kwekwe	29.80	18.90	1095	3.4
Marawa	29.30	17.80	960	3.5
Marondera	31.60	18.20	1,392	3.6
Masvingo	30.90	20.10	1,095	3.2
Mhangura	30.20	16.90	862	3.5
Mt Darwin	31.60	16.80	782	3.6
Mutare	32.70	19.00	1,332	3.7
Ruwa	32.60	19.20	976	3.7
Shurugwi	30.00	19.70	1,281	3.4

- **Financial analysis**

An analysis of the wind energy potential is of importance to the investors and decision makers in both private and public sectors. RETScreen modelling software version 4.0 was employed in this present study for the financial feasibility study of proposed 10MW wind power plants. Some of the financial parameters used to perform this analysis are; energy cost, inflation rate, greenhouse gas emission credit, project lifetime, electricity export escalation rate, etc.

The financial input parameters and some assumptions in Table 4.3 were used for the cost analysis. The source of some input parameters is RETScreen Clean Energy Project Analysis software unless otherwise stated.

Table 4.3. Input parameters for the financial analysis [76].

Parameter	Value
Energy cost escalation rate	5%
Inflation rate	-0.95% [77]
Discount rate	7.17% [78]
Interest rate	10.71% [79]
Project lifetime	20 years [75]
Debt ratio	70%
Debt interest rate	7%
Debt term	20 years
Transmission and distribution losses	18% [80]
Electricity export escalation rate	4%

Development	US$63/kW [75]
Installed Capital Cost	US$1,200/kW
Feasibility study	US$35,300
Balance of plant	US$418/kW [75]
Renewable energy production credit	0.025 $/kWh
Miscellaneous	US$418/kW [75]
Annual Operation costs	US$10/kW/year
Engineering	US$24/kW [75]
Renewable energy production credit duration	10 years
Renewable energy credit escalation rate	2.5 %
GHG emission reduction credit	40 $/$t_{CO2}$ [81]
GHG reduction credit	21 years
Energy cost escalation rate	5 %

In the first phase, before the construction of the wind farm, the following were considered:

A feasibility analysis comprising resource assessment, detailed cost estimate, site investigation, environmental assessment, greenhouse gases baseline study, project management, report preparation, and travel and accommodation.

The development, consisting of site survey and land rights, project financing, contract negotiation, project management, permits and approval, travel and accommodation, greenhouse gases validation and registration, and legal and accounting.

During the implementation of the wind power project, engineering, power system and balance of system and miscellaneous were considered. After project implementation, the periodic costs, contingencies and operation and maintenance costs were then considered. From the analysis, in total, the investment of a 10MW wind farm costs US$17,085,300 and using the rule of thumb by Tom Gray, 60 acres per megawatt that are 242,811 m^2/MW is required for the proposed project [82].

4.3. Problems Related with Wind Energy Harvesting

As expected with any technological advances, there will always be problems accompanying the technology development. The following where the major problems associated with wind energy harvesting;

- **Community Acceptance**

Decisions on the acceptable sites on which wind farms are to be constructed should be made paying respect to other land users or surrounding inhabitants. As stated before these wind farms are mostly located in isolated regions or rural areas since in Sub-Saharan Africa rural electrification has been on the spotlight. A lot of people, especially those who have always stayed in rural areas have a strong bond with their surrounding and their land. Because of some reasons like these, wind turbine installation has been having some objections despite it being viewed globally as a clean source of energy. As it has been scientifically proven that wind speeds increase with height, for these wind turbines to have a maximized efficiency, they have to be very tall. Sometimes they are very tall that they can even be seen from a distance of around forty or fifty kilometres away. Anyone in this range might have his or her attention caught by these machines since most of the time they will be in motion, so this means anyone who dislikes them is constantly reminded of their existence.

- **Environmental Impacts**

Wind turbines do not emit any harmful substances, hence no addition to global warming. Even though wind energy resource is referred to as a very clean source of energy, it has some impacts on wildlife, though these are low compared to present industrial and other forms of human activities. During operation of wind turbines, they do not emit any hazardous pollutants, but during their manufacturing and maintenance, little amounts of pollutants are produced, for example, considering the offshore wind farms, oil leakages into the water bodies have been observed during construction and maintenance and this has a negative impact on marine life.

Additionally, some onshore windfarms are created on lands that need to be cleared first, thus causing deforestation as well as soil erosion. As with any machine that has moving parts, wind turbines generate a lot of noise during operation due to the rotating blades even though there have been some technological advances in the construction of these machines. This noise arises mainly from the gearbox and from the interaction between the turbine blades and the wind. Research on noise impact was done in West Virginia wind farm, Eric Rosenbloom wrote, ‘incredible. It surprised me. It sounded like aeroplanes or helicopters. And it travelled. Sometimes, you could not hear the sound standing right under one, but you heard it 3,000 yards down the hill.' [83].

The spinning rotor blades have also been recorded to have aesthetic impacts and a lot of bats, birds and other flies are being killed. Research by a bats enthusiast in 2009 showed that there was a 73% drop in bat deaths when they stopped operating the wind turbines at a low wind in which bats will be active [83]. As an environmental impact as well, there are chances of wind turbines to affect weather in that they lead to a slight increase in nighttime temperatures and a slight decrease in daytime temperatures.

- **Other Problems**

Construction of wind farms might also impact humans negatively by the destruction of some historical sites or recreational sites as well. In recent cases, turbines have also been recognized for their electromagnetic interference especially with radio and television broadcasting. Technical problems are also very common, turbine nacelles sometimes catch fire due to high rotor speeds and they cannot be extinguished due to their heights. This sometimes may lead to toxic fumes or even lead to veld fires, hence polluting the air as well as the environment.

CHAPTER 5

MODEL AND METHODOLOGY

The main goal of the thesis is to evaluate a techno-economic and environmental feasibility of grid-connected hybrid solar PV-Wind power in Zimbabwe so as to partially or fully meet the growing energy demand. Factors such as solar price, fuel price, and hydrological conditions or demand that may affect the costs of solar in Zimbabwe were also investigated.

The model developed was a single node one, thus ignoring the transmission aspects, i.e. the transmission network is omitted and the generation and the load are assumed to be in the same location. A multi-node model includes the transmission network and the locations of the load centres and generation plants. The obtained results will be compared with the ones for solar potential reported by [30] so as to investigate the feasibility of the developed model. This chapter is divided into 6 sections; the first one was for the determination of the energy demand and electricity demand forecast in Zimbabwe. Additionally, the determination of the sites for the construction of the power plants was done. An analysis of the following four power system configurations was then performed; solar PV, Wind, hybrid solar PV/ Wind/Energy storage system and hybrid solar PV/Wind.

With the above goal in mind, the hybrid PV/Wind power system model was designed with the following characteristics:

- **Single node:** this is so because it addresses the primary question whether or not this hybrid generation is competitive with other candidate technologies regardless of network constraints or location (those will be considered for future works). Also, the majority of load shedding is as a result of generation, not network constraints.
- **Hourly periods:** these outline the relationship between generation from the hybrid system and the demand.
- Energy and electricity demand forecast up to 2030 using ARIMA model

5.1. Model Inputs (MS Excel-based)

- Geographical coordinates of the location under study
- Hourly solar radiation, wind speed, ambient temperature, financial, environmental and techno-economic parameters
- Equation formulation.

5.2. Possible Shortfalls

- Demand might not grow as expected, as with any demand forecast, thus resulting in under or overestimations of peak demands.
- This method does not take into account possible consumption pattern shifts (the shape of the demand profile might change).
- The transmission network and the locations of the load centres are excluded, these might affect the overall feasibility of the system

5.3. Zimbabwe Energy Demand Forecast

5.3.1. Methodology

The dataset employed in this present study consists of macroeconomic variables. Seven macroeconomic variables recorded yearly from 1980 to 2012 are analysed [84]. These variables are then used to econometrically forecast the energy demand of Zimbabwe up to the year 2030.

Time series data on Total greenhouse gas emissions (kt of CO_2 equivalent), Total carbon dioxide emissions (kt), Total population (million), GDP per capita (2010US$), Total Primary Energy Production (quadrillion Btu), Total Primary Energy Consumption (Quadrillion Btu), Total Electricity Net Generation (Billion Kilowatt hours) are employed. The data utilized are spanning the period 1980 to 2012 obtained from World Data Atlas [84]. Linear regression analysis is then employed for the examination of the causal relationship between these variables under study.

5.3.2. Results and discussions

i. Descriptive statistical analysis

This section is an outline of the descriptive statistical analysis of the study variables. Figure 5.1 displays the trend of the variables after imputation. It is visible from the trend of the population that it increases rapidly, the trend of GDP follows that of total greenhouse gas as well as carbon dioxide emissions, but fluctuations are observed in the trend of energy consumption.

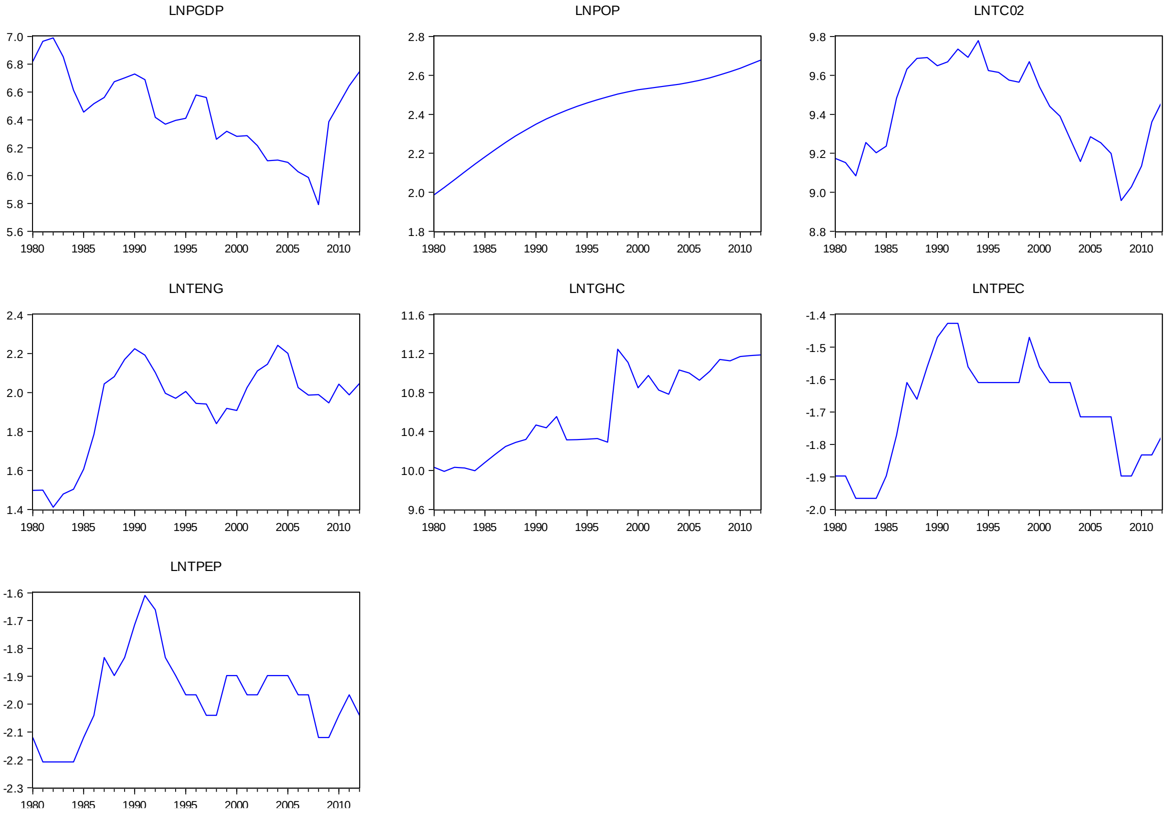

Figure 5.1. The plot of series in natural logarithm.

Table 5.1. Summary Statistics.

	LNPGDP	LNPOP	LNTC02	LNTENG	LNTGHC	LNTPEC	LNTPEP
Mean	6.457	2.413	9.414	1.936	10.599	-1.699	-1.971
Median	6.455	2.475	9.441	1.989	10.466	-1.661	-1.966
Maximum	6.989	2.679	9.778	2.242	11.244	-1.427	-1.609
Minimum	5.791	1.987	8.958	1.411	9.991	-1.966	-2.207
Std. Dev.	0.289	0.195	0.238	0.234	0.436	0.162	0.151
Skewness	-0.208	-0.722	-0.160	-0.980	0.075	-0.166	0.341
Kurtosis	2.524	2.407	1.696	2.913	1.450	1.946	2.921
Jarque-Bera	0.549	3.352	2.481	5.288	3.333	1.678	0.646
Probability	0.760	0.187	0.289	0.071	0.189	0.432	0.724
Sum	213.073	79.641	310.662	63.873	349.764	-56.073	-65.037

Sum Sq.							
Dev.	2.671	1.219	1.806	1.754	6.078	0.842	0.725
Observations	33	33	33	33	33	33	33

Table 5.1 presents a summary of the descriptive statistical analysis of the study variables. Further analysis of the parameters indicates that Total Population and Energy Generation has long-left tails (negative skewness), similar negative skewness was observed in Carbon Dioxide emissions, GDP and Energy Consumption all have long-left tails. However Total primary energy production and total greenhouse gas exhibited positive skewness. Furthermore, Energy Production shows a leptokurtic distribution since its excess kurtosis is greater than zero whilst the rest of the variables all have an excess kurtosis less than zero thus presenting a platykurtic distribution.

Grubbs' test was then used to estimate outliers in the study variables. Evidence from Table 5.2 reveals the highest values of all the variables, except Total Population, are outliers. The Anderson-Darling test was done to test for the normality of the data variables. Testing at a 5% significance level, if the p-value is less than or equal to 5% the null hypothesis is rejected and therefore it can be concluded that the data do not follow a normal distribution. If the p-value is greater than 5% then the test is significant and the decision is to fail to reject the null hypothesis because there is not enough evidence to conclude that the data does not follow a normal distribution.

Table 5.2. The Grubb's test for outliers

Variable	G	U	P-value	Alternative hypothesis
GDP	2.0	0.9	0.4	Highest value 1084.21 is an outlier
Population	2.0	0.9	1.0	Lowest value 5.39 is an outlier
CO_2 emissions	2.0	0.9	1.0	Highest value 17645.6 is an outlier
GHG emissions	2.0	0.9	1.0	Highest value 76391.8 is an outlier
Energy production	3.0	0.8	0.1	Highest value 0.2 is an outlier
Energy consumption	2.0	0.9	0.9	Highest value 0.24 is an outlier

Energy generation	2.0	0.9	1.0	Highest value 9.41 is an outlier

This study also proceeds to show the correlation matrix that exists between the variables under consideration as presented in Table 5.3.

Table 5.3. Correlation Coefficient

	LNPGDP	LNPOP	LNTC02	LNTENG	LNTGHC	LNTPEC	LNTPEP
LNPGDP	1						
t-stat	-----						
P-value	-----						
No. Obs.	33						
LNPOP	-0.667	1					
t-stat	-4.987	-----					
P-value	0.00	-----					
No. Obs.	33	33					
LNTC02	0.158	0.045	1				
t-stat	0.893	0.250	-----				
P-value	0.379	0.8039	-----				
No. Obs.	33	33	33				
LNTENG	-0.486	0.721	0.404	1			
t-stat	-3.095	5.788	2.459	-----			
P-value	0.004	0.000	0.020	-----			
No. Obs.	33	33	33	33			
LNTGHC	-0.635	0.886	-0.177	0.550	1		

t-stat	-4.578	10.642	-0.999	3.665	-----		
P-value	0.0001	0	0.3255	0.0009	----		
No. Obs.	33	33	33	33	33		
LNTPEC	-0.217	0.336	0.823	0.697	0.163	1	
t-stat	-1.238	1.987	8.077	5.415	0.917	-----	
P-value	0.225	0.056	0.000	0.000	0.366	-----	
No. Obs.	33	33	33	33	33	33	
LNTPEP	-0.186	0.314	0.700	0.787	0.164	0.890	1
t-stat	-1.055	1.843	5.451	7.103	0.925	10.878	-----
P-value	0.299	0.075	0.000	0.000	0.362	0.000	
No. Obs.	33	33	33	33	33	33	33

Note: Table reports the estimates of the Pearson correlation coefficient between the pairs of variables. t-stat is the t-statistics for the significance of the correlation coefficient and p-value is its marginal probability.

The correlation coefficient estimate results show a positive significant relationship between per capita GDP and total population. Thus, this implies that a higher population increase national income for the study country which is indicative of policymakers. Similarly, negative association but significant relationship exists among PGDP and TENG as well as TPEC but for TPEC and PGDP was not significant. This revelation implies that energy intensity impedes economic growth at certain threshold validating the environmental Kuznets curve hypothesis (EKC).

ii. Model specification

The functional relationship among total greenhouse emission, total carbon dioxide emission, total population, per capita GDP, total energy production, total primary energy consumption and total electricity net generation leverage on the works of [85], [86] for empirical backing. The functional forms can be represented as follows:

Model A: ln TPEC = f (LnTGHC,lnTENG,lnTC02,lnTPOP,lnPGDP,lnTPEP)

Model A will help us ascertain the impact of total energy consumption on other explanatory variables.

$$\ln TPEC_t = \alpha + \beta_1 \ln TGHC + \beta_2 \ln TENG + \beta_3 \ln TC02 + \beta_4 \ln TPOP + \beta_5 \ln PGDP + \beta_6 \ln TPEP + \varepsilon_t \tag{33}$$

While model B seeks to verify the extent of C02 emission on economic growth and the impact of population growth.

Model B: lnTC02= f (lnPGDP, lnTPOP, lnTENG, lnTGHC,lnTPEC,lnTPEP)

$$\ln TC02 = \alpha + \beta_1 \ln PGDP + \beta_2 \ln TPOP + \beta_3 \ln TENG + \beta_4 \ln TGHC + \beta_5 \ln TPEC + \beta_6 \ln TPEP + \varepsilon_t \tag{34}$$

Where t is time trend also $\alpha, \beta_{1,} \beta_2 .... \beta_6$ are unknown coefficients of repressors, ε_t is the stochastic error term for the formulated models.

The empirical route of this study proceeds as follows; first, determination of the order of integration of series. Second, estimation of the ordinary least squares (OLS) regression and subsequently the forecast estimation.

iii. Stationarity Test

It is well established that most macroeconomic variables possess trends/seasonality thus, the need to know the order of integration of such series is pertinent to avoid spurious regression trap and misleading policy implication by extension. This current study employs Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit root test to ascertain the stability traits and asymptotic properties of the variables under consideration. These tests are conducted with the null hypothesis of a unit root against the alternative of stationarity. (Dickey and Fuller 1998; Phillips and Perron 1988). Table 5.4 presents the unit root test. The general form of the unit root test is given as in Eq. (35).

$$\Delta Y_t = \beta_1 + \beta_2 t + \gamma Y_{t-1} + \sum_{i=1}^{k} \alpha_i \Delta Y_{t-i} + \in_t \tag{35}$$

Here, $\in_t$ denotes the Gaussians white noise term which is asymptotically characterized by zero mean and constant variance. The null hypothesis of the unit root test is non-stationarity against the alternative of stationarity.

Table 5.4. Unit root results

	Level				First Difference			
Variables	ADF		PP		ADF		PP	
	τ_μ	τ_T	τ_μ	τ_T	τ_μ	τ_T	τ_μ	τ_T
LNGDPC	-2.01	-2.08	-2.19	-3.18	-5.21^{***}	-5.14^{***}	-5.09^{***}	-5.17^{***}
LNTCO2	-1.69	-0.67	-6.23	-6.17	-6.23^{***}	-4.19^{***}	-6.18^{***}	-6.18^{***}
LNTGHC	0.99	-3.63	-7.55	-7.47	-0.99^{**}	-8.20^{**}	3.64^{**}	-8.14^{***}
LNTPOP	-2.50	-3.10	-2.18	-3.08	-3.68^{**}	-1.29^{**}	1.17^{***}	1.11^{***}
LNTPEP	-2.45	-3.72	-3.64	-3.82	1.72^{***}	1.73^{***}	-4.63^{***}	-4.65^{***}
LNTPEC	-1.57	-1.42	-4.57	-4.67	-1.69^{***}	-1.41^{**}	-4.57^{***}	-4.62^{***}
LNTENG	-3.79	-3.61	-3.74	-3.81	-1.99^{***}	1.76^{***}	-6.18^{***}	-6.23^{***}

*Note: τ_μ represents a model with intercept while τ_T denotes model with intercept and trend. ** Significant at 5% level*

The unit root rest reported in Table 5.4 reveals that all series are integrated of order one ~ I (1), that is it has a unit root. However, all variables became stationary after differencing. Thus, we conclude that the series is the integration of the series ~ (1). Subsequently, this study proceeds with the ordinary least square estimation (OLS).

Table 5.5. Regression Estimation (A)

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	-3.7982	1.1311	-3.3580	0.0024
LNTGHC	0.0489	0.0555	0.8803	0.3868
LNTENG	-0.0245	0.1185	-0.2071	0.8376
LNTC02	0.3689	0.0705	5.2314	0.0000
LNPOP	-0.0486	0.1586	-0.3065	0.7617
LNPGDP	-0.1020	0.0473	-2.1592	0.0402
LNTPEP	0.5421	0.1672	3.2420	0.0032
R-squared	0.9091			
F-statistic	43.3549			
Prob(F-statistic)	0.0000			

Model A: ln TPEC = f(LnTGHC,lnTENG,lnTC02,lnPOP,lnPGDP,lnTPEP)

Table 5.6. Regression Estimation (B)

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	11.7740	1.2570	9.3668	0.0000
LNPGDP	0.2396	0.0878	2.7282	0.0113
LNPOP	0.5429	0.2895	1.8754	0.0720
LNTENG	-0.1941	0.2270	-0.8551	0.4003
LNTGHC	-0.2367	0.0991	-2.3897	0.0244
LNTPEC	1.3901	0.2657	5.2314	0.0000
LNTPEP	-0.0148	0.3846	-0.0386	0.9695
R-squared	0.8404			
F-statistic	22.8174			
Prob(F-statistic)	0.0000			

Model B : lnTC02= f(lnpgdp,lnTPOP,lnTENG,lnTGHC,lnTPEC,lnTPEP)

Table 5.5 and 5.6 present the OLS regression estimation for model A and B respectively. Table 5.5 shows a tradeoff between total population and total primary consumption. That is, 1% increase in the total population decreases the total energy consumption by 0.0486%. Similarly, a negative trend was seen among per capita GDP total energy consumption with a magnitude of 0.1020%. Thus, we can infer that the population does not increase CO_2 emission in Zimbabwe. However, a positive and significant relationship is observed among TPEP and TGHC with the dependent variable with a magnitude of 0.5421% and 0.0489%. The fitted model has a robust coefficient of determination (R^2) of 90%, implying that 90% of the variation in total primary energy consumption was explained by the explanatory variables while the rest 10% are left uncaptured in this model. The joint significance of the model by the F-statistic was also significant at all level (1%, 5% and 10%). In the same fashion, Table 5.6 targeted for model B. The model has a coefficient of 84%. That is, 84% of the variation in CO_2 was explained by another explanatory variable with F-statistic significant indicating joint significant among all variables. Interestingly, the fitted model shows that a 1% increase in PGDP increases CO_2 by 0.2398%. Similarly, also a positive trend between CO_2 and TPOP with over 0.5429%.

iv. Model Suggestions

Based on relevant studies [85], [87] and since long-term forecasting using macro variables is to be studied, the following models are suggested. Autoregressive integrated moving average (ARIMA) and spatial ARIMA (ARIMASp) models have proved to be good for forecasting a lot of environmental and non-environmental variables. These projections include forecasts of electrical energy demand and consumption, greenhouse gas emissions and economic growth and day ahead forecasting of electricity prices [85], [88]–[92].

Some studies have utilised neural networks for a medium-term demand forecasting and concluded that the results were better than those obtained using ARIMA models [93]. Linear regression analysis is also another option and also modelling a new statistical model can be very possible. Based on further analysis of the data variables and available literature and resources, a suitable model will be chosen for the continuation of this study. The ARIMA model is conducted in this study ARIMA (*p. d, q*) represented by Eq. (36).

$$\varphi(B)\nabla^d z_t = \phi(B)\alpha_t or Z_t = \sum_{i=0}^{p}\gamma Z_{t-1} + \alpha_t - \sum_{k=1}^{q}\gamma_i \alpha_{t-k} \tag{36}$$

where, $\varphi(B) = 1 - \varphi_1 B - \varphi_2 B^2 ... - \varphi_k B^k$ (37)

Table 5.7 reports the ARIMA (1, 1,1) which is the best fit and parsimonious model for the choice regression fit. The estimation for the forecast reveals that electricity consumption for Zimbabwe as reported in Table 5.7 was conducted utilizing the dataset from 1980 to 2012 because of missing data as well as to avoid spurious estimation. Empirical evidence shows that in 2030 energy consumption will reach 0.183 Quadrillion Btu against the currently available 0.174 Quadrillion Btu.

The current study estimation affirms the goodness of fit with a coefficient of determination R^2 of over 80%. This study also shows that F-statistic rejected at ($p < 0.01$) indicating joint significant of the selected model. Finally, the study forecast also displays high parsimony with harmony among the Root Mean Square Error (RSME) of 0.03993, while the mean absolute error of 0.0328. Similarly, the Theil inequality coefficient was also 0.11423.

Table 5.7. Forecast (ARIMA) for Total Energy consumption.

Year	TPECF(predicted)	TPEC
1980		0.15
1981		0.15
1982	0.151	0.14
1983	0.151	0.14
1984	0.152	0.14
1985	0.153	0.15
1986	0.153	0.17
1987	0.154	0.2
1988	0.155	0.19
1989	0.155	0.21
1990	0.156	0.23
1991	0.157	0.24
1992	0.157	0.24
1993	0.158	0.21
1994	0.159	0.2
1995	0.159	0.2
1996	0.160	0.2
1997	0.161	0.2
1998	0.161	0.2
1999	0.162	0.23
2000	0.163	0.21
2001	0.163	0.2
2002	0.164	0.2
2003	0.165	0.2
2004	0.165	0.18
2005	0.166	0.18

2006	0.167	0.18
2007	0.167	0.18
2008	0.168	0.15
2009	0.169	0.15
2010	0.169	0.16
2011	0.170	0.16
2012	0.171	0.17
2013	0.171	
2014	0.172	
2015	0.173	
2016	0.173	
2017	0.174	
2018	0.175	
2019	0.175	
2020	0.176	
2021	0.177	
2022	0.177	
2023	0.178	
2024	0.179	
2025	0.179	
2026	0.180	
2027	0.181	
2028	0.181	
2029	0.182	
2030	0.183	

Additionally, the study forecast also displays high parsimony with harmony among the Root Mean Square Error (RSME) of 0.03993, while the mean absolute error of 0.0328. Similarly, the Theil inequality coefficient was also 0.11423. All forecast indicators resonate with Figure 5.2. Figure 5.2 reports the diagrammatic view with relatively fair deviation from the forecast variable.

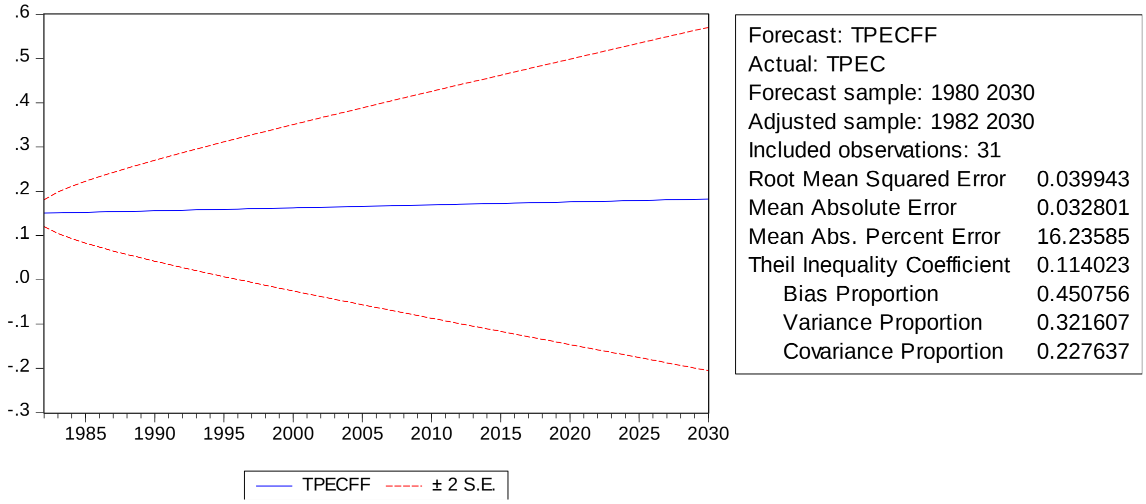

Figure 5.2. ARIMA forecast for Zimbabwe electricity consumption.

5.3.3. Conclusion and Policy Implications

The Zimbabwe energy policy which does not suggest any large scale utilization of solar and/ wind resources suggest the following measures;

- Encourage the generation of electricity from biomass cogeneration and mini-hydro projects
- Bagasse from sugar cane – Hippo Valley and Triangle sugar estates generate for their own consumption.

However, the policy suggested the implementation of the following strategies even though none has been fulfilled;

- Extension of Kariba south by end of 2016, which was not done until 2018.
- 800 MW Batoka hydro by 2020
- Mandate the installation of solar geysers by 2013, which was not done.
- To fix (REFIT) renewable feed-in tariffs, which has not been done up to date.

The Zimbabwe energy policy does not have any energy consumption forecast hence this current study is indicative of policymakers who design energy policy framework. Among such are the results outlined in Table 5.3 which show the Pearson correlation matrix that shows the relationship between two variables, though not a sufficient condition to substantiate a claim. Thus, the current study proceeds to estimate an ordinary least squares (OLS). It is visible from these results that a positive relationship exists between carbon dioxide emissions (CO_2), population (POP) and gross domestic product (GDP). Thus, we imply that population triggers economic growth. However, there is a negative deteriorating effect on the quality of the environment significantly. So, as such policymakers are enjoined to bring forth environmental friendly regulations to combat the excess. Among such environmental friendly regulations, renewable energy policy could be suggested and large-scale utilization of renewable energy resources can be of paramount importance.

This study employs econometric techniques to forecast Zimbabwe's energy consumption by 2030. Further analysis of the obtained results in Table 5.7, shows the forecast for energy consumption for the study area. To this end, an ARIMA (1, 1,1) model was employed for data spanning from 1980 to 2012. Empirical evidence report that all noted series were integrated of order one ~ I (1) which informed our choice of ARIMA model. The results show that by 2030 Zimbabwe total primary energy consumption will increase to 0.183 Quadrillion Btu from the last reported 0.174 Quadrillion Btu in 2017. Thus, the need to diversify and intensify into clean energy sources is crucial among policymakers. This is in order to meet the energy demands given the dynamic fast-growing nature of the study area. The study will also draw the attention of all stakeholders as well as energy policy and decision makers as there will be a need to diversify the energy portfolio mix available to Zimbabwe.

5.4. The Solar Geometry

The amount electricity produced from PV modules is dependent on the of solar resources available. The incident angle reaching the surface of the module determines the estimated output generation. A deeper analysis of the geometrical components, as well as the angles involved in solar PV energy analysis, is given in [5]. Figure 5.3 is an outline of the description of involved geometrical angles.

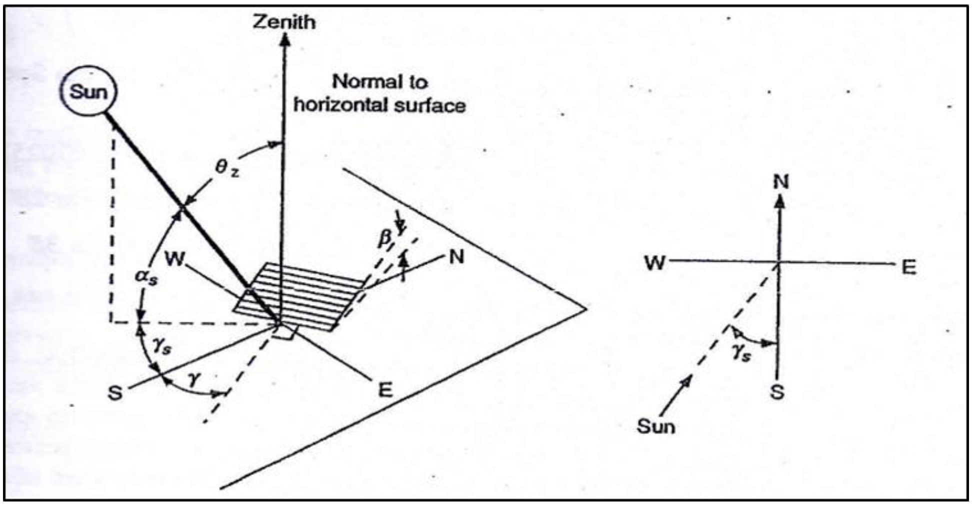

Figure 5.3. Angles involved in the description of the solar energy analysis [5].

As time changes, the position of the sun also changes. The required time for the solar analysis, solar time (t_s), is only dependent on apparent sun's angular motion and not on the location. The solar time is the one then used for solar analysis. For the conversion from local time to solar time, Eq.(4) [5].

$$t_s = t_{std} + 4 \times (L_{st} - L_{loc}) + E \tag{4}$$

where L_{st} is determined using Eq.(5) , L_{loc} is calculated using Eq. (6) and E is determined by employing Eq.(7) [5].

$$L_{st} = \begin{cases} -T_z \times 15\,, & T_z \leq 0 \\ 360 - T_z \times 15\,, & T_z > 0 \end{cases} \tag{5}$$

$$L_{loc} = \begin{cases} L_{loc} & , \quad if\ L_{loc}\ in\ the\ West \\ 360 - L_{loc} & , \quad if\ L_{loc}\ in\ the\ East \end{cases} \tag{6}$$

$$E = 229.2 \times (0.000075 + 0.001868 \times \cos B - 0.032077 \times \sin B - 0.014615 \times \cos(2 \times B) - 0.04089 \times \sin(2 \times B)) \tag{7}$$

where E and B are constants and B is calculated by employing Eq. (8)[5].

$$B = (n-1) \times \frac{360}{365} \tag{8}$$

The utilized solar time is however used in an angular form termed hour angle, (ω) , which is determined by employing Eq. (9) [5].

$$\omega = (t_s - 12) \times 15 \tag{9}$$

The solar azimuth and zenith angles are used for the description of the sun's position. The angle between the vertical and the solar radiation is called the zenith angle calculated by using Eq. (10). While the one between the perpendicular sun's projection onto the horizon line which is measured clockwise and the direction of due north is the solar azimuth angle determined by Eq. (11) [5]. Both the zenith and the azimuth angles are dependent on the declination angle (δ) and location. (δ) is the angle equator and the beam radiation at solar noon, given by Eq. (12) [5].

$$\cos\theta_z = \cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta \tag{10}$$

$$\gamma_s = sign(\omega) \times \left|\cos^{-1}\left(\frac{\cos\theta_z\sin\phi - \sin\delta}{\sin\theta_z\cos\phi}\right)\right| \tag{11}$$

$$\delta = 23.45 \times \sin\left(360 \times \frac{284+n}{365}\right) \tag{12}$$

The azimuth angle (γ) and the tilt angle (β) are required for the geometrical description of a surface. The angle between the horizontal and the surface is the tilt angle. The incident angle, θ, is then calculated by using Eq. (13).

$$\cos\theta = \cos\theta_z\cos\beta + \sin\theta_z\sin\beta\cos(\gamma_s - \gamma) \tag{13}$$

5.5. The Solar Resources

The three main components to determine the global insolation on a tilted surface, I_T, are the reflected, diffuse and beam insolation employed as shown in Eq. (14) and the reflected insolation is not considered in the study [5].

$$I_T = I_{b,t} + I_{d,t} \tag{14}$$

where $I_{d,t}$ is calculated using Eq. (15) and $I_{b,t}$ is calculated by employing Eq. (16) [5], basing the analysis on the isotropic sky model which outlines that diffuse radiation approaches from all directions with equal magnitude [94].

$$I_{d,t} = I_d \times \left(\frac{1+\cos\beta}{2}\right) \tag{15}$$

$$I_{b,t} = I_{b,n} \times \cos\theta \tag{16}$$

Meteonorm v7.1 software was utilized to obtain the hourly diffuse and beam insolation for the locations in Zimbabwe that were considered for this study.

5.6. Solar PV Energy Production

For the energy generation from a PV module, the efficiency is of paramount importance and this is highly dependent on the module temperature. An increase in the PV module temperature causes a decrease in its efficiency thus decreasing the production of energy as well. The photovoltaic module efficiency is calculated by using Eq. (17) [95], where the humidity and wind effects on the PV module efficiency and temperature are not considered in for this analysis.

$$\eta_{PV} = \eta_{PV,Ref} \times (1 - |\beta_{Ref}| \times (T_{PV} - T_{Ref,STC})) \tag{17}$$

where T_{PV} is estimated by Eq. (18) [95]. In [95] only the positive β_{Ref} is considered. In a couple of literature analyses, a negative β_{Ref} is considered. Hence, the absolute $\beta_{Ref}$is considered in Eq. (17) to avoid obtaining some errors and confusion.

$$T_{PV} = T_{amb} + (NOCT - T_{Ref,NCT}) \times \frac{I_T}{I_{Ref}} \tag{18}$$

Meteonorm v7.1 software that provides the data which is based on a typical meteorological year was utilized to obtain the hourly ambient temperature for the sites in Zimbabwe under study. The PV modules specifications are important for the determination of the output energy from the system. The module used in this analysis is the SunPower SPR-320E-WHT-D and the module specifications are given in Table 5.8.

Table 5.8. PV module specifications [96].

Item	Parameter
Manufacturer	SunPower
Type	Monocrystalline Silicon
Solar module	SPR-320E-WHT-D
STC power rating (P_{max})	320 W
Power tolerances	-3% / +5%
Number of cells	96
Rated current (I_{mpp})	5.86A
Rated voltage (V_{mpp})	54.70V
Short circuit current (I_{sc})	6.24 A
Open circuit voltage (V_{oc})	64.80V
NOCT	45 °C

The temperature coefficient of power	-0.38%/K
Temperature coefficient of voltage	-0.177 V/K
Maximum system voltage (UL)	600V
Peak efficiency (η)	19.62%
80% power output warranty period	25 years
90% power output warranty period	12 years
Length	61.4in (1,559mm
Width	41.2in (1,046mm)
Depth	1.8in (46mm)
Weight	41lb (18.6kg)

The total energy generated hourly by the PV power plant is calculated using Eq.(19) [95],

$$E_{gen,PV} = \eta_{PV} \times I_T \times A_m \times N_{modules} \times PR \quad (19)$$

where PR is 85% basing the analysis on [97]–[99] where the other 15% is considered to cater for system losses including shading, inverter , dust and wiring losses.

5.7. Wind Energy Generation

As mentioned before, the HAWTs will be used in this study. The production of energy from these turbines is highly dependent on the wind speed at certain hub height. Factors such as hub height, ground level wind speed, time, the ambient temperature and the terrain affect the production of energy from wind turbines. The wind shear coefficient or the wind profile exponent,α, represent all the mentioned factors that affect wind energy production. The values of the coefficient are determined by utilizing site-specific data, or taking the value 1/7 if site-specific data is not available [100], and speed of the wind at a hub height (u_Z) is estimated by using Eq.20.

$$u_Z = u_1 \times \left(\frac{Z}{Z_1}\right)^{\alpha} \quad (20)$$

Meteonorm v7.1 software was used to obtain the ground level wind speeds for this study.

Eq. (21) is used to estimate the hourly electrical power produced since the wind speeds follow a Weibull distribution and Eq. (23) is used to estimate the energy generated by the wind turbines at each hour, assuming all the turbines in a wind farm generate an equal amount of energy [101].

$$P_e = \begin{cases} 0 & , u_Z < u_C \;\; or \;\; u_Z > u_F \\ P_{e,R} \times \frac{(u_C)^K - (u_Z)^K}{(u_C)^K - (u_R)^K} & , u_c \leq u_Z \leq u_R \\ P_{e,R} & , u_R < u_Z \leq u_F \end{cases} \tag{21}$$

According to Justus theory, Eq. (19) is used to calculate the value of K [101].

$$K = \{ \; (\sigma/\bar{u})^{-1.086}, \; 1 \leq \; K \leq 10 \tag{22}$$

$$E_{gen,wind} = N \times P_e \tag{23}$$

The wind turbine used for the analysis in this study is Gamesa G114-2.0MW prototype and its specifications are given in Table 5.9.

Table 5.9. Wind turbine specifications, wind energy losses and its related coefficients [102]

Variable	Corresponding Value
Turbine Rated power	2,000 kW
Turbine cut-in wind speed	2.5 m/s
Turbine rated wind speed	10 m/s
Turbine cut out speed	25 m/s
Rotor diameter	114 m
Turbine Hub height	93 m
Swept area	10,207 m²

5.8. RES Performance Assessment

The fraction of the demand that is met by the renewable energy system is called the RES Fraction (F_{RES}). This fraction is of paramount importance for monitoring the mismatch between the demand and the RES energy production. Another important parameter, the Demand Supply Fraction abbreviated as (DSF), is used to inspect the fraction in terms hours per year when the demand was totally met by the RES. DSF and F_{RES} are calculated using Eq. (24) and Eq. (25) respectively.

$$DSF = \frac{H}{24 \times 365} \tag{24}$$

$$F_{RES} = \frac{\sum D_{RES}}{\sum D} \tag{25}$$

The Capacity factor is also an important parameter for the performance analysis for RES [103], and it is calculated as in Eq. (26).

$$CF = \frac{E_{gen}}{(P_{e,R} \times N+P)\times 365\times 24} \tag{26}$$

5.9. RES Environmental Assessment

Global warming as a result of greenhouse gasses (GHG) such as CO_2, emissions to the atmosphere has been a major concern as of recent. In trying to mitigate the concentrations of these released GHG emissions, renewable energy resources are thus being utilized and the avoided emissions can be calculated by employing Eq. (27).

$$A_{CO_2} = R_{CO_2} \times E_{RES} \tag{27}$$

where the value of R_{CO_2} is yet still to be truly obtained, in this study it is taken as 0.584 [kg/kWh] [104].

5.10. RES Financial Assessment

To determine whether or not to continue with a project, the economic or financial feasibility is a very important parameter considered for this decision to be made. Traditionally when determining the economic feasibility of energy systems, the levelized cost of electricity, abbreviated as LCOE, is one of the most important parameters to consider as it is the generated electricity cost by the system. Eq. (28) is used to calculate LCOE for the RES. The mismatching effect between the demand and generation was incorporated in the equation by utilizing the demand met by the system, not the energy generated. A summary of the employed financial parameters for this study is given in Table 5.10.

$$LCOE = \frac{C_i + \sum_{t=1}^{L} \frac{M_t}{(1+r)^t}}{\sum_{t=1}^{L} \frac{D_{RES}}{(1+r)^t}} \tag{28}$$

Since there is no renewable energy policy being implemented in Zimbabwe right now, the excess energy generated by the RES going to be fed to the grid free of charge, thus the energy fed freely to the grid is considered a loss. Additionally, as the RES is unable to curb 100 per cent of the demand, the deficit will be acquired from the grid at the local grid tariff, (GT), and this will affect the Cost of Electricity, abbreviated as (COE), of the RES. The RES COE is then calculated using Eq. (29).

$$COE = \frac{D_{RES} \times LCOE + D_{grid} \times \text{GT}}{D} \quad (29)$$

Table 5.10. The financial parameters of the wind turbine and PV systems.

Parameter	Value	Ref.
PV power plant capital cost (USD/kW)	2150	[39]
PV power plant annual maintenance cost (USD/kW)	24.68	[105]
Wind turbine capital cost (USD/kW)	1980	[106]
Wind turbine annual maintenance cost (USD/kW)	39.53	[106]
System expected lifetime (year)	20	[39], [75], [107]
Local Grid Tariff (USD/kWh)	0.0986	[108]
Annual discount rate (%)	7.17	[78]

To further analyze the economic feasibility of the RES, two other economic parameters are considered, namely; the simple payback period (PBP) and the Net Present Value, abbreviated as (NPV). In the event of obtaining a negative NPV, the system will be considered not feasible, otherwise, it will be feasible. Additionally, the system with a higher NPV will be considered more feasible than the one with lesser [39]. Eq. (30) and Eq. (31) are used to calculated the PBP and the NPV respectively [109].

$$PBP = \frac{C_i}{R_{t1}} \quad (30)$$

$$NPV = \sum_{t=1}^{L} \frac{R_t}{(1+r)^t} - C_i \quad (31)$$

5.11. Loss of Power Supply Probability (LPSP) Method

Loss of Power Supply Probability is defined as the probability that the load demand is not met by total generation from the hybrid system [110], thus the load non-satisfaction is expressed here. An efficient configuration is determined by utilizing this methodology based on the system cost and system reliability, thus avoiding blind capital spending. The LPSP values range from 0-1. If the LPSP value is 1, then the load is never satisfied and if it is 0 then the load is 100% satisfied. The LPSP value is determined using Eq. (32) [110].

$$LPSP = \frac{\sum_{t=1}^{T}\{D(t)-[E_{gen}(t)\times\eta_{inv}]\}}{\sum_{t=1}^{T}D(t)} \quad (32)$$

where, T is normally taken as one year, which if the RES operation time.

5.12. Electrical Energy Demand and the RES Model

An econometric approach was utilized to determine the electricity demand forecast up to 2030 which is the then demand employed for the sensitivity analysis. The hourly solar and wind resources utilized were obtained from Meteonorm software. Employing several predefined equations mentioned earlier in this study, Microsoft Excel was then used to model RES in this study. This developed model determines the electricity produced hourly, the hourly excess electricity, the hourly demand met by the grid, and some economic parameters such as the RES COE, PBP and NPV. Additionally, environmental analysis is also performed using the model to determine the amount of CO_2 emission avoided annually and its monetary value.

5.13. Hybrid PV/Wind/ESS Systems

For a detailed criticism of Energy Storage System (ESS), three ESS scenarios were studied and analyzed namely without ESS, with Zinc-Bromine and with Lithium-Ion batteries where the optimal size of the PV/wind hybrid system was determined for each. The excess energy generated by the hybrid system was used to charge the ESS. Figure 5.4 is the flowchart of the hybrid system. 5.11 shows the overall efficiency and the depth of discharge (DOD) for the Lithium-Ion and the Zinc-Bromine batteries. Only one location (Gwanda) was chosen for this section of the study.

Table 5.11 Technical Specification of the Lithium-Ion and Zinc-Bromine Batteries [52], [97].

Parameter	Lithium-Ion	Zinc-Bromine
Round-Trip efficiency (%)	95	72
DOD (%)	60	80

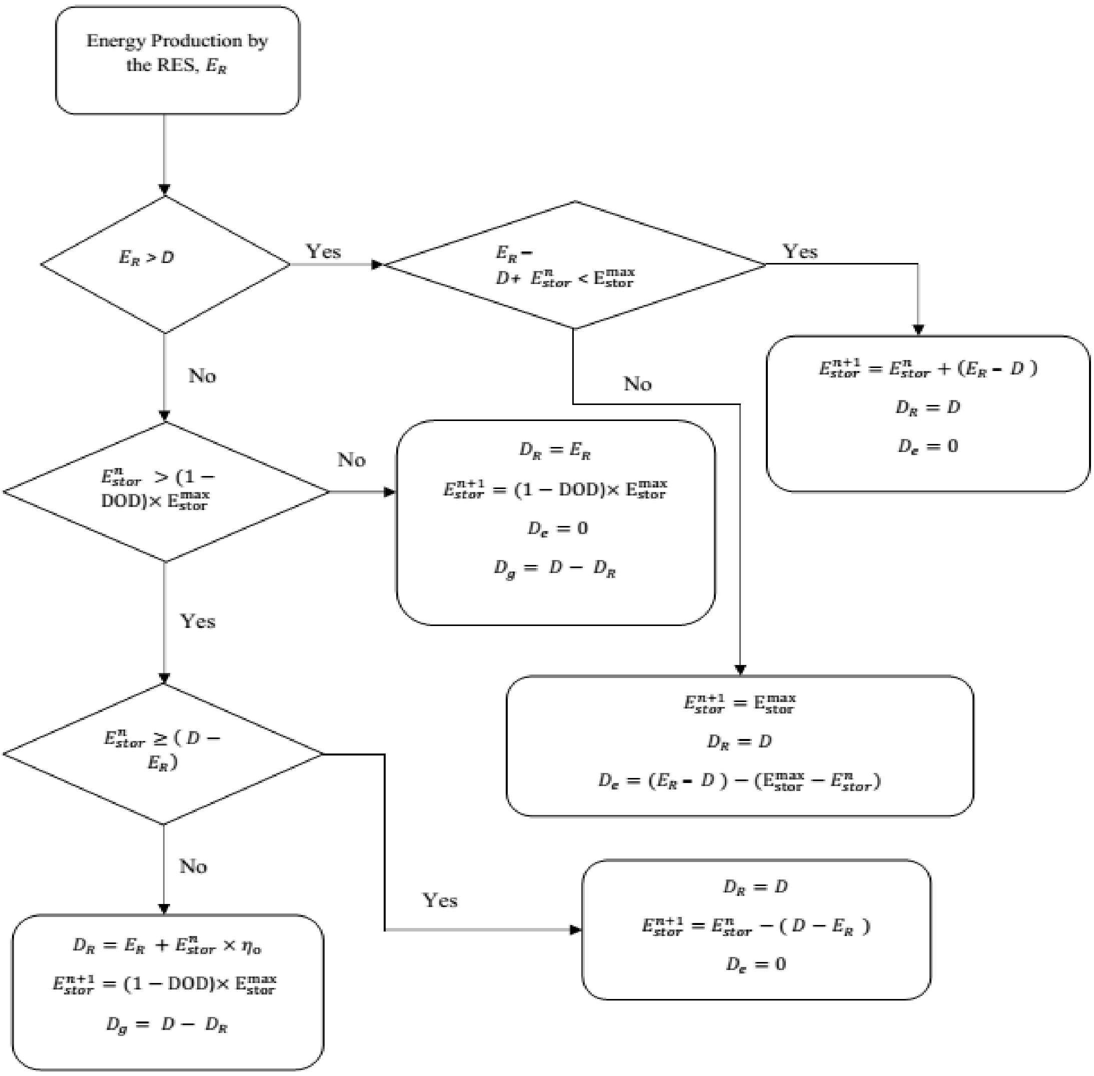

Figure 5.4. The RES energy flow chart in the presence of ESS where E_R is the hourly energy produced by the hybrid system [kWh], E_{stor}^{n} is the hourly energy stored in the ESS at time n [kWh], DOD is the depth of discharge of the ESS, E_{stor}^{max} is the ESS size [kWh], η_o is the overall efficiency of the ESS, D_g is the hourly energy consumed from the grid [kWh] and D_e is the hourly excess energy from the hybrid system [kWh] [28].

5.14. Hybrid PV/Wind

Efficient capacities and RES configurations depending on the location are also estimated using the model as well in which the main aim is to maximize the RES fraction prior to the location's demand keeping the COE equal or less than the Zimbabwean grid tariff and where this condition is not satisfied, the configuration with the least COE is considered feasible. The LSPS concept is then employed to determine the most suitable location and configuration taking into count the configuration reliability and the system cost. The integration of PV and Wind improves the matching between the demand and the RES. The modelled system is a grid connected system where the excess energy generated by the proposed system will be fed to the grid for free and the demand deficit will be met by the grid as well. The flow chart in Figure 5.5 is a summary of the model, where, E_{gen} is the energy generated by the RES, D is the electrical energy demand of the location, (D_{RES}) is the demand met by the RES , (D_{grid}) is the demand provided by the grid and (D_{excess}) is the excess energy generated by the RES, in this study this (D_{excess}) is fed to the grid, free of charge.

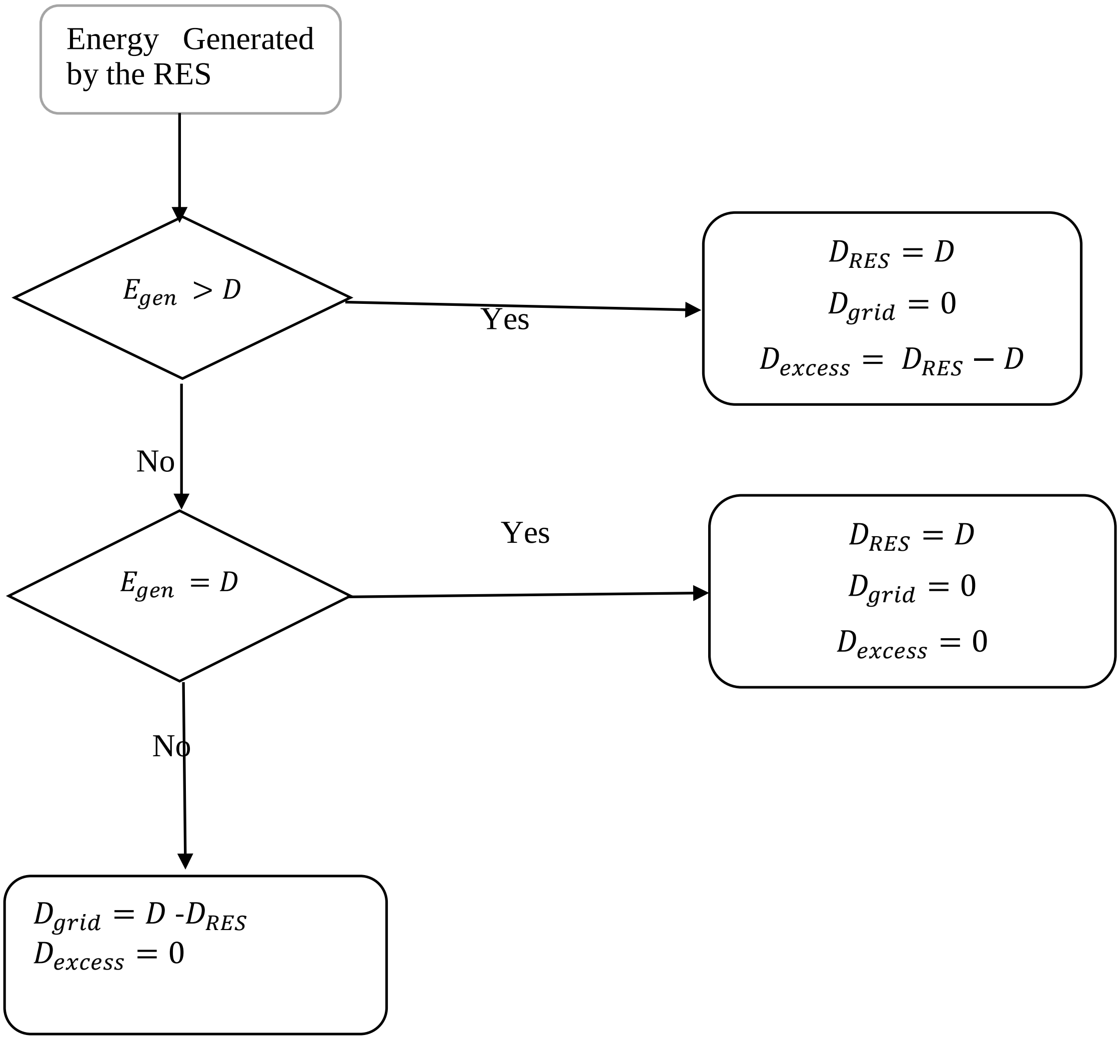

Figure 5.5. The electrical energy flow chart of the RES without ESS.

5.15. Optimization Procedure

The model developed comprises several variables. The relationship between the capacities of the RES fraction and the RES is nonlinear, hence a nonlinear solving algorithm is employed to determine the optimal solutions. Microsoft Excel has a built-in algorithm called the Generalized Reduced Gradient (GRG). This algorithm was employed to calculate the optimal wind and solar PV systems' capacities with the main goal being the RES fraction maximization, with the constraint of COE being equal to or less than the utility tariff for each of the RES sizing scenarios in this present study. However, there are limitations of this algorithm, one of them being it cannot perform a multi-purpose or multi-goal optimization.

The proposed PV modules in this study will are mounted on a fixed tilt angle. The hybrid model determines the optimal tilt angle of each location based on maximizing the total radiation on the tilted surface. Microsoft Excel was utilized in this study due to its simplicity. Some programming software might be useful for almost a similar modelling but it is easier to embed the equations in excel. The built-in algorithms in Microsoft Excel which can be employed easily also adds to the simplicity and comprehensibility of the developed model.

5.16. Site Selection

In choosing the possible sites, a number of factors. First the availability of the resources in which both solar and wind resources were proven to be available by [27], [28], [30]. Secondly the availability of land was considered and finally, the selected site is supposed to be accessible to the grid since the power system was a grid-connected one.

In their analysis on CSP potential in Zimbabwe, [63], mapped all possible sites which are within 30 km from the grid and at the same time, feasible for the implementation of CSP plants. In mapping these sites, some of their indicators were; accessibility to the grid, land availability and availability of the solar resource, which are also the key indicators to choosing potential sites for this present study. Figure 5.6 shows the map of all potential sites located within 30 km from the national grid. Figure 5.7 is a generated map, using MapTiler software, showing possible geographical sites in Zimbabwe. Figure 5.8 is the political map of Zimbabwe showing all cities and towns.

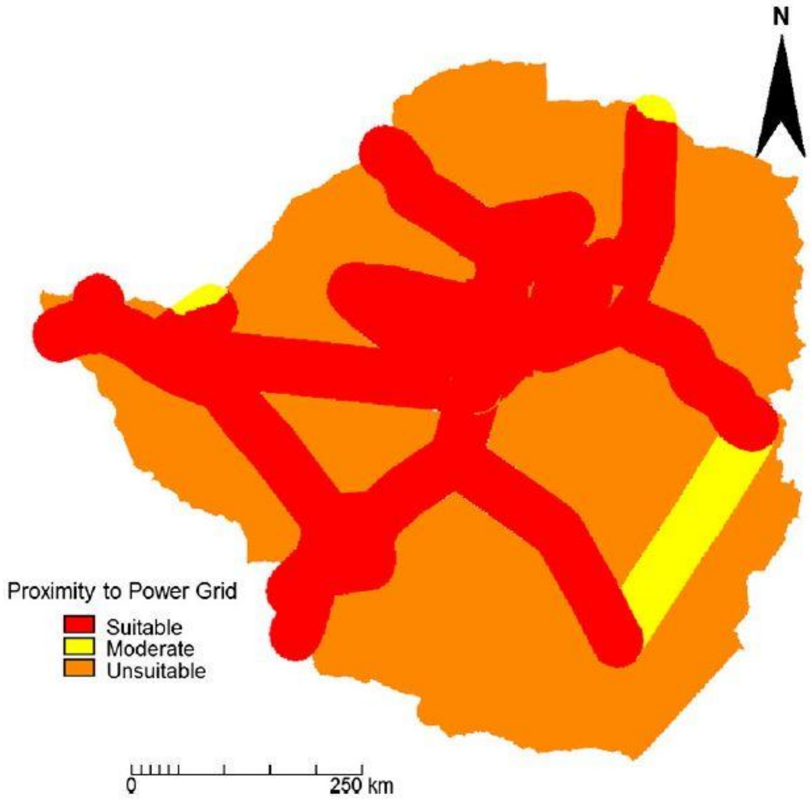

Figure 5.6. Map of potential sites located within 30 km from the national grid [63].

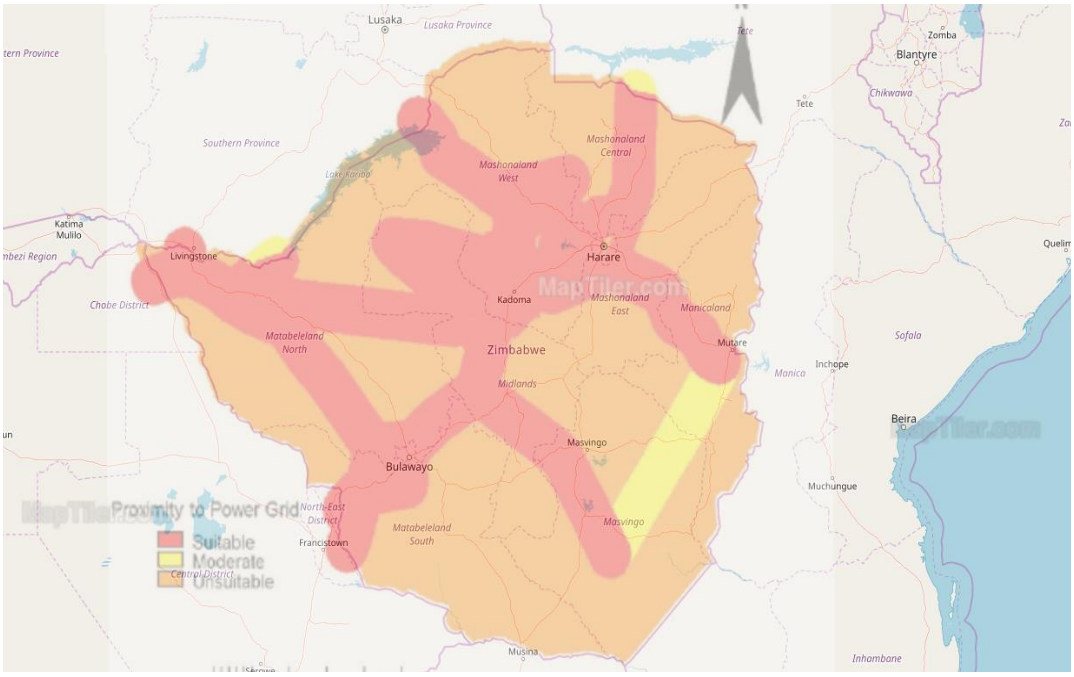

Figure 5.7. Generated map showing potential sites using MapTiler.

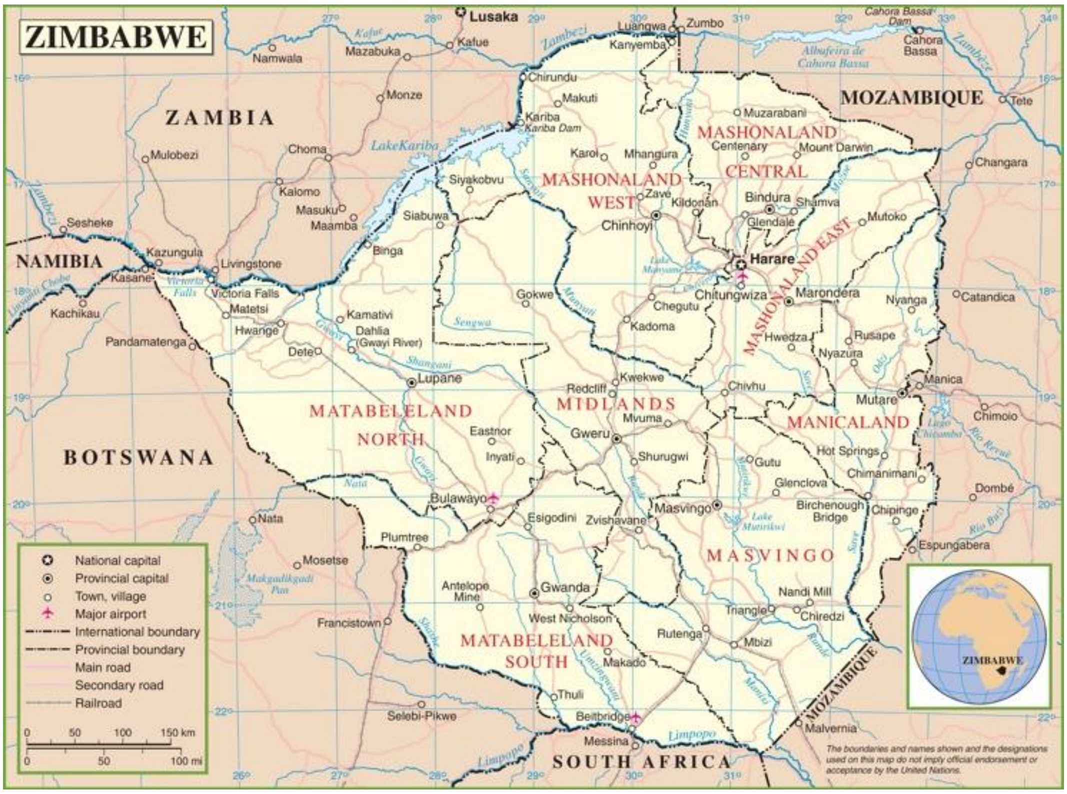

Figure 5.8. The geographical map of Zimbabwe [111].

By mapping Figures 5.6 and 5.7, the possible sites for the construction of the renewable energy power systems for this study were determined. Sixteen sites namely; Victoria Falls, Hwange, Kamativi, Bulawayo, Plumtree, Gweru, Kadoma, Harare, Chegutu, Chinhoyi, Gokwe, Bindura, Mount Darwin, Marondera, Rusape and Mutare were then selected for this study.

CHAPTER 6

RESULTS AND DISCUSSIONS

The methodology employed in this study utilizes data from Zimbabwe. The model inputs include the latitude and longitudes of the site, the hourly solar and wind resources for the whole year, the hourly demand, the wind turbine and PV module specifications, financial parameters such as the interest rate of Zimbabwe and the carbon dioxide intensity of electricity of Zimbabwe. The outputs include the efficient RES configurations based on the RES fraction, LPSP, generated energy from each RES, excess generated energy and the avoided carbon dioxide emissions. The excess electricity will be fed to the grid for free since there is no renewable energy policy set in Zimbabwe at the time this thesis was written as well as the LCOE was set to USD 0.20$/kWh. There is no renewable energy feed-in tariff set for Zimbabwe as well but since the Dema emergency diesel plant was awarded a tender to sell their electricity at USD 0.1545$/kWh, Nyamingura mini-hydro plant sells to ZETDC at USD 0.16$/kWh and the 100 MW plant tender which was initially awarded to Intratrek company had set an LCOE of USD 0.1833$/kWh, it was then decided to assume USD 0.20$/kWh to be the LCOE used for this present study.

6.1. PV Systems

An analysis was done for PV systems alone for 28 different locations by Samu and Fahrioglu in [29], where they used RETScreen software for estimating technical, economic, financial and environmental parameters. For the determination of feasible locations for PV investments, parameters such as the NPV, SPB, the capacity factor, the CO_2 emissions reduction and the equity payback were considered.

The parameter called equity payback is of paramount importance since it estimates the time that the project owner will recoup the initial investment given the project's generated cash flows. Unlike SPBP, the equity payback considers the project's cash debt level and cash flow from inception. The NPV, which estimates the differences between all the outflows and inflows of cash determines whether or not the project is financially feasible. Out of the 28 different locations analyzed by [29], 11 were considered for in this study for a strong comparative analysis between the systems' configurations. A maximum NPV value of USD 31.4 million was recorded at Chegutu location whilst a minimum of USD 29.1 is observed at Mutare as outlined by Table 6.1.

Table 6.1. Techno-economic and Environmental Parameters of the 11 locations [29].

Location	Capacity factor (%)	Simple payback (year)	Equity payback (year)	Net present value (NPV) US$	Net annual GHG emission reduction (t CO2) PV
Chegutu	18.1	6.7	3.0	31,411,313	9,843
Kamativi	18.0	6.7	3.1	30,913,422	9,754
Hwange	18.0	6.7	3.1	30,850,327	9,743
Chinhoyi	17.9	6.7	3.1	30,735,953	9,722
Gokwe	17.9	6.8	3.1	30,588,193	9,696
Marondera	17.8	6.8	3.1	30,327,529	9,649
Mt Darwin	17.6	6.9	3.2	29,891,674	9,571
Gweru	17.6	6.9	3.2	29,812,933	9,557
Bulawayo	17.5	6.9	3.2	29,463,312	9,495
Harare	17.4	7.0	3.3	29,199,970	9,447
Mutare	17.4	7.0	3.3	29,099,220	9,429

As shown in Table 6.1, all the sites considered in this study were feasible for installation of 10 MW grid connected PV plants. Observations from Table 6.1, therefore, show that the most profitable and feasible location for investment is Chegutu and the least preferable location is Mutare. From an environmental feasibility perspective, still, Chegutu is estimated as being the most environmentally feasible locations since the annual avoided carbon dioxide emissions are largest in that location with a value of around 9800 tons whilst the lowest value of 9429 tons is observed at Mutare.

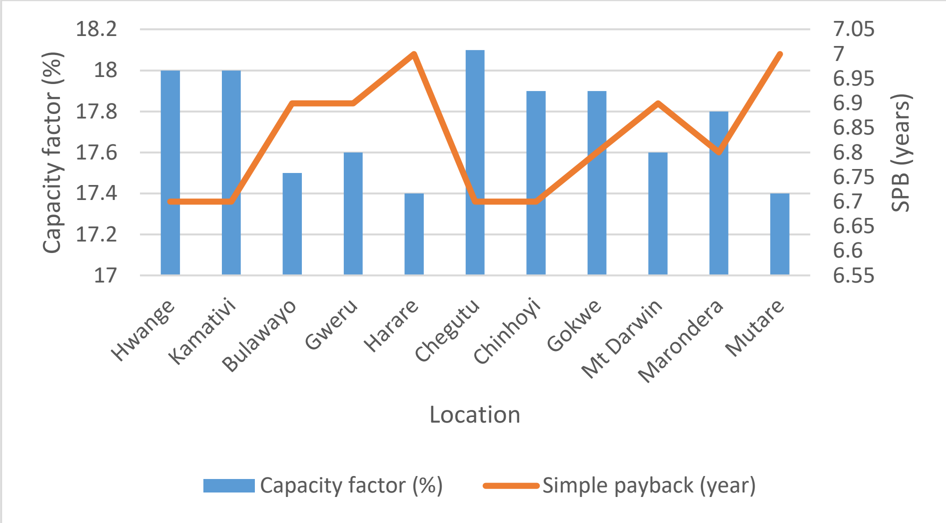

Figure 6.1. The relationship between the capacity factor and the SPBP.

Figure 6.1 is an outline of the relationship between the capacity factor and the SPBP. As observed in Figure 6.1, capacity factor and SPB are inversely proportional. The higher the capacity factor, the lesser the simple payback as well as the more preferable an investment is. Chegutu has the highest capacity factor of 18.1% and the lowest SPBP 6.7 years whilst the lowest capacity factor of 17.4% was observed at Harare and Mutare, with both having the highest SPBP of 7 years. Figure 6.2 shows a relationship between NPV and the avoided carbon dioxide emissions. As shown in Figure 6.2, the higher the NPV, the higher the annually reduced carbon dioxide emissions. Both highest NPV and annual carbon dioxide reductions are observed at Chegutu and the lowest at Mutare.

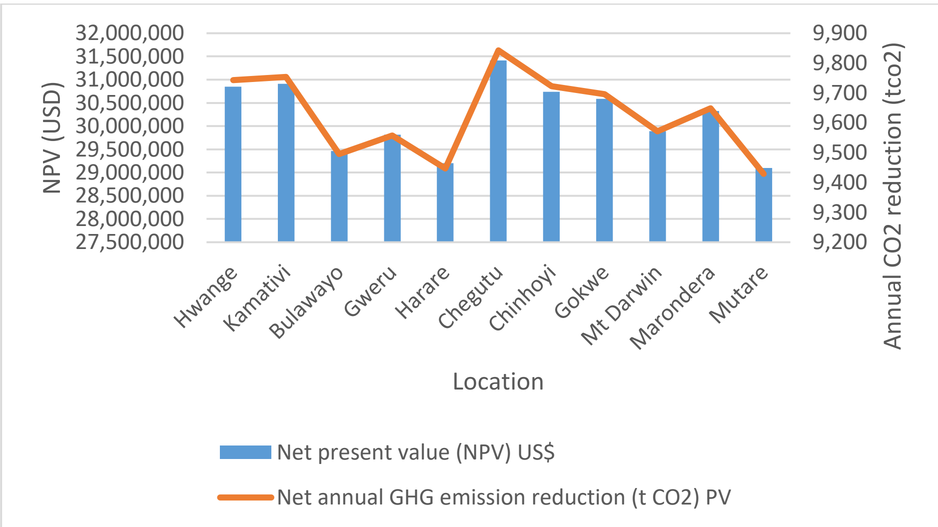

Figure 6.2. The relationship between NPV and annual avoided carbon dioxide emission.

6.2. Wind Systems

For the analysis of wind energy potential in Zimbabwe, Gamesa G114-2.0 MW wind turbine was used. This wind turbine was selected because it is the most powerful wind turbine [112]. This wind turbine model also has a low cut in speed of 1.5 m/s [113], thus maximizing energy generation at low wind speeds making it most suitable for Zimbabwe which has low average wind speed [32]. The electricity export rate in this present study was taken as US$200 per MWh [114].

For the determination of feasible locations, a few noteworthy parameters were used. These include the gross energy production, specific yield, capacity factor, net present value, simple payback, net annual GHG emission reduction and resulting avoided crude oil consumption in 11 different locations. A summary of the 10 MW wind farms in 11 different locations is shown in Table 6.2. As the results in Figure 6.3 show, the higher the capacity factor present at a certain location, the higher the output gross energy production. Figure 6.4 is clearer and pictorial summary and proof of the relationships between the parameters under analysis for the wind energy potential in Zimbabwe.

Table 6.2. 10 MW Wind Plants' Feasibility Analysis Parameters for the 11 locations

Location	Capacity factor (%)	Simple payback (year)	Gross energy production (MWh)	Specific yield (kWh/m^2)	Net present value (NPV) US$	Net annual GHG reduction (t CO2) Wind	Barrels of crude oil not consumed (bbl)
Mutare	12.4	6.5	6,460	396	19,195,907	6,719	15,626
Kamativi	12.0	6.8	6,267	385	18,090,563	6,519	15,160
Hwange	11.9	6.8	6,223	382	17,836,805	6,473	15,053
Mt Darwin	11.8	6.9	6,153	378	17,433,908	6,400	14,884
Harare	11.5	7.0	6,021	370	16,677,911	6,263	14,565
Marondera	11.3	7.2	5,908	363	16,027,040	6,145	14,291
Gokwe	11.2	7.2	5,856	359	15,730,752	6,092	14,167
Chinhoyi	10.9	7.4	5,709	350	14,884,310	5,938	13,809
Chegutu	10.5	7.8	5,465	335	13,484,663	5,685	13,221
Gweru	9.2	8.9	4,799	295	9,663,081	4,992	11,609
Bulawayo	8.6	9.6	4,488	275	7,876,793	4,669	10,858

The results outline the gross energy production of the Gamesa G132-5.0 MW wind turbine with a rated power of 5000 kW. It is evident from the results that all the locations under study produce energy above 4000 MWh. Contrary to some previous studies by [32], [67], [115], the results of this study prove otherwise because the employed wind turbine model has a relatively low cut-in speed and low rated wind speed thus favouring all the sites under study.

In Table 6.2., the specific yield of the wind turbine is reported. This is a more accurate parameter used for the calculation of wind energy cost ($/kWh) since it takes into account the annual energy output per square meter of the swept area by the wind turbine blades upon rotation [116]. Since this specific yield is directly proportional to the capacity factor as well as the wind speed, all locations under study produced an annual energy above 250 kWh/m^2, though Mutare had the highest yield of 396 kWh/m^2 followed by Kamativi with 385 kWh/m^2 and the lowest was 275 kWh/m^2 observed in Bulawayo.

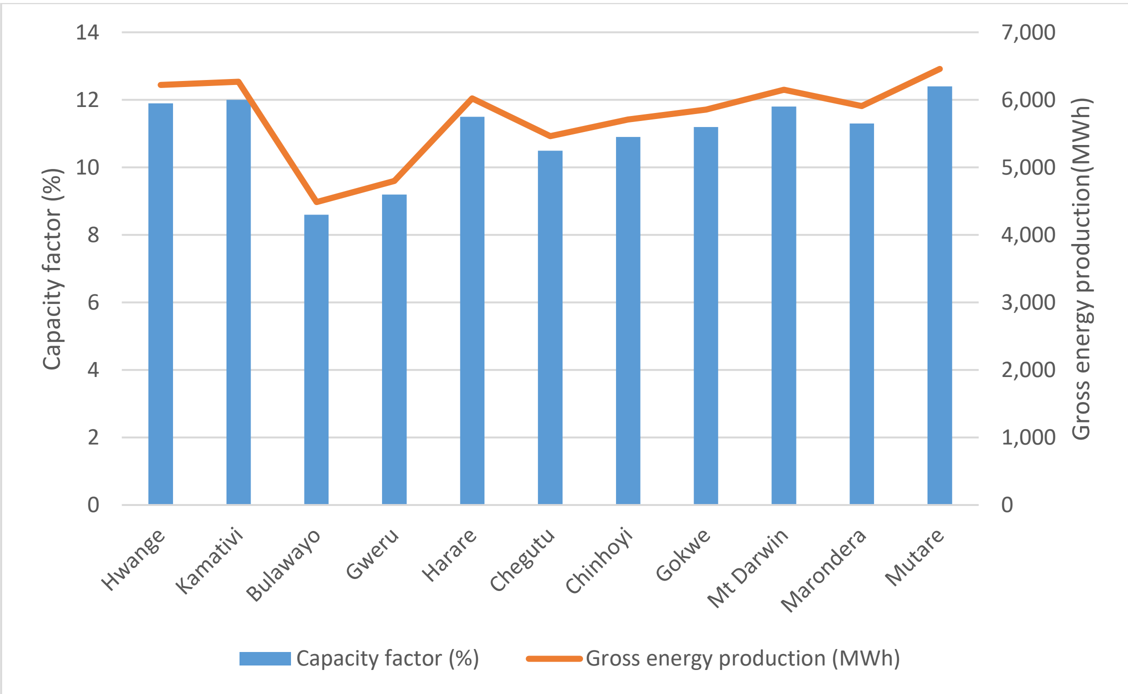

Figure 6.3. A relationship between the capacity factor and the gross energy production for the 11 locations in Zimbabwe.

The investment financial feasibility is highly depended on the NPV. If the NPV is positive the project is potentially feasibility if otherwise, then the project is rejected. A maximum NPV of US$ 19.2 million is observed at Mutare location while the minimum value is US$ 7.8 million observed at Bulawayo. The simple payback period is reported in Table 6.2. The shortest simple payback period is 6.5 years for Mutare whilst the longest is 9.6 years for Bulawayo. The longer the simple payback, the less desirable is the investment [73]. However, the project lifetime is 20 years, therefore Bulawayo can still be considered for investment regardless of it having the longest simple payback period of 9.6 years.

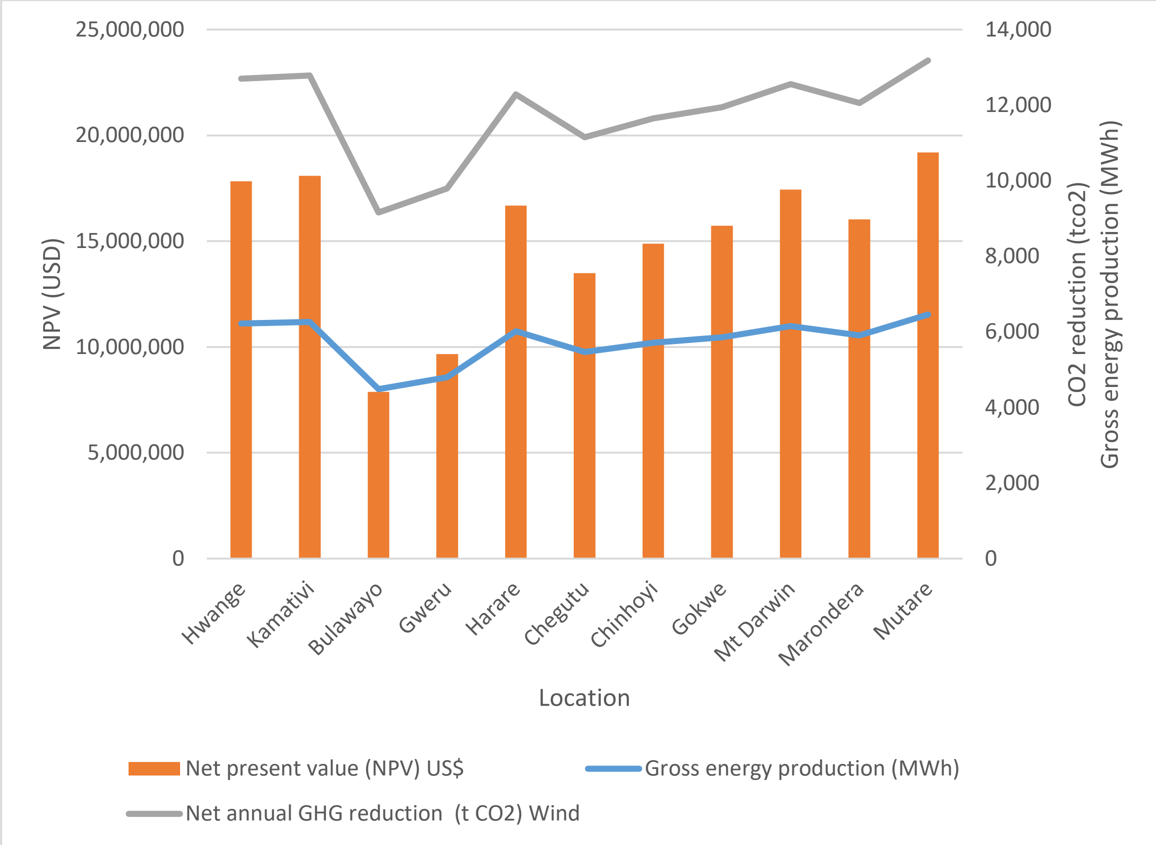

Figure 6.4. A relationship between the NPV, CO_2 reductions, the Gross energy productions for the 11 locations in Zimbabwe.

However, this study shows that all the sites under study are profitable and feasible for a 10 MW grid-connected wind farm construction. From a financial and techno-economic feasibility points of view, Mutare location, having the highest profit, is highly preferable contrary to Bulawayo location which results in the minimum profit. Further emissions analysis shows that Mutare has the largest net annual GHG emission reduction value of 6719 tons of carbon dioxide whilst Bulawayo has a value of 4669 tons of carbon dioxide, which is the minimum. Generally, all sites under study reduce net annual GHG emissions with an equivalent of more than 10,000 barrels of crude oil not consumed per year.

6.3. Hybrid PV/Wind/ESS Systems

Hybrid renewable energy systems integrated with ESSs are considered to have better power generation quality and to be more reliable. However, the current high costs of ESSs are a major drawback for the utilization of battery storage systems in renewable energy power systems. These high costs affect the economic feasibility of RESs. In this present study, a comparative analysis between a hybrid PV/Wind system without ESS and those with Zinc-Bromine and Lithium-Ion is performed. Table 6.4 summarises the techno-economic parameters of the suitable sizes of PV/wind hybrid system with Zinc-Bromine and with Lithium-Ion batteries; and with no ESS, in Gwanda. The more efficient, or feasible systems where determined by setting the COE equal to the grid tariff and maximizing the RES fraction

Table 6.4 The suitable sizes of PV/wind hybrid system with a Zinc-Bromine and with Lithium-Ion batteries; and with no ESS, in Gwanda based on forecasted demand [28].

Configuration	No ESS	Lithium-Ion	Zinc-Bromine
PV Capacity (MW)	0.544	0.331	0.503
Wind Capacity (MW)	2	2	2
Battery Capacity (kWh)	-	279.75	156.51
Energy Produced (MWh)	6815	6518.1	6757.8
Excess Energy (MWh)	2184	850.25	2143.67
Energy Met by the Grid (MWh)	3034	1962.84	3029.7
Energy Production to Demand Ratio (%)	88.90	85.00	88.16
Capacity Factor (%)	30.58	31.92	30.82
RES Fraction (%)	60.42	59.10	60.47
COE ($/kWh)	0.20	0.20	0.20
NPV (k$)	0	138.48	39.13

As outlined in Table 6.4 the integration of ESSs decreased the feasible PV capacity from 544 kW, the case without any ESS, to 503 kW, the case with Zinc-Bromine and to 331 kW, the case of utilizing Lithium-Ion as ESS. The drop in the PV capacity in the Lithium-Ion scenario caused the drop in the RES fraction due to the increase in the capital cost of the system with low revenues from the integration of the battery. The RES fraction was slightly increased in the case of Zinc-Bromine where stored energy in the battery compensated the drop in the PV capacity. The effect of the integration of the batteries is controlled by the capital cost despite both batteries having different round-trip efficiencies and DODs. In both ESSs, configurations, the NPV value of the systems increased despite having a slight increase in the RES fraction in the case of Zinc-Bromine and a decrease in the case of Lithium-Ion. This increase is as a result of a decrease in the capacities of PV which have a high capital cost and a low capacity factor of 15.91 %, which is lower than 34.57% for wind systems in Gwanda.

In all the configurations in this present study, the electricity grid meets around 40% of the demand despite the ratio between the demand and the produced energy is greater than 85%. The major reason behind this is the mismatch between the demand and the generated energy generation and also mostly because of the high capital cost of the batteries which prevents the common integration of ESSs to reallocate and utilize the excess energy generated by the RESs.

6.4. Suitable Systems

16 locations were considered for the analysis of the most suitable and efficient grid connected hybrid PV/Wind power generation systems. The locations considered for this study are Victoria Falls, Hwange, Kamativi, Bulawayo, Plumtree, Gweru, Kadoma, Harare, Chegutu, Chinhoyi, Gokwe, Bindura, Mt Darwin, Marondera, Rusape and Mutare. A comparative analysis was performed for PV, Wind and hybrid PV/Wind systems. Hybrid PV/Wind/ESS system was not considered for this comparison as it already proved unfeasible because of the high capital cost of the ESSs. Since only 11 locations were once considered for separate wind and PV systems, the same 11 locations out of 16 were considered and there were Hwange, Kamativi, Bulawayo, Gweru, Harare, Chegutu, Chinhoyi, Gokwe, Mt Darwin, Marondera and Mutare. Figure 6.6, Figure 6.7 and Figure 6.8 show relationship between SPBP and capacity factor for PV systems, Wind systems and hybrid PV/Wind systems respectively.

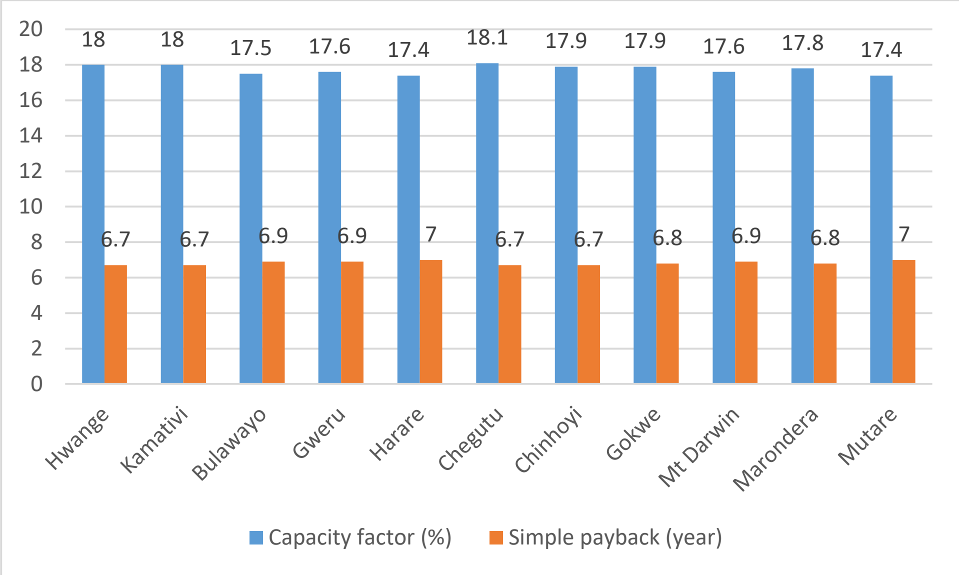

Figure 6.6. The relationship between SPBP and Capacity Factor for a PV System.

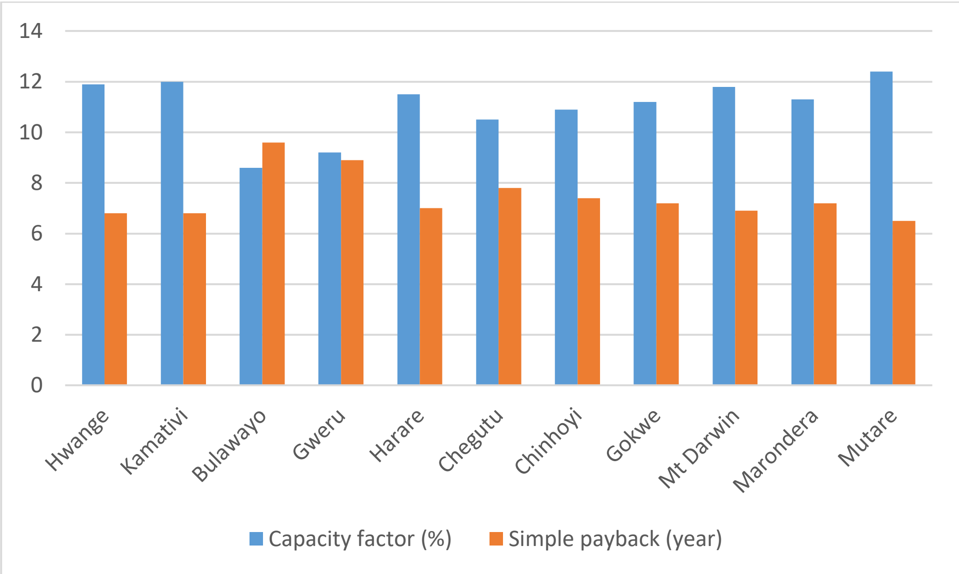

Figure 6.7. The relationship between SPB and Capacity Factor for a Wind Turbine System.

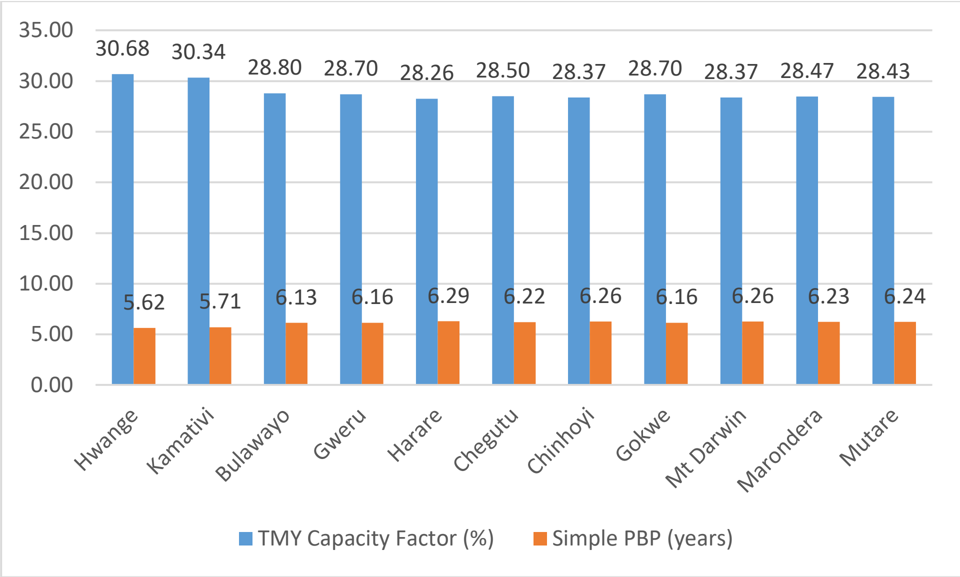

Figure 6.8. The relationship between SPB and Capacity Factor for a grid-connected hybrid PV/Wind System.

Notice an inverse relationship between the capacity factor and the simple payback period is observed in all the three scenarios. However, the capacity factor is almost doubled for all locations in the hybrid configuration. Taking Hwange for instance, the capacity factor increased to 30.68% in the grid-connected hybrid PV/Wind configuration compared to the recorded 18% and 11.9% for the solar PV and Wind configurations respectively. Likewise, the SPBP for the same Hwange location has been observed to have decreased to 5.62 years from 6.7 and 6.8 years for the PV system and Wind system, respectively. Therefore, the grid connected hybrid PV/Wind system is the most efficient and preferred configuration. Based on SPBP and capacity factor, Hwange location with an SPBP of 5.62 years and a capacity factor of 30.68% is considered the most suitable and feasible location and Harare is the least feasible of these 11 compared locations, with a capacity factor of 28.26% and 6.29 years as its SPBP. However, all the 11 locations for the hybrid configuration are considered more feasible than their respective wind and PV cases and since they all have a simple payback period way less 20 years which is the systems' lifetime, all locations can be considered for investments in grid-connected hybrid PV/Wind systems.

Energy production is also seen to have increased in the hybrid system as compared to the individual wind and PV cases. Energy production has a direct relationship with the net amount of the avoided annual carbon dioxide emissions. Figure 6.9 shows the comparison between the amounts of avoided CO_2 emissions of all the three systems' configurations for all the 11 locations.

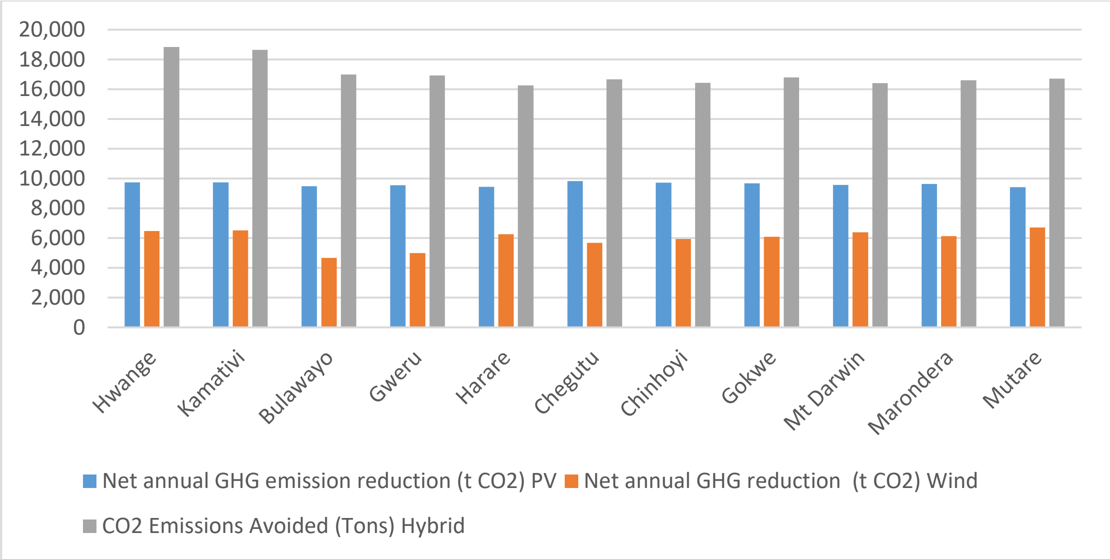

Figure 6.9. A comparison of the net annual CO_2 Emissions for the PV systems, Wind systems and hybrid PV/Wind systems for the 11 locations.

Notice in Figure 6.9, in all locations, the hybrid PV/Wind configuration results in the highest amount of avoided carbon dioxide emissions compared to PV systems alone or wind systems alone. It can be observed as well that Hwange, a location with the highest capacity factor, highest net annual energy production, lowest SPBP has the highest amount of avoided CO_2 emissions and off these 11 locations, Harare has the least amount CO_2 emissions. Considering all the techno-economic, financial and environmental factors it is, therefore, necessary to consider a further analysis of only the grid-connected hybrid PV/Wind systems.

6.5. Grid-connected Hybrid PV/Wind Systems

A deeper analysis of the suitable locations for the investment in hybrid PV/Wind systems was carried out. In total, 16 locations were considered for the construction of hybrid systems. These locations were chosen based on the availability of land for the construction of these plants, the site's connectivity to the grid, availability of their data and availability of the solar and wind resources feasible to harness electrical energy in a large scale.

As stated before, traditionally the NPV had been used to quickly determine whether or not a project is financially feasible. A positive NPV would mean a project is financially feasible, and a negative value would mean the project is unfeasible. However, adding to the traditional parameters used to determine the feasibility of a project, LSPS and the annual avoided the cost of carbon have been added for deeper analysis in determining the feasibility of the project. As explained before, the lower the LSPS the more feasible the project is. Figure 6.10 shows the relationship between the NPV, SPBP and LSPS.

Notice in Figure 6.10 that Victoria Falls has the lowest LSPS of 0.414 meaning it is the most feasible location contrary to Harare with the highest LSPS of 0.484. This result supports the observation drawn from considering NPV and SPBP. Victoria Falls location has the highest NPV of USD 9.41 million and the shortest SPBP of 5.58 years. The least preferable for investment but still a feasible location in Harare, with the lowest NPV of USD 6.62 million and the longest SPBP of 6.29 years.

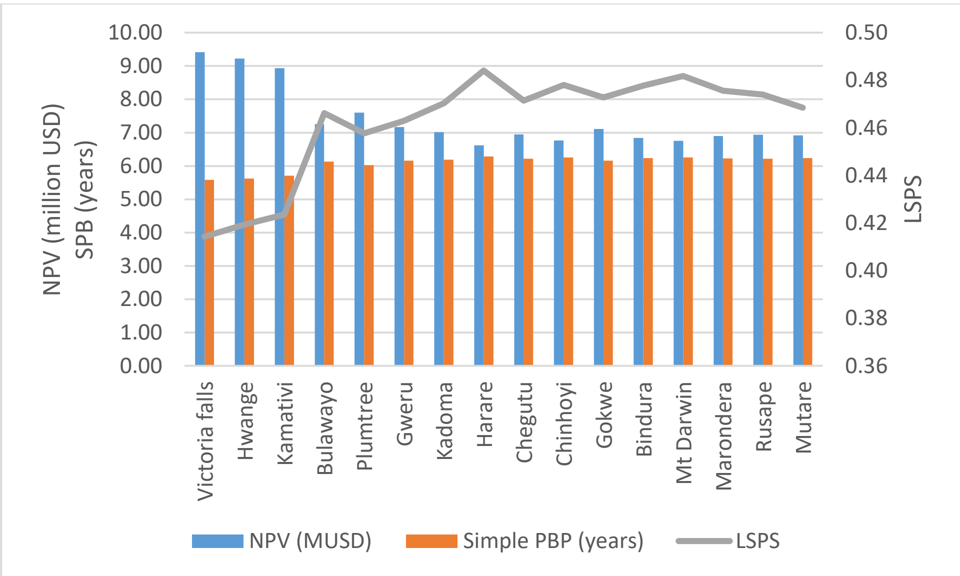

Figure 6.10. The relationship between the NPV, SPBP and LSPS for the 16 locations in Zimbabwe.

Since Zimbabwe is facing a huge electricity crisis, which the current generation system failing to meet the demand, it is therefore of paramount importance to maximize RES fraction. An increase in RES fraction will mean an increase in the annual generated energy as well as an increase in the yearly avoided CO_2 emissions. As shown in Figure 6.11, there is a direct relationship between the RES fraction of the met demand, TMY yearly produced energy and the yearly avoided carbon dioxide emissions. As seen in Figure 6.11, the highest values of the yearly energy produced, RES fraction and avoided CO_2 emissions are at Victoria Falls and the least value is at Harare. An inverse relationship between the RES Fraction and LSPS is observed in Figure 6.12. And Table 6.5 is a summary of the feasible configurations of the hybrid systems in this study. As expected in this analysis, where the main aim is to maximize RES fraction, the higher the RES fraction, the more feasible the location is and at the same time the lower the LSPS at that location. Harare has the lowest RES fraction of 68.99% and a highest LSPS 0.484 making it less feasible compared to the other locations, but still feasible, whilst Victoria falls has the highest RES fraction of 74.03% and lowest LSPS of 0.41 making it the most feasible location in this study.

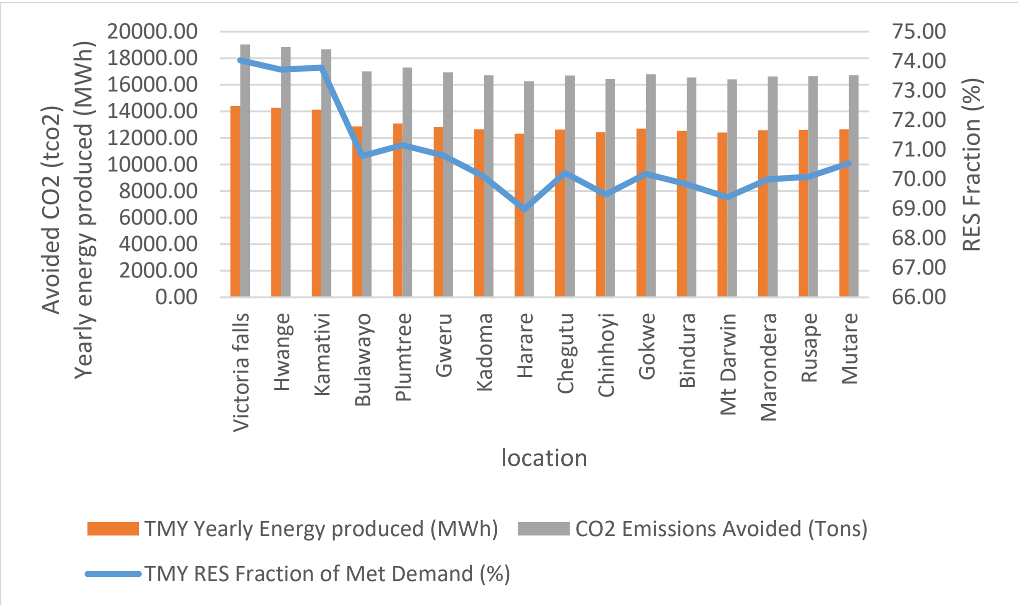

Figure 6.11. The relationship between the TMY yearly produced energy, TMY RES fraction met demand and yearly avoided CO_2 emissions.

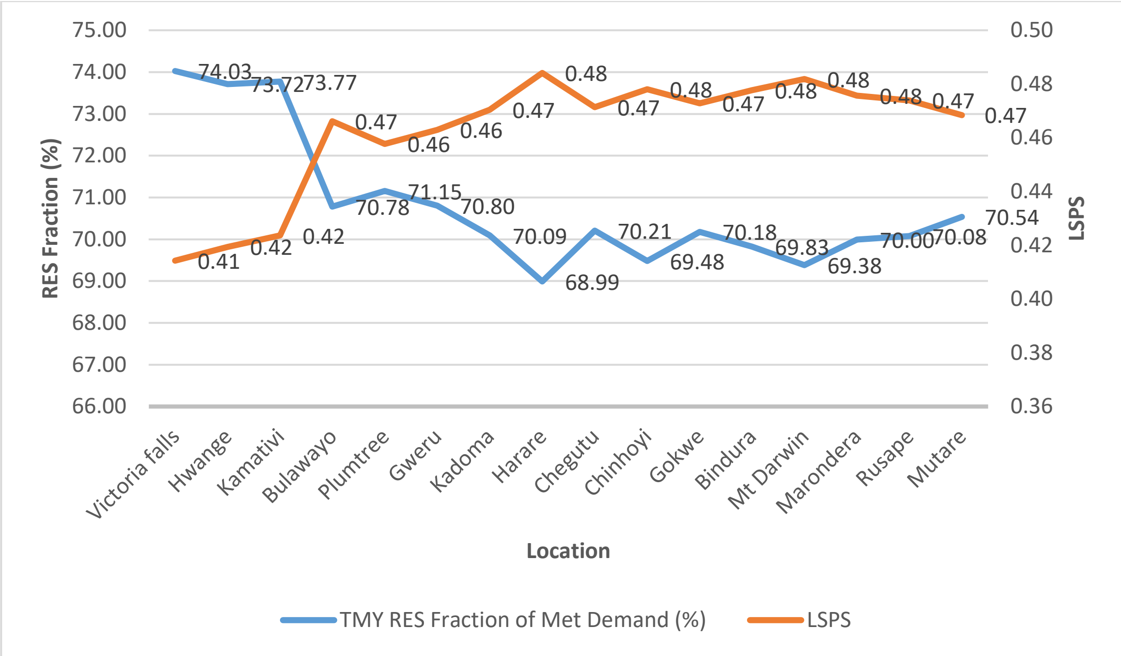

Figure 6.12. The relationship between LSPS and the RES fraction.

Table 6.5. Feasible configurations of the hybrid systems in this study.

City	PV (kW)	Wind (MW)	TMY RES Fraction of Met Demand (%)	CO2 Emissions Avoided (Tons)	Avoided Social Cost of Carbon (Million USD)
Victoria falls	1328.76	4	74.03	19034.64	0.76
Kamativi	1310.62	4	73.77	18660.42	0.75
Hwange	1306.44	4	73.72	18850.53	0.75
Plumtree	1122.95	4	71.15	17296.62	0.69
Gweru	1097.81	4	70.80	16944.39	0.68
Bulawayo	1096.12	4	70.78	16996.04	0.68
Mutare	1078.70	4	70.54	16721.96	0.67
Chegutu	1055.27	4	70.21	16686.13	0.67
Gokwe	1052.93	4	70.18	16794.71	0.67
Kadoma	1046.82	4	70.09	16715.17	0.67
Rusape	1045.70	4	70.08	16656.33	0.67
Marondera	1039.87	4	70.00	16618.91	0.66
Bindura	1027.78	4	69.83	16549.43	0.66
Chinhoyi	1003.13	4	69.48	16438.30	0.66
Mt Darwin	995.95	4	69.38	16414.09	0.66
Harare	967.66	4	68.99	16257.15	0.65

Both wind and solar resources to be harnessed in these proposed systems are intermittent, but since Zimbabwe observes seasonal shifts, it is possible to estimate the days with most sun and those with least. This prediction is possible for the solar resources but not easily predictable for the wind resources, so for a close analysis 15 October and 15 June were chosen to depict the sunny and not sunny days respectively. An analysis of the energy parameters of these days was done only for Victoria Falls and Harare locations since these were observed to the most feasible and least feasible locations respectively. Figure 6.13, Figure 6.14, Figure 6.15 and Figure 6.16. Show a summary of the observed energy parameters for the Victoria Falls and Hwange location.

Figure 6.13 and Figure 6.14 show a typical summer day where the day is expected to be longer thus maximum generation from PV is expected on these days for both Victoria Falls and Harare respectively. In Figure 6.13 it can be observed that a maximum generation is observed around 12.00 noon with a total generation of 4185 kWh, whilst in Figure 6.14 a maximum of 2696 kWh is observed at 18.00 hours.

Figure 6.15 and Figure 6.16 show a typical winter day for Victoria Falls and Harare respectively. The total maximum energy of 5027 kWh is recorded at 14.00 hours in Victoria Falls and a maximum of 4419 kWh is expected at 15.00 hours in Harare on June 15. Notice in Figure 6.13-6.16, at night time when the sun is absent, the total energy generated by the hybrid system is equal to the energy generated by wind turbines only. Additionally, the hybrid systems were configured so as to try and maximize RES fraction, thus minimizing the deficit, hence why in some cases a deficit of 0 kWh is observed. Also in the absence of sunlight, the excess energy is seen to have a similar but shifted down, shape as that of the generated energy from the wind turbine. All the excess energy generated in by these systems is fed to the national grid for free and when the system cannot the energy to cater for the whole demand, the deficit is obtained from the grid. Figure 6.17 shows the relationship between the energy parameters for the hybrid PV/Wind configuration for Victoria Falls for a typical year. As observed, generally the deficit is much smaller compared to the energy generated by the system in a typical year. The designed RES configuration is, therefore, able to generate energy almost throughout the year.

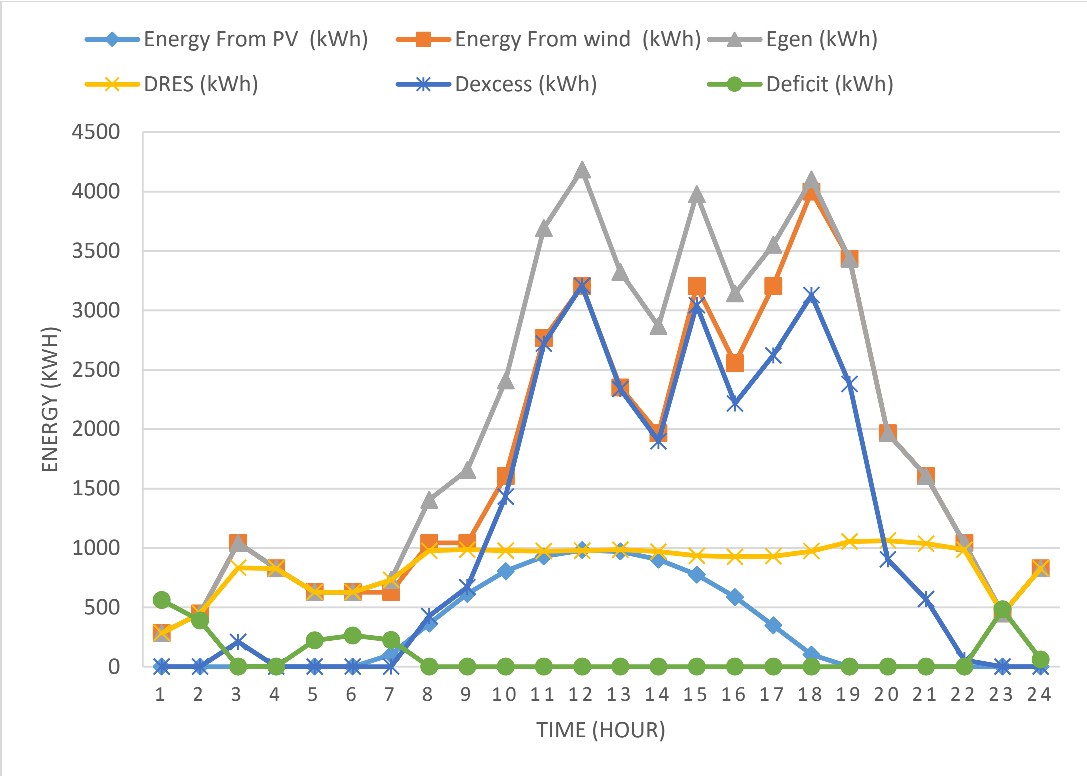

Figure 6.13. Estimated energy parameters for October 15, Victoria Falls Location.

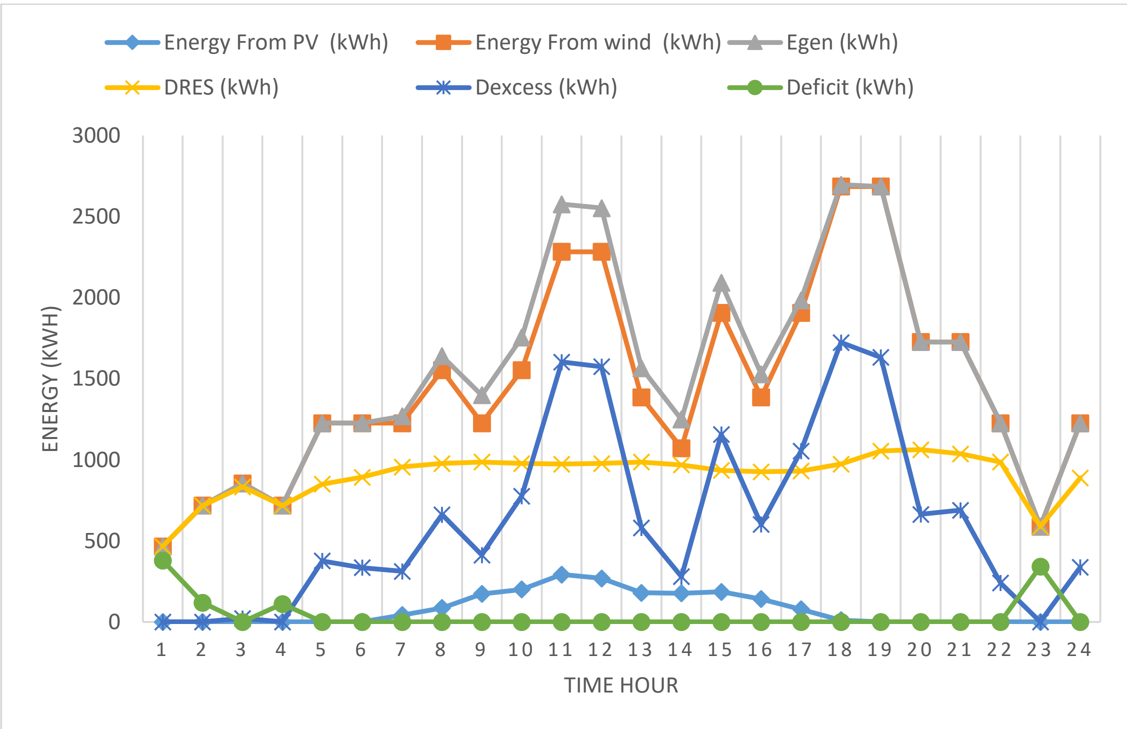

Figure 6.14. Estimated energy parameters for October 15, Harare Location

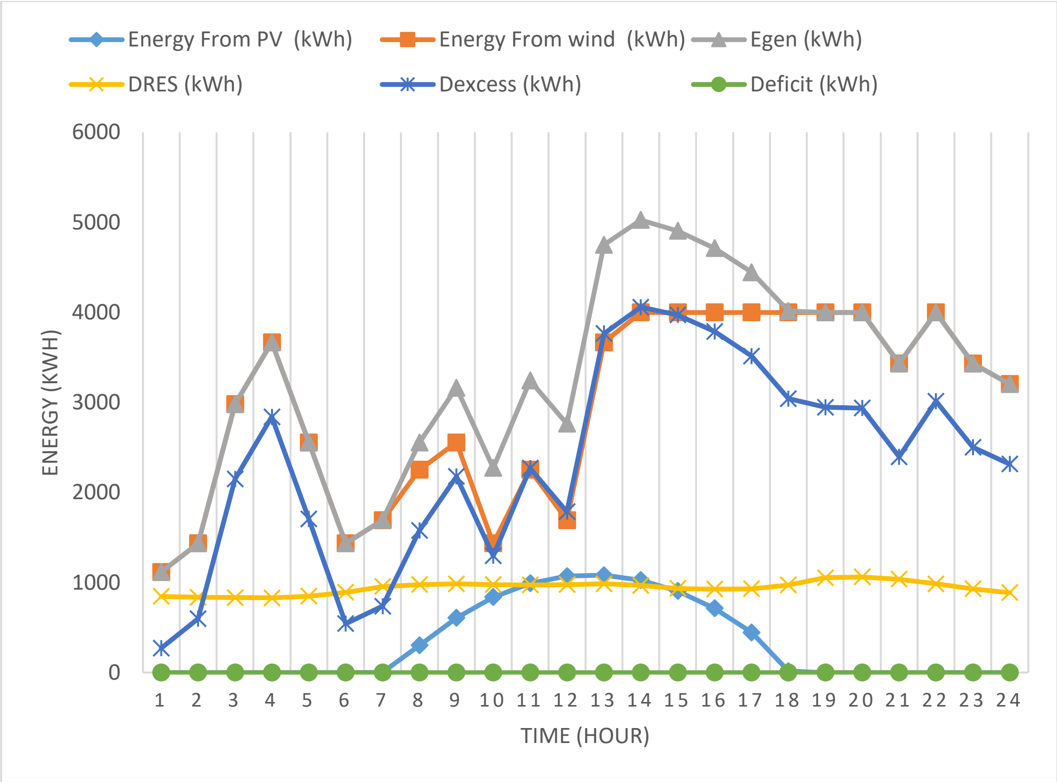

Figure 6.15. Estimated energy parameters for June 15, Victoria falls Location

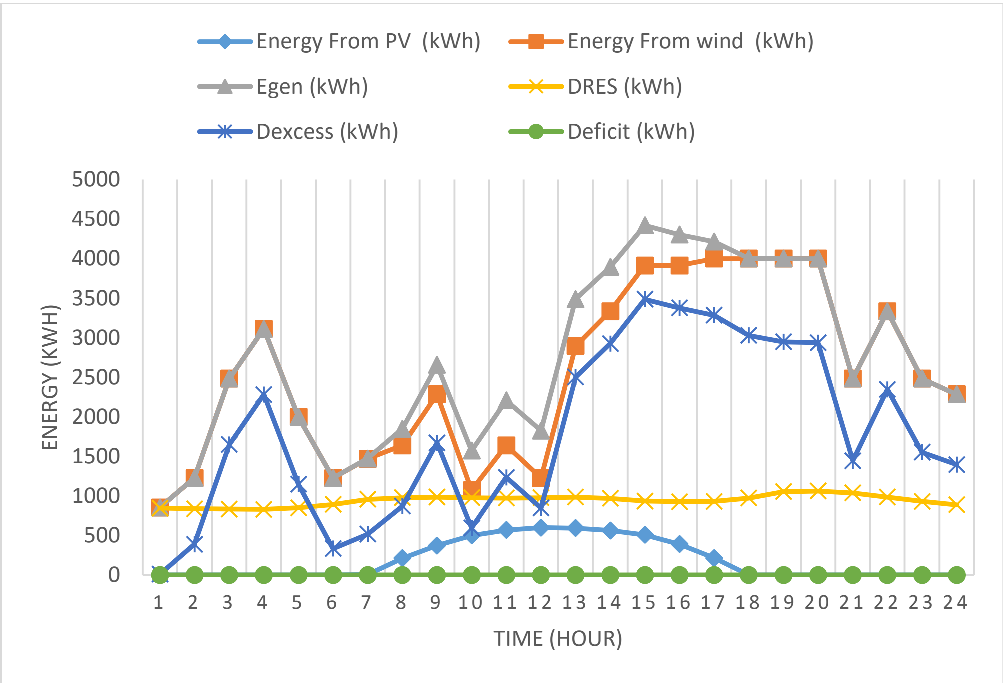

Figure 6.16. Estimated energy parameters for June 15, Harare Location

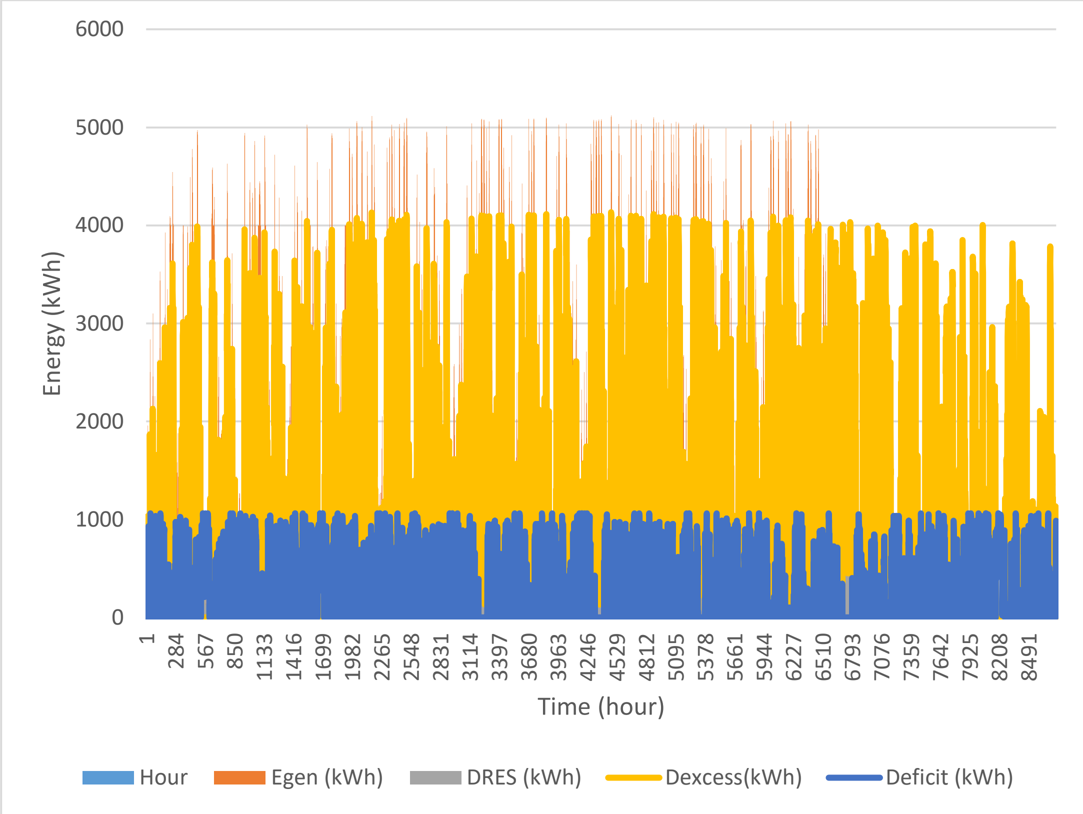

Figure 6.17. The relationship between the energy parameters for the hybrid PV/Wind configuration for Victoria falls for a typical year.

CHAPTER 7

CONCLUSIONS AND FUTURE WORK

7.1. Conclusions

A couple of studies have been done in the hybrid renewable energy field. These studies had different goals to reach but none of these studies considered externalities such as the annually avoided carbon cost. They also did not set a target goal that should be reached such as projecting energy demand thus setting a goal or advising the policy makers to work towards 100% connectivity by considering the projected electricity demand. Zimbabwe is a crumbling economy facing a lot of challenges, and electricity is one biggest challenge, so the main aim of this study was to maximise the RES fraction.

A lot of technical, economic, financial and environmental parameters were taken into account for the feasibility of these systems. One newly employed parameter is the LSPS, which allows for an efficient configuration by avoiding blind capital spending basing the feasibility of the systems on the system cost and system reliability. The systems feasibility were also determined by setting the LCOE at USD 0.20 $/kWh, and any system configuration whose LCOE is greater than this value was regarded not feasible.

As the study was done in stages, the following are the findings from this study;

- The whole of Zimbabwe has enough solar resources for the generation of electricity utilizing the photovoltaic technology. For the analysis, the locations where chosen based on the availability of the data on Meteonorm software, availability of land for the construction of the plants, connectivity to the grid and the availability of the solar and wind resources.
- However, for wind analysis alone, there is a need to really utilize a wind turbine with a low cut-in speed since generally, the whole of Zimbabwe is not rich in wind resources. Highest wind speeds are observed in the mountainous regions like Mutare. The gross energy production in MWh ranged from 4,488 to 6,658 for the locations under study with the minimum observed at Bulawayo and maximum at Mutare. Furthermore, 7,500 to 11,200 MWh of energy can also be exported to the grid. The wind turbine model was selected because of its low cut-in speed of 1.5 m/s, a high cut-

out speed of 27 m/s and a rated power of 5,000 kW at a hub height of 95 m. For the investment of the proposed 10 MW wind farm, 242,811 m^2/MW of land is required.

- As the energy forecast study show, there will be an increase in primary energy consumption from 0.17 quadrillion Btu in 2015 [117] to 0.183 Quadrillion Btu by 2030. Of this primary energy consumption of 2015, 761 ktoe accounted for electricity consumption [118], which is 17.75% of the total primary energy consumption. With the assumption that the same percentage of electricity will be consumed by 2030, a total of 819.18 ktoe is then expected to be the 2030 electricity consumption. By employing a simple proportion and assuming all other factors constant, the peak demand in Zimbabwe is then expected to rise from 2200MW to 2368.19MW by 2030. Against an average daily electricity generation of 1300MW [12], there is, therefore, a need to add more than 1000MW to the current electricity mix of Zimbabwe. All the electricity demand used in this study is therefore scaled by 7.65%, as this is the expected demand increase.
- Integration of ESSs to a hybrid PV/Wind system increases the capital cost of the system without significantly increasing the RES fraction. Only Gwanda location was studied for by integrating Zinc Bromine and Lithium-Ion batteries and this system only had RES fraction of 60.5%, NPV of US$39,130 and a capacity factor of 30.82%. This system consisted of 157 kWh of Zinc Bromine batteries, a wind capacity of 2 MW and a PV capacity of 503 kW.

A couple of assumptions were made in developing the model used to configure the grid-connected hybrid PV/Wind systems in this study and the following conclusions can be drawn;

- A grid connected hybrid system consisting of 4 MW wind capacity and 1328.76 kW PV capacity has the highest RES fraction of 74.03%, highest capacity factor of 30.84%, the highest NPV of US$ 9.41 million and the highest yearly avoided carbon dioxide emissions of 19042.64 tons which gave a total yearly avoided cost of US$ 760000. However, During the construction of such a system, a round figure of the PV capacity will be used, for example, in the event of 1328.76 kW, 1400 or 1500 kW capacity will be constructed. This system was located at Victoria Falls location and it had the lowest SPBP of 5.58 years. The LSPS being used to determine the systems' feasibility by taking into account power reliability and cost as well as recorded to be lowest at this same location with a value of 0.41. Thus grid-connected hybrid PV/Wind investments are more favourable at Victoria falls than any other location in Zimbabwe.

- Harare is the least favourable location for an investment of a hybrid PV/Wind system. The feasible system at this location consists of 967.66 kW PV and 4 MW wind capacity. This system has the lowest capacity factor of 28.26%, lowest NPV of US$ 6.62 million and the lowest yearly avoided carbon dioxide emissions of 16257.15 tons which gave a total yearly avoided the cost of US$ 650000. The highest LSPS of 0.484 is observed at this location with also a corresponding highest SPBP of 6.29 years. These results are highly influenced by the reduction of the PV capacity in the system's configuration. However, the system is still feasible since it has a positive NPV and the SPBP is only 6.29 years, which is way less than the system's lifetime which is 20 years.
- Overall the hybrid system gave rise in RES fraction, capacity factor and annual energy production compared to the individual PV only or wind only configurations. The intermittency problem can also be overcome by integrating wind and PV thus increasing the RES fraction and the power reliability of the hybrid system. In summary, the hybrid systems decrease the mismatch between the demand and the generated electrical energy.
- A total power generation from RES of 81.58 MW is, therefore, proposed as an addition to the Zimbabwean grid by this study. This is almost 10% of the forecasted addition required. Against this backdrop, Zimbabwe is a low-income country in which there is a need to increase connectivity without significantly increasing the tariffs.
- The findings from this study can then be suggested to energy policy makers to integrate the utilization of hybrid RES with what the policy is suggesting, to increase electrification percentage in Zimbabwe.

7.2. Future Work

As projected in this study, solar PV and wind energy alone cannot curb for the electricity deficit in Zimbabwe, therefore, there is need to do a feasibility analysis of other possible renewable energy sources in Zimbabwe such as biomass. It was impossible to have real hourly demand data of all the locations under this study, therefore if real demand data can be accessed and given as input to the developed model, more accurate and real results will be obtained. Since there is no renewable energy policy in Zimbabwe as of yet, and REFIT does not exist, a better study could be conducted by substituting the USD 0.20 $/kWh used in this study by the real one once it is announced. In the presence of real demand data, it might then be possible to even utilize the Gamesa 132-5.0 MW wind turbine which is bigger and at the same time having the lowest cut-in wind speed of 1.5 m/s, which then allows it to harness more energy at the low wind speeds in Zimbabwe. With the advances in ESSs, a further study could incorporate ESSs in the hybrid configurations as well. Where water bodies are present, pumped hydro storage could be considered for long-term storage of the energy from a hybrid system.

REFERENCES

[1] Geo-Ref, "Map Zimbabwe - Population density by administrative division," 2012. [Online]. Available: http://www.geo-ref.net/ph/zwe.htm. [Accessed: 15-Oct-2018].

[2] SOLARGIS, "Bankable solar data for better decisions | Solargis," 2018. [Online]. Available: https://solargis.com/. [Accessed: 17-Oct-2018].

[3] ETCGREEN, "Horizontal Axis Wind Turbine – 2MW," 2009. [Online]. Available: http://etcgreen.com/horizontal-axis-wind-turbine-2mw/. [Accessed: 18-Oct-2018].

[4] Top-Alternative-Energy-Sources, "Vertical Axis Wind Turbine," 2018. [Online]. Available:http://www.top-alternative-energy-sources.com/vertical-axis-wind turbine.html. [Accessed: 18-Oct-2018].

[5] W. A. B. John A. Duffie, *Solar engineering of thermal processes / John A. Duffie, William A. Beckman - Details - Trove*. 2013.

[6] Dinkelman, T. "American Economic Association The Effects of Rural Electrification on Employment: New Evidence from South Africa," 2011.

[7] Y. ScienceDirect (Online service), Wolde-Rufael, and Yemane, *Energy economics.*, vol. 31, no. 2. IPC Science and Technology Press, 2009.

[8] Yoo and S.-H., "The causal relationship between electricity consumption and economic growth in the ASEAN countries," *Energy Policy*, vol. 34, no. 18, pp. 3573–3582, 2006.

[9] "WORLD ENERGY OUTLOOK 2012 EXECUTIVE SUMMARY."

[10] World Bank, "Zimbabwe Energy Situation - energypedia.info," 2017. [Online]. Available: https://energypedia.info/wiki/Zimbabwe_Energy_Situation. [Accessed: 15-Oct-2018].

[11] Collinsenergy, "The Zimbabwean Power Situation | collinsenergy," 2014. [Online]. Available:https://collinsenergy.wordpress.com/2014/04/08/the-zimbabwean-power-situation/. [Accessed: 18-Oct-2018].

[12] ZPC, "Stations - Zimbabwe Power Company," 2018. [Online]. Available: http://www.zpc.co.zw/powerstations. [Accessed: 16-Oct-2018].

[13] Eskom, "South Africa supplies neighbouring Zambia and Zimbabwe with

emergency power," 2016. [Online].

Available: http://www.eskom.co.za/news/Pages/Jan15B.aspx. [Accessed: 18-Oct-2018].

[14] SADC, "Southern African Development Community :: Zimbabwe," 2018. [Online]. Available: https://www.sadc.int/member-states/zimbabwe/. [Accessed: 15-Oct-2018].

[15] Tim Worstall, "With 95% Unemployment Rate Robert Mugabe Insists Zimbabwe Is Not Fragile, "2017.[Online].

Available:https://www.forbes.com/sites/timworstall/2017/05/05/with-95-unemployment-rate-robert-mugabe-insists-zimbabwe-is-not-fragile/#715dc83968e8. [Accessed: 15-Oct-2018].

[16] Lincoln Towindo, "ED spells out Vision 2030 | The Sunday Mail," 2018.

[17] MTHANDAZO NYONI, "ED's vision 2030 gets the nod - The Standard," 2018.

[18] Muza Mpofu, "President Mnangagwa promises brighter days ahead, announces 'Vision 2030' My Zimbabwe News," 2018.

[19] Worldometers, "Zimbabwe Population (2018) - Worldometers," 2018. [Online]. Available:http://www.worldometers.info/world-population/zimbabwe-population/. [Accessed: 15-Oct-2018].

[20] Tony and Boo Peel, "7 Wonders of the World - Natural Wonders of the World," 2018. [Online]. Available: https://www.victoriafalls-guide.net/7-wonders-of-the-world.html. [Accessed: 15-Oct-2018].

[21] TRADING ECONOMICS, "Zimbabwe GDP 1960-2018 Data Chart Calendar Forecast News," 2018. [Online].

Available: https://tradingeconomics.com/zimbabwe/gdp. [Accessed: 15-Oct-2018].

[22] TRAVEL & TOURISM, ECONOMIC IMPACT 2018, and ZIMBABWE, "TRAVEL & TOURISM ECONOMIC IMPACT 2018 ZIMBABWE," 2018.

[23] ZIMFACT, "Agriculture in Zimbabwe - ZimFact," 2018. [Online].

Available: https://zimfact.org/agriculture_in_zimbabwe/. [Accessed: 15-Oct-

2018].

[24] R. Samu and A. S. Kentel, “An analysis of the flood management and mitigation measures in Zimbabwe for a sustainable future,” *Int. J. Disaster Risk Reduct.*, vol. 31, pp. 691–697, Oct. 2018.

[25] “Zimbabwe Geography,” 2016. [Online].

Available:
http://www.worldatlas.com/webimage/countrys/africa/zimbabwe/zwland.htm.

[26] FAO, “FAO CORPORATE DOCUMENT REPOSITORY: Fisheries Management of small water bodies in seven Countries in Africa,” 2015.

[27] R. Samu, M. Fahrioglu, and O. Taylan, “Feasibility Study of a Grid Connected Hybrid PV- Wind Power Plant in Gwanda, Zimbabwe,” in *IEEE Honet Symposium*, 2016, pp. 122–126.

[28] L. Al-Ghussain, R. Samu, and M. Fahrioglu, “TECHNO-ECONOMIC FEASIBILITY OF PV/WIND-BATTERY STORAGE: CASE ANALYSIS IN ZIMBABWE,” in *16th International Conference on Clean Energy (ICCE-2018) 9-11 May 2018, Famagusta, N. Cyprus*, 2018.

[29] R. Samu and M. Fahrioglu, “An analysis on the potential of solar photovoltaic power,” *Energy Sources, Part B Econ. Planning, Policy*, vol. 12, no. 10, pp. 883–889, Oct. 2017.

[30] Samu, R. and Fahrioglu, M. “An analysis on the potential of solar photovoltaic power,” *Energy Sources, Part B Econ. Planning, Policy*, 2017.

[31] Knoema, “World Energy Electricity Data Base, 2014,” 2017. [Online]. Available: https://knoema.com/WEEDB2015/world-energy-electricity-data-base-2014?tsId=1002040. [Accessed: 30-Mar-2017].

[32] Samu, R., Fahrioglu, M., and Taylan, O. “Feasibility Study of a Grid Connected Hybrid PV-Wind Power Plant in Gwanda, Zimbabwe,” 2016.

[33] O. N. O. World, “Human Development Index - Countries with low human development,” 2017. [Online].

Available:http://www.nationsonline.org/oneworld/human_development_low.htm.

[34] World Bank, “Zimbabwe CO2 Emissions Per Capita,” 2013. [Online]. Available:

http://www.multpl.com/zimbabwe-co2-emissions-per-capita. [Accessed: 30-Mar-2017].

[35] African Development Bank Group, "African Development Bank Group," 2018. [Online].Available: http://www.afdb.org/fileadmin/uploads/afdb/Documents/Generic-%0ADocuments/10. Zimbabwe Report_Chapter 8.pdf %0A.

[36] R. Samu, M. Fahrioglu, and O. Taylan, "Feasibility study of a grid connected hybrid PV-wind power plant in Gwanda, Zimbabwe," in *13th HONET-ICT International Symposium on Smart MicroGrids for Sustainable Energy Sources Enabled by Photonics and IoT Sensors, HONET-ICT 2016*, 2016.

[37] CIA world factbook, "CIA world factbook," 2016. [Online]. Available: http://www.indexmundi.com/g/g.aspx?c=zi&v=81. [Accessed: 20-Oct-2016].

[38] Ministry of Energy and Power Development, "ENERGY SECTOR IN ZIMBABWE," 2016.

[39] R. Samu and M. Fahrioglu, "An analysis on the potential of solar photovoltaic power," *Energy Sources, Part B Econ. Plan. Policy*, 2017.

[40] M. D. A. Al-falahi, S. D. G. Jayasinghe, and H. Enshaei, "A review on recent size optimization methodologies for standalone solar and wind hybrid renewable energy system," *Energy Convers. Manag.*, vol. 143, pp. 252–274, Jul. 2017.

[41] M. A. M. Ramli, H. R. E. H. Bouchekara, and A. S. Alghamdi, "Optimal sizing of PV/wind/diesel hybrid microgrid system using multi-objective self-adaptive differential evolution algorithm," *Renew. Energy*, vol. 121, pp. 400–411, Jun. 2018.

[42] A. S. Al Busaidi, H. A. Kazem, A. H. Al-Badi, and M. Farooq Khan, "A review of optimum sizing of hybrid PV–Wind renewable energy systems in oman," *Renew. Sustain. Energy Rev.*, vol. 53, pp. 185–193, Jan. 2016.

[43] S. Kamali, "Feasibility analysis of standalone photovoltaic electrification system in a residential building in Cyprus," *Renew. Sustain. Energy Rev.*, vol. 65, pp. 1279–1284, Nov. 2016.

[44] A. González, J. R. Riba, A. Rius, and R. Puig, "Optimal sizing of a hybrid grid-

connected photovoltaic and wind power system," *Appl. Energy*, 2015.

[45] M. H. Amrollahi and S. M. T. Bathaee, "Techno-economic optimization of hybrid photovoltaic/wind generation together with energy storage system in a stand-alone micro-grid subjected to demand response," *Appl. Energy*, vol. 202, 2017.

[46] K. M.. I. Udumbara Ranaweera, "Techno-Economic Optimum Sizing of Hybrid Renewable Energy System Rural Electrification in Sri Lanka," 2013.

[47] M. S. Adaramola, M. Agelin-Chaab, and S. S. Paul, "Assessment of wind power generation along the coast of Ghana," *Energy Convers. Manag.*, vol. 77, pp. 61–69, Jan. 2014.

[48] S. Bahramara, M. P. Moghaddam, and M. R. Haghifam, "Optimal planning of hybrid renewable energy systems using HOMER: A review," *Renew. Sustain. Energy Rev.*, vol. 62, pp. 609–620, Sep. 2016.

[49] "Getting Started Guide for HOMER Legacy (Version 2.68)," 2011.

[50] S. Mohd, S. Ramli, A. Sufiah, K. Wahid, and H. Kamarudin, "A comparison of renewable energy technologies using two simulation softwares: HOMER and RETScreen A review on highlights and feasibility studies on solar energy utilization in Malaysia AIP Conference," *J. Renew. Sustain. Energy*, vol. 1875, p. 30014, 2017.

[51] S. M. S. Sadati, E. Jahani, and O. Taylan, "TECHNICAL AND ECONOMIC ANALYSES FOR SIZING PV POWER PLANT WITH STORAGE SYSTEM FOR METU NCC," 2015.

[52] Loiy Al-Ghussain ; Remember Samu; Murat Fahrioglu; Onur Taylan, "Techno-Economic Analysis of Photovoltaic-Hydrogen Fuel Cell/Pumped Hydro Storage System for Micro Grid Applications: Case Study in Cyprus - IEEE Conference Publication," in *2018 International Conference on Photovoltaic Science and Technologies (PVCon)*, 2018.

[53] W. Mungwena, "The distribution and potential utilizablity of Zimbabwe's wind energy resource," *Renew. Energy*, vol. 26, no. 3, pp. 363–377, Jul. 2002.

[54] Green Energy Zimbabwe, "Huge potential for wind power generation in Zimbabwe - Green Energy Zim," 2017. [Online].

Available:http://greenenergyzim.misa.org/2017/08/18/huge-potential-wind-power-generation-zimbabwe/. [Accessed: 23-Oct-2018].

[55] Beatrice Companies Inc, “Bell System Memorial- Bell Labs The Solar Battery (Photovoltaics).” [Online]. Available:https://beatriceco.com/bti/porticus/bell/belllabs_photovoltaics.html. [Accessed: 17-Oct-2018].

[56] J. L. Gray, “The Physics of the Solar Cell,” in *Handbook of Photovoltaic Science and Engineering*, Chichester, UK: John Wiley & Sons, Ltd, 2005, pp. 61–112.

[57] S. & Associates, “Overview of the Solar Energy Industry and Supply Chain Prepared for the BlueGreen Alliance,” 2011.

[58] MIKE MUNSELL, “Global Solar PV Installations to Surpass 104GW in 2018 | Greentech Media,” 2018. [Online]. Available:https://www.greentechmedia.com/articles/read/global-solar-pv-installations-to-surpass-104-gw-in-2018#gs.cMvNifY. [Accessed: 17-Oct-2018].

[59] B. Kelly, “Nexant Parabolic Trough Solar Power Plant Systems Analysis; Task 2: Comparison of Wet and Dry Rankine Cycle Heat Rejection, 20 January 2005 - 31 December 2005,” 2005.

[60] “Technology Roadmap - Concentrating Solar Power.”

[61] CSP PLAZA, “2018: The Year Sees Explosive Expansion of CSP Capacity Globally, New Installed CSP Capacity Expected to Exceed 1GW – CSPPLAZA,” 2018. [Online]. Available: http://en.cspplaza.com/2018-the-year-sees-explosive-expansion-of-csp-capacity-globally-new-installed-csp-capacity-expected-to-exceed-1gw/. [Accessed: 17-Oct-2018].

[62] A. M. Rose, “Prospects for grid-connected solar PV in Kenya,” 2013.

[63] S. Ziuku *et al.*, “Potential of Concentrated Solar Power (CSP) in Zimbabwe Biomonitoring of Mucheke and Shagashe Rivers in Masvingo, Zimbabwe Using Macro-Invertebrates as Indicators of Water Quality View project Cost-Benefit analysis of solar water heater installation for a.”

[64] RECP, “Renewable Energy Potential – RECP,” 2018. [Online]. Available:

https://www.africa-eu-renewables.org/market-information/zimbabwe/renewable-energy-potential/. [Accessed: 17-Oct-2018].

[65] S. A. Kalogirou, *Solar energy engineering : processes and systems*. 2014.

[66] EIA, "Types of Wind Turbines - Energy Explained, Your Guide To Understanding Energy-Energy Information Administration," 2018. [Online].

Available:
https://www.eia.gov/energyexplained/index.php?page=wind_types_of_turbines. [Accessed: 18-Oct-2018].

[67] D. M. Tawanda Hove, Luxmore Madiye, "Mapping wind power density for Zimbabwe: a suitable Weibull-parameter calculation method," *J. Energy South. Africa*, vol. 25, no. 4, 2014.

[68] "ZERA Farmers INDABA workshop 2015," 2015.

[69] World Bank, "The World Bank, Food, and Agriculture Organization," 2016.

[70] W. Mungwena, "The distribution and potential utilizablity of Zimbabwe's wind energy resource," *Renew. Energy*, vol. 26, no. 3, pp. 363–377, Jul. 2002.

[71] D. Mentis, S. Hermann, M. Howells, M. Welsch, and S. H. Siyal, "Assessing the technical wind energy potential in Africa a GIS-based approach," *Renew. Energy*, vol. 83, pp. 110–125, Nov. 2015.

[72] S. S. Adaramola, M. S., Agelin-Chaab, M., and Paul, "Assessment of wind power generation along the coast of Ghana.," *Energy Convers. Manag.*, p. 61–69., 2014.

[73] Y. Himri, A. Boudghene Stambouli, and B. Draoui, "Prospects of wind farm development in Algeria," *Desalination*, vol. 239, no. 1–3, pp. 130–138, Apr. 2009.

[74] C. Fant, B. Gunturu, and A. Schlosser, "Characterizing wind power resource reliability in southern Africa," *Appl. Energy*, vol. 161, pp. 565–573, Jan. 2016.

[75] NREL.gov, "Nrel.gov. 2010 Cost of Wind Energy Review," 2015.

[76] "RETScreen International. Clean Energy Project Analysis."

[77] "Zimbabwe inflation rate," 2016. [Online].

Available: http://www.tradingeconomics.com/zimbabwe/inflation-cpi.

[78] "Zimbabwe Central bank discount rate," 2016. [Online].

Available:
http://www.indexmundi.com/zimbabwe/central_bank_discount_rate.html.

[79] "Zimbabwe interest rate," 2016. [Online].
Available: http://www.tradingeconomics.com/zimbabwe/interest-rate.

[80] International Energy Agency, "World Energy Outlook Special Report," 2014.

[81] EPA, "EPA FACT SHEET SOCIAL COST OF CARBON," 2016.

[82] Aweo.org, "Area Used by Wind Power Facilities," 2015.

[83] Eric Rosenbloom, "Argument: Wind turbines are noisy - Debatepedia," 2010. [Online].Available: http://debatepedia.idebate.org/en/index.php/Argument:_Wind_turbines_are_noisy. [Accessed: 19-Oct-2018].

[84] World Data Atlas, "World Data Atlas," 2017. [Online].
Available: https://knoema.com/atlas/Zimbabwe.

[85] Samuel Asumadu-Sarkodie and Phebe Asantewaa Owusu, "Forecasting Nigeria's energy use by 2030, an econometric approach," *Energy Sources, Part B Econ. Planning, Policy*, vol. 11, 2016.

[86] M. Mohiuddin, O., Asumadu-Sarkodie, S., and Obaidullah, "The relationship between carbon dioxide emissions, energy consumption, and GDP: A recent evidence from Pakistan," *Cogent Eng.*, 2016.

[87] Samuel Asumadu-Sarkodie & Phebe Asantewaa Owusu, "The causal nexus between energy use, carbon dioxide emissions, and macroeconomic variables in Ghana," *Energy Sources, Part B Econ. Planning, Policy*, vol. 12, no. 6, pp. 533–546, 2017.

[88] P. Sen, M. Roy, and P. Pal, "Application of ARIMA for forecasting energy consumption and GHG emission: A case study of an Indian pig iron manufacturing organization," *Energy*, vol. 116, pp. 1031–1038, 2016.

[89] J. de A. Cabral, L. F. L. Legey, and M. V. de Freitas Cabral, "Electricity consumption forecasting in Brazil: A spatial econometrics approach," *Energy*, vol. 126, pp. 124–131, 2017.

[90] H.-T. Pao and C.-M. Tsai, "Modeling and forecasting the CO2 emissions, energy

consumption, and economic growth in Brazil," *Energy*, vol. 36, no. 5, pp. 2450–2458, 2011.

[91] S. Barak and S. S. Sadegh, "Forecasting energy consumption using ensemble ARIMA–ANFIS hybrid algorithm," *Int. J. Electr. Power Energy Syst.*, vol. 82, pp. 92–104, 2016.

[92] I. V. Javier Campillo, Fredrik Wallin, Daniel Torstensson, "ENERGY DEMAND MODEL DESIGN FOR FORECASTING ELECTRICITY CONSUMPTION AND SIMULATING DEMAND RESPONSE SCENARIOS IN SWEDEN," in *International Conference on Applied Energy*, 2012.

[93] D. C.-F. Eva González-Romera, Miguel Á. Jaramillo-Morán, "Monthly Electric Energy Demand Forecasting Based on Trend Extraction," *IEEE Trans. Power Syst.*, vol. 21, 2006.

[94] P. G. Loutzenhiser, H. Manz, C. Felsmann, P. A. Strachan, T. Frank, and G. M. Maxwell, "Empirical validation of models to compute solar irradiance on inclined surfaces for building energy simulation," *Sol. Energy*, vol. 81, no. 2, pp. 254–267, 2007.

[95] S. Dubey, J. N. Sarvaiya, and B. Seshadri, "Temperature-dependent photovoltaic (PV) efficiency and its effect on PV production in the world - A review," *Energy Procedia*, vol. 33, pp. 311–321, 2013.

[96] SUNPOWER, "CAUTION: READ SAFETY AND INSTALLATION INSTRUCTIONS BEFORE USING THE PRODUCT. Electrical Data," 2010.

[97] S. M. S. Sadati, E. Jahani, and O. Taylan, "Technical and economic analyses for sizing PV power plant with storage system for METU NCC," in *ASME International Mechanical Engineering Congress and Exposition*, 2015.

[98] Y. Ueda, K. Kurokawa, K. Kitamura, M. Yokota, K. Akanuma, and H. Sugihara, "Performance analysis of various system configurations on grid-connected residential PV systems," *Sol. Energy Mater. Sol. Cells*, vol. 93, no. 6–7, pp. 945–949, 2009.

[99] N. H. Reich, B. Mueller, A. Armbruster, W. G. J. H. M. Van Sark, K. Kiefer, and C. Reise, "Performance ratio revisited: is PR>90% reaslistic?," *Prog. Photovolt Res. Appl.*, vol. 20, no. 6, pp. 717–726, 2012.

[100] J. F. Manwell, J. G. McGowan, and A. L. Rogers, "Wind Energy Explained: Theory, Design and Application," 2010.

[101] J. F. Manwell, J. G. McGowan, and A. L. Rogers, *Wind energy explained: theory, design and application*, 2nd ed. Chichester, U.K: Wiley, 2009.

[102] GAMESA, "Gamesa G114-2.0MW - 2,00 MW - Wind turbine," 2018. [Online]. Available:https://en.wind-turbine-models.com/turbines/428-gamesa-g114-2.0mw. [Accessed: 13-Nov-2018].

[103] USNRC, "NRC: Glossary -- Capacity factor (net)," 2018. [Online]. Available: https://www.nrc.gov/reading-rm/basic-ref/glossary/capacity-factor-net.html. [Accessed: 24-Oct-2018].

[104] L. Al Ghussain, "Economic Assessment of PV Investments in Jordan," *Innov. Energy Res.*, vol. 06, no. 02, pp. 1–4, Nov. 2017.

[105] A. J. Sangster, "Solar Photovoltaics," *Green Energy Technol.*, vol. 194, no. 4, pp. 145–172, 2014.

[106] P. Breeze, "Wind Power," *Power Gener. Technol.*, vol. 1, no. 5, pp. 223–242, 2014.

[107] Y. Sawle, S. C. Gupta, and A. Kumar Bohre, "PV-wind hybrid system: A review with case study," *Cogent Eng.*, vol. 3, no. 1, Jun. 2016.

[108] RECP, "Energy Sector – RECP," 2018. [Online]. Available: https://www.africa-eu-renewables.org/market-information/zimbabwe/energy-sector/.

[Accessed: 25-Oct-2018].

[109] "Net Present Value - The Environmental Literacy Council." .

[110] Y. Fu, J. Yang, and T. Zuo, "Optimal Sizing Design for Hybrid Renewable Energy Systems in Rural Areas *."

[111] Ontheworldmap, "Zimbabwe political map," 2018. [Online].

Available:http://ontheworldmap.com/zimbabwe/zimbabwe-political-map.html. [Accessed: 22-Oct-2018].

[112] Gamesa, "Gamesa platform catalogue," 2016.

[113] Gamesa, "Gamesa G132-5.0MW," 2016.

[114] R. Henbest, S., Mills, L., Orlandi, I., Serhal, A., Pathania, “Bloomberg new energy finance: Levelised cost of electricity,” 2015.

[115] Indaba daily news, “Only in Africa,” 2015.

[116] Windenergyfoundation.org, “Economics,” 2015.

[117] Knoema, “Zimbabwe Primary energy consumption, 1973-2017 - knoema.com,” 2018. [Online]. Available: https://knoema.com/atlas/Zimbabwe/Primary-energy-consumption. [Accessed: 26-Oct-2018].

[118] “Zimbabwe Figure 1: Energy profile of Zimbabwe Figure 2: Total energy production, (ktoe) Figure 3: Total energy consumption, (ktoe) Energy Consumption and Production Production of coking coal Production of charcoal Production of crude oil, NLG and additives Production of natural gas Total production of electricity Refinery output of oil products.”