Kernel Estimation Modelling and Optimization of Hybrid Power System for a typical South African Rural Area

by

MAGENUKA THAND'UXOLO KENNETH

(21557014)

A dissertation submitted in fulfilment of the requirements for the degree of Master of Engineering in Electrical Power Engineering

In the Department of Electrical Power Engineering
Faculty of Engineering and the Built Environment

at the

Durban University of Technology (DUT)

Kwa-Zulu Natal, South Africa.

Supervisor: **Dr Musasa Kabeya**

Co-Supervisor: **Dr Kayode Timothy Akindeji**

November 2022

As the candidate's supervisor, I agree to the submission of this thesis

DR MUSASA KABEYA

NAME OF SUPERVISOR

SIGNATURE

DR KAYODE TIMOTHY AKINDEJI

NAME OF Co-SUPERVISOR

SIGNATURE

DEDICATION

This thesis is dedicated to my grandparents, the late Ntombomzi Nobandla Ann-Sarah and Mzamo Austin Magenuka. I would not be who I am today without their genuine love, teachings, and support. To God be the Glory to whom my dreams live.

DECLARATION OF AUTHORSHIP; PLAGIARISM

I, Mr. Magenuka Thand’uxolo Kenneth, declare that:

1. The research work presented in this study, except where otherwise indicated, is my original research work.

2. This dissertation has not been submitted for any degree or examination at any other institution.

3. This dissertation does not contain other persons’ data, pictures, graphs, or other information unless specifically acknowledged as being sourced from other persons.

4. This dissertation does not contain other persons' writing unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:
    i. Their words have been rewritten, but the general information attributed to them has been referenced.

    ii. Where their exact words have been used, then their writing has been placed in italics and inside quotation marks and referenced.

5. This dissertation does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source is detailed in the dissertation and References sections.

Signed

………………………………………………………………

Magenuka Thand’uxolo Kenneth

ACKNOWLEDGMENTS

Firstly, I express my gratitude to Dr. Musasa Kabeya and Dr. Kayode Timothy Akindeji for their total commitment to this research. I thank them for their time, encouragement, guidance, patience, and valuable input which have aided my thorough understanding of the study and steered me toward the right path to achieve the research objectives.

I express my gratitude to the Faculty of Engineering Built Environment and Science, Department of Electrical Power Engineering for accepting this research project, for letting me use their facilities, and for making a pathway to achieve my goals.

I owe my sincere thanks to my employer the Mangosuthu University of Technology for the financial support, time, and resources to complete this research. A special word of thanks to my colleagues Dr. Pappy Bubele Numbi and Mr. Matthew Sibanda for their encouragement and timeous advice.

I owe my deepest gratitude to my mentor Prof. Pius Adewale Owolawi for guiding me as an emerging academic and researcher.

My appreciation goes to my family, parents, brothers, and sisters for their prayers and moral support. My heartfelt gratitude goes to my partner, who showed great consideration and understanding toward my work schedule. Her presence and support contributed to the timely completion of this thesis.

Finally, I thank God and my spiritual fathers, Canon Mervyn Singh, Rev. Prof John Aitchison, and Dr. Andrew-John Bethke, for their prayers and support during my studies.

ABSTRACT

To increase the accessibility of electricity even to those rural sparsely scattered isolated rural regions, renewable energy seems to be a viable and sustainable option. Before investing in renewables in these areas, a feasibility study is of paramount importance starting with assessing and determining the amount of available solar irradiance and wind speeds for the area. In addition, a techno-economic feasibility study is of paramount importance to determine the most economical and sustainable standalone hybrid system. This research presents a study using a nonparametric kernel density estimation method to determine solar irradiance and wind speeds. In addition to this kernel determination method, the study performs a feasibility analysis using a hybrid renewable energy system that consists of two renewables with biodiesel and battery backup to supply the energy demands of a rural household in South Africa.

The research commences with a literature review of several probability distribution functions (pdfs) commonly used in testing both solar irradiance and wind speeds. It established that not all sites can be defined by the same pdf and there is no science in selecting a distribution function but rather random testing of a range of functions. The parametric probability functions tested in this work are Gamma, Weibull, and Lognormal. The work then compares the performance of these parametric pdfs with the nonparametric kernel density estimation method which this study advocates for its application. In judging the performance and correctness of these pdfs, mean bias error (mbe) and root mean square error (rmse) are used as performance test criteria for the parametric probability distribution function. As for the nonparametric pdf which this research advocates for its use, an integral squared error, ISE is used for the presentation assessment with the conventional parametric normal distribution. From the results, it is observed with the proposed nonparametric kernel density estimator gives precise estimation and improved adaptableness, as opposed to the widely used conventional parametric distribution for both the use in solar irradiation and wind, speeds estimations. In addition, the research results demonstrated that the commonly used Epanechnikov and Gaussian KDE methods were the most adjustable methods for all seven tested stations.

The second aspect of the study applies the tested data to design and perform a feasibility study of using a hybrid renewable energy system that consists of two renewables with biodiesel and battery backup to supply energy demands for a typical rural household. Thus, the study makes use of a simulation to design and determine an optimized hybrid renewable energy system for application in rural households. The energy resources considered for this standalone hybrid system are solar PV, wind, diesel generator, and a storage battery system. In performing the system simulation and optimization concerning economic viability, sustainability, energy efficiency, and environmental impact is carried out using the Hybrid Optimization Model for Electric Renewables (HOMER) simulation and optimization software tool.

Concerning the results obtained, HOMER gave seven best-optimized systems. In breaking down the seven optimized results, four of the results were hybrid energy systems and three with only one energy resource. Moreover, from these results, three systems were pure green energy supplied and not utilizing any diesel generator (DG). The best-optimized system for this rural household consisted of PV/DG with an NPC of $ 72,720, while the system which utilized all resources available was second-ranked with an NPC of $ 79,272. The use of only renewable resources for this region was fourth-ranked with NPC of $ 86,760. The study demonstrates the feasibility and viability of having rural areas benefit from electricity access. Moreover, this study will contribute towards the strides of just energy transition envisaged by the country in solving the energy crisis currently being experienced.

Table Of Contents

DEDICATION iii

DECLARATION OF AUTHORSHIP; PLAGIARISM iv

ACKNOWLEDGMENTS v

ABSTRACT vi

Table Of Contents viii

LIST OF FIGURES xiii

LIST OF TABLES xv

ACRONYMS xvi

CHAPTER 1: INTRODUCTION 1

1.1 Background and Motivation of the study 1

1.2 Problem statement 2

1.2.1 Sub-Problem 1: The unpredictability of renewable energy resources. 3

1.2.2 Sub-Problem 2: The unavailability of real-time site data. 3

1.2.3 Sub-Problem 3: The optimal sizing and allocation of a standalone hybrid system 3

1.3 Research aims and objectives 5

1.4 Research methodology 6

1.5 Hypothesis 7

1.6 Contributions of the study 7

1.7 Scope of work and limitations 8

1.8 Thesis structure 9

1.9 Publications during the study 10

Chapter 2: Literature Review 11

2.1 Introduction 11

2.2 Country profile 12

2.3 South African energy context and history 13

2.4 South Africa energy matrix and electricity profile 14

2.5 Utilization and potential of renewable energy 15

2.6 Solar energy in SA 17

2.6.1 Solar Energy potential assessment review 18

2.7 Wind energy in SA 22

2.7.1 Assessment related to parametric probability distribution functions 23

2.7.2 Wind and Solar Assessment Using nonparametric probability distribution functions 26

2.8 Review of Hybrid Power System Optimization 27

2.8.1 Review of various approaches for optimal modelling and sizing for hybrid systems 27

2.9 Summary 31

Chapter 3: Mathematical Modelling of the System 33

3.1 Introduction 33

3.2 Area Under Study and Data Used 33

3.2.1 Stellenbosch University Station 34

3.2.2 University of Free State Station ... 36

3.2.3 University of Pretoria Station ... 38

3.2.4 University of KwaZulu Natal Data Station ... 40

3.2.5 Graaff-Reinet Station ... 40

3.2.6 Alexander Bay Station ... 42

3.2.7 Vryheid Station ... 42

3.3 Materials and Methods ... 45

3.3.1 Parametric Distribution Models ... 46

3.3.2 Non-parametric Kernel Density Model ... 48

3.4 Comparative Analysis of Estimated Distributions ... 49

3.4.1 Statistical Test ... 49

3.4.2 Kernel Density Estimator ... 51

3.5 Station Results and Discussions ... 51

3.6 Summary ... 59

Chapter 4: Optimal Modelling for A Typical South African Rural Household ... 60

4.1 Introduction ... 60

4.2 Selection of HOMER Pro Software ... 60

4.2.1 HOMER: Simulation ... 60

4.2.2 HOMER: Optimization ... 61

4.2.3 HOMER: Sensitivity Analysis ... 61

4.3 Hybrid System Components ... 61

4.3.1 Diesel Generator 62
4.3.2 Wind energy technology 63
4.3.3 Photovoltaic system 64
4.3.4 Battery storage system 65
4.3.5 Inverter 66
4.3.6 Load Profile and Electricity Demand 66
4.4 Summary 68
Chapter 5: Rural House-hold Simulation and Results Discussion 69
5.1 Introduction 69
5.2 Site Description and Data Collection 69
5.3 System Configuration 69
5.4 Sizing Of the Proposed Hybrid System 70
5.5 Component Cost 71
5.5.1 PV System cost 71
5.5.2 Batteries 71
5.5.3 Wind Turbine 71
5.5.4 Converter cost 71
5.5.5 Diesel Generator Costs 72
5.6 System Results, Analysis and Discussion 72
5.6.1 Economic Analysis 72
5.6.2 System architecture and cost analysis 73

5.7 Summary 84

Chapter 6: Conclusion and Recommendations 85

References 88

LIST OF FIGURES

Figure 2.1 Final use of electricity in South Africa 14

Figure 2.2 Eskom power generation by source 15

Figure 2.3 DNI for South Africa 17

Figure 2.4 GHI for South Africa 18

Figure 2.5 Wind Map for South Africa 23

Figure 3.1 Graaf-Reinet Station 40

Figure 3.2 Alexander Bay Data Station 42

Figure 3.3 Overview of All Stations 45

Figure 3.4 Fitting of pdfs for AL 55

Figure 3.5 Fitting of pdfs for UZ 55

Figure 3.6 Fitting of pdfs for UF 55

Figure 3.7 Fitting of pdfs for UP 56

Figure 3.8 Fitting of pdfs for GR 56

Figure 3.9 Fitting of pdfs for VR 56

Figure 3.10 Gaussian KDE for AL 57

Figure 3.11 Gaussian KDE for UZ 57

Figure 3.12 Gaussian KDE for UF 57

Figure 3.13 Gaussian KDE for UP 58

Figure 3.14 Gaussian KDE for GR 58

Figure 3.15 Gaussian KDE for VR 58

Figure 4.1 Construction of a PV cell, a PV module, and a PV array........................ 64

Figure 4.2 Daily Load Profile 67

Figure 5.1 Hybrid System Diagram 70

Figure 5.2 NPC for PV/DG system.. 77

Figure 5.3 NPC for PV/WT/DG system 78

Figure 5.4 NPC for WT/DG system 78

Figure 5.5 NPC for PV/WT system.. 79

Figure 5.6 NPC for DG system.. 79

Figure 5.7 NPC for PV system 80

Figure 5.8 NPC for WT system 80

Figure 5.9 Monthly average electricity production for PV/DG system...................... 81

Figure 5.10 Monthly average electricity production for PV/WT/DG 81

Figure 5.11 Monthly average electricity production for WT/DG system.................... 82

Figure 5.12 Monthly average electricity production for PV/WT system 82

Figure 5.13 Monthly average electricity for DG 82

Figure 5.14 Monthly average electricity production for PV system.......................... 83

Figure 5.15 Monthly average electricity production for the WT system 83

LIST OF TABLES

Table 2.1 Pdf’s Performance Evaluation Results for Goodness of Fit. 20

Table 2.2 Residential Load Demand 29

Table 3.1 University of Stellenbosch Station Details 35

Table 3.2 University of Free State Station Details 37

Table 3.3 Average Monthly Solar Radiation for UP 39

Table 3.4 Average Monthly Wind Speeds for GR 41

Table 3.5 Average Solar Irradiance for All Stations 43

Table 3.6 Average Monthly Wind Speeds for All Sites 44

Table 3.7 50

Table 3.8 Statistical analysis for each pdf 53

Table 3.9 Statistical Error Results for Solar Irradiance 54

Table 4.1 Load Demand 67

Table 5.1 Optimized System architectures for the rural household 73

Table 5.2 Cost analysis of the rural household architectures 74

Table 5.3 Electrical analysis for the rural household 75

Table 5.4 Electrical production analysis 76

ACRONYMS

AC	Alternating Current
AL	Alexander Bay
COE	Cost of Electricity
CPV	Concentrator Photovoltaic
CSP	Concentrated Solar Power
DC	Direct Current
DG	Diesel Generator
DHI	Direct Horizontal Irradiation
DIF	Diffused Horizontal Irradiation
DNI	Direct Normal Irradiation
DOE	Department of Energy
DUT	Durban University of Technology
GHI	Global Horizontal Irradiance
GHI	Global Horizontal Irradiation
GOF	Goodness of Fit
GR	Graaff-Reinet
HOMER	Hybrid Optimization Model for Electric Renewables
IC	Initial Capital
IITA	International Institute of Tropical Agriculture
Index_A	Index of Agreement

IPP	Independent Power Producers
IRP	Integrated Resource Plan
ISE	Integral Square Error
KDE	Kernel Density Estimator
K-S	Kolmogorov-Smirnov
LCE	Life Cycle Emission
Log-LH	Log Likelihood
LPSP	Loss of Power Supply Probability
MABE	Mean Absolute Bias Error
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
MBE	Mean Bias Error
MBE	Mean Bias Error
MEP	Maximum Entropy Principle
NDP	National Development Plan
NPC	Net Present Cost
O&M	Operation and Maintenance
OCGT	Open Cycle Gas Turbine
PDF	Probability Distribution Function
PSO	Particle Swarm Optimization
PV	Photo-Voltaic

REIPPP	Renewable Energy Independent Power Producers Program
RES	Renewable Energy Sources
RMSE	Root Mean Square Error
SA	South Africa
SAURAN	Southern African University Radiometric Network
SOC	State of Charge
STC	Standard Test Conditions
SU	Stellenbosch University
TNPC	Total Net Present Cost
UF	University of Free state
UP	University of Pretoria
UZ	University of KwaZulu Natal
VR	Vryheid
WT	Wind Turbine

CHAPTER 1: INTRODUCTION

1.1 Background and Motivation of the study

Globally, most countries including South Africa have started looking at using renewable energy (RE) as an alternative energy source. As it stands with fossil fuels, they make most energy sources resulting from their advantageous massive electrical energy produced from one determined location as a power station. This reliance on these non-renewable however has created energy security risks as these fossil fuels are not ecologically viable in the long future and will eventually be depleted. In South Africa, electricity produced from coal which accounts for more than 75% of the grid is currently high compared to other options [1], however burning these fuels and converting them to electric energy generates major pollution complications, like the release of greenhouse gases in the environment which contribute to the global warming phenomenon.

Since the beginning of the 21st century, there has been a major need to generate more electricity for the global population. This electricity is required to be produced in a manner that will not add security threats that exist with fossil fuels electricity generation, but it should meet the new global environmental standards. This continuous depletion of the limited fossil fuel reserve, and rising global energy pollution issues as stated, have resulted in increasing integrations of RES such as wind, biomass, hydrogen, and photovoltaic power systems. This mixing of resources resulted in a new concept known as a hybrid system.

In terms of renewable energy systems, South Africa is still in its infancy when compared to first-world nations, but it is developing quickly, and by 2030, according to the country's medium-long-term goals set in 2010, renewables will make up around 11.4 GW of the country's overall energy mix. Additionally, it appears that wind and solar energy have the potential for a widespread rollout for both small-scale and large-scale in many South African regions and will thereafter have a sizable role in energy production in the future [1].

Solar irradiation information in an area is of utmost importance in determining the potential use of the solar system before embarking on the project. Equally, wind speeds of an area are as vitally important as that of solar before commencing with the project. This data can be gathered by using meteorological measuring instruments as it is highly reliable, dependable, and accurate. However, due to the high cost of these instruments, tolerances, and accuracy deficiencies at times resulting in missing records, it is not feasible to install all these devices in some places. As a result of this drawback, there is a need for solar models that defines mathematical relationships between solar radiation and meteorological variables using solar astronomy and geometry principles. In addition to solar models, wind turbine utilization for different areas requires upfront information. This can be achieved by using probability distribution functions which will describe the wind characteristics for the envisaged area.

This research work will undertake to investigate the probability of using parametric and non-parametric density estimators to qualify and quantify the use and accuracy of using meteorological data in the wind and solar modelling. In this study, the wind and sun irradiation data were measured at seven separate geographic locations spread over various South African provinces utilizing ground monitoring equipment. These seven locations, which are open to the public without charge, are now using ground monitoring stations to track solar irradiance for study. The Southern African Universities Radiometric Network's (SAURAN) seven stations' meteorological measuring equipment was used to collect this very reliable ground-based data. In the case of solar data, the data included global horizontal irradiance in $kWh/m^2/day$ and wind speeds in m/s for wind data. The data obtained from the ground measuring equipment was compared to the satellite-based surface meteorology data to distinguish any differences or similarities. The span of the data obtained is three years starting from 2014 to 2016.

1.2 Problem statement

Before beginning any solar energy initiatives, it is crucial to accurately estimate the daily sun irradiation. Similarly, to this, accurate prediction of the probability distribution of wind speed is crucial and critical in renewable energy applications. The implementation of such systems is challenging for the following listed reasons:

1.2.1 Sub-Problem 1: The unpredictability of renewable energy resources.

The amount of existing renewable energy resources for any given geographical site is always unknown and is a function of location, time, and season. As a result of these varying parameters, the energy provided to the load will always be not constant. Thus, the energy from these renewables for any hybrid system will always tend to impact on the economy of the non-renewables in this case the biodiesel generator (DG).

The previous work has mostly used average monthly renewable resources to estimate and calculate the project costs of using stand-alone hybrid systems. As a result of this, a detailed study will be done to model and predict renewable resources using a daily average of renewable resources over a period of three-year span. To achieve this, probability distribution functions will be used.

1.2.2 Sub-Problem 2: The unavailability of real-time site data.

Meteorological information for both wind and sun are needed when modelling these renewable energy-generating systems. The most crucial step for the economic sustainability of these renewable energy projects is to assess the features and capability of wind and solar energy. The wind speed and sun irradiance pdfs represent, respectively, the wind speed and solar irradiance accumulated over a lengthy period. Their data is crucial for assessing a location's capacity for producing solar and wind energy. The data used to model for different sites can be satellite-based or real-time measured data.

Previous work in modelling for the project sites has used satellite-based data sources which results in the overestimation of available resources for envisaged investment sites. In this study, ground-measured data was utilised as it was obtained from SAURAN.

1.2.3 Sub-Problem 3: The optimal sizing and allocation of a standalone hybrid system

With South Africa’s population of about 59.8 million, 31% of this population dwells in rural areas and does not have access to the national grid even for 28 years at the dawn of democracy [2], [3]. Even though extending the grid is still the chosen mode of rural electrification, this mode of reticulation to remote locations and sporadically populated rural areas can be economically infeasible [4]. To liberate these rural areas and improve their living standards, off-grid clean green electrification can be of help in such areas.

Moreover, to boost the economy of these rural areas, some form of electricity is required, and standalone hybrid electrical reticulation seems to be a viable option for these areas but needs to be reliable, available, and sustainable for the efficient operation demands of these areas. With PV systems and Wind farms having uncontrollable output characteristics as they fully depend on weather conditions [5], a prerequisite for a hybrid energy mix is essential to sustain the needs of the country.

The substantial reliance on fossil fuels and other drawbacks can be significantly reduced by the hybrid energy system. The use of solar energy and wind energy has the major drawback of being unpredictable as they depend heavily on weather and climate conditions as mentioned previously. This, as a result, renders the use of solely using wind turbine alone or photovoltaic alone without a backup extremely less favourable as their systems will provide and meet the load demands when there are sufficient available wind speeds or solar irradiance, while when these conditions change the load demands will not be met. Subsequently, an alternative backup energy source or storage system is required to prevent energy loss. In situations where renewable energy is not possible, the backup energy source supplies power. On the other hand, the power supply from DG is dependable, independent of the local climate, and has low upfront expenses. Diesel generators do, however, have drawbacks, including high operating and maintenance costs and potential environmental contamination. Due to the drawbacks that both renewable and non-renewable energy sources have, several alternative energy sources are developed to partially supplement one another. As a result, appropriately sized, constructed, and optimized multi-source hybrid alternative energy systems are offered as a substitute that has a better chance of providing services of higher quality and dependability than systems that rely on a single energy source.

1.3 Research aims and objectives

Before beginning any renewable energy initiatives, it is crucial to accurately estimate the amount of available renewable resources. In addition to this choice, it is difficult and crucial work to produce an economically viable project to locate, size, and operate any isolated hybrid power system sources optimally.

The study focuses on investigating the use of nonparametric density functions to estimate and determine the number of renewable resources for the seven selected sites across the country. It further selects the best site among the seven sites and designs an optimally sized and operationally controlled hybrid system for the chosen site.

The following is a list of the study's precise goals:

- Given that the availability of renewable resources at various locations varies concerning the time of day, season, and geographic location, a precise estimation of these resources will be made first using both parametric and nonparametric probability distribution functions to provide information on whether it is viable to invest in such a region.
- The model developed for each site will be achieved by using measured data obtained through SAURAN so to determine the best pdf for both parametric and nonparametric.
- Develop a comparative study of parametric and nonparametric probability distribution functions for all the sites to obtain the pdf that best describes each site and the best site among the seven for renewable energy investment.
- Create a hybrid energy system model that includes a battery storage bank, a WT, a DG, and a PV system to best depict a typical rural South African family.
- Optimal sizing and allocation model possessing a technical and economic aspect is to be developed. This model will be designed using HOMER which will consider the power flow from the different energy sources, battery storage system as well as converters considering all impacts up to the load.

Respectively, the research will provide solutions to the following questions.

- How can solar irradiance data and wind speed data be utilized to evaluate and test distribution functions, aiming to determine the most accurate probability distribution function for both wind resources and solar irradiance at each of the seven sites?

- By applying the measured solar and wind data, what is the most suitable Kernel Density Estimator model that effectively characterizes each of the seven sites?

- Through a comparative study, what are the justifications for using parametric and non-parametric modelling approaches for all seven sites?

- How can an optimized hybrid standalone power system be developed for a typical rural area in South Africa, using tested data and considering the integration of solar and wind resources?

1.4 Research methodology

Several methodical procedures must be taken in the design of an effective tool. The steps that this thesis undertook and followed are:

- Reviewed the literature related to the use of statistical probability distribution functions for site wind and solar energy potential assessment. By so doing, the research ascertained existing methods used related to these methods.
- Obtained the necessary daily renewable resources data for selected locations and applied the statistical probability distribution functions to firstly determine which function best describe the locations and verify the adaptability of the nonparametric method.
- Reviewed the literature related to optimal sizing of hybrid renewable energy systems.
- Selected one of the seven locations under study and used the required daily renewable resource data from that area to construct the technical and financial components of a hybrid system, as well as the daily load data. Additionally, HOMER is used to size the developed hybrid system to perfection.

- The proposed model is used through simulations to reduce the costs associated with both the hybrid's sizing and operation under changing domestic demand and shifting renewable resource availability. This was done by using genuine and actual data.

1.5 Hypothesis

In pursuing this research, below are some of the hypotheses made at various stages:

- The first hypothesis is that the proposed data used from SAURAN is reliable as the equipment used is accurate and dependable in most cases.
- The second hypothesis is that the four selected pdfs for testing will provide a possibility of having one as the best pdf to define the data in the seven selected regions.
- The third assumption is that the suggested optimized hybrid system will use less fuel than the diesel-only configuration.
- The fourth hypothesis is that the daily operating costs of the hybrid system will be significantly impacted by seasonal load changes and variations in renewable energy resources.
- The fifth hypothesis is that different manufacturers will have varied effects on the hybrid system's daily operation cost minimization for the same voltage rating for batteries and the same kilowatt rating for inverters and DGs.

1.6 Contributions of the study

The general contributions of this study to the body of knowledge are;

- The author first presents the use of probability distribution functions to assess the availability and probability of using renewable energy resources for seven different sites in South Africa. Ordinary, the use of pdf has been only limited to wind availability estimations mainly in Asia, northern and western parts of

Africa, and not here in South Africa. Moreover, global solar irradiance is also estimated in this study.

- The method of using nonparametric pdf over parametric ones being proposed in this study is vastly used in the field of telecommunication and others but not so much in the field of renewable energy. This method proves to better estimate the available renewable data used in the study. In addition, during the development of these models, real-time ground-measured data is used instead of satellite-based data as the norm.
- The study further develops a typical rural hybrid standalone energy system for the one site with the best renewable resources as determined by the pdfs. In-depth presentations and discussions are provided for the various energy sources and other elements used in this hybrid system. A techno-economic analysis of this standalone hybrid system is performed for this typical rural household.

1.7 Scope of work and limitations

This research work will undertake to investigate the probability of using parametric and non-parametric density estimators to qualify and quantify the use and accuracy of using meteorological data in the wind and solar modelling. In this study, ground monitoring equipment was used to collect data from seven separate geographic stations spread across various South African provinces on wind and solar irradiation. These seven locations are open to the public and are currently used for scientific purposes to record sun irradiance using ground monitoring stations. The span of the data obtained is three years starting from 2014 to 2016. The study further applies the tested data from the best site and uses it to develop an optimal controlled hybrid standalone system for a typical South African rural area.

The thesis will cover;

- A deeper analysis of the literature about the testing and forecasting of solar irradiance and wind speeds using pdfs, which are used in the reliability assessment of these renewable energy sources.
- Develop a typical rural PV/WT/DG hybrid standalone energy system for the one site with the best renewable resources as determined by the pdfs.

- Develop a load profile for a typical rural area to use as load demand.
- A techno-economic analysis of this standalone hybrid system is performed for this typical rural household.

The scope of this thesis will not include;

- The grid-connected hybrid system.
- Hybrid power other than PV/WT/DG with storage batteries.
- Power plant architecture.

1.8 Thesis structure

The primary study findings are reported in Chapter 3 and Chapter 5 of this thesis, which is divided into 6 chapters.

The introduction and context of the work are presented in Chapter 1 along with the study's aims and purpose.

Chapter 2 reports an in-depth research review relating to the area of study. It also discusses research on hybrid renewable energy system operation control and a study on the use of pdfs in renewable estimating.

Chapter 3 describes the different types of mathematical models of probability distribution functions used to estimate renewable energy resources. An explanation of the experimental setup and data collection zones is given at the outset. Also covered in the chapter are the probability density functions used to simulate the probability distributions of both wind speed and solar radiation. Further covered here are the statistical factors used to assess the effectiveness of the used probability distribution functions as well as a comparison study of the estimated distribution. The results obtained from these probability density functions will be discussed in this chapter with the selection of the best representation selected to model for a typical rural area in the next chapter.

The various parts of the architecture of this freestanding hybrid system are described in Chapter 4 of the thesis. The designs of the components, their features, and issues in standalone operation, as well as how they function in this hybrid system arrangement, will be the focus of the discussion. The optimization problem is described in general in this chapter.

All the optimization outcomes derived from the simulation are presented and covered in detail in Chapter 5.

Finally, Chapter 6 provides a general conclusion of this thesis and gives recommendations that set the stage for future studies.

1.9 Publications during the study

DETAILS OF THE CONTRIBUTION TO PUBLICATIONS that form part/or include research presented in this thesis (include publications in preparation, submitted, in the press and published and give details of the contributions of each author to the experimental work and writing of each publication).

Publication 1: **Thand'uxolo Kenneth Magenuka, Kabeya Musasa, Kayode Timothy Akindeji,** " Kernel Density Estimation of Solar Radiation and Wind Speed for South," in 5th NA International Conference on Industrial Engineering and Operations Management Detroit, Michigan, USA, August 10 - 14, 2020

Chapter 2: Literature Review

2.1 Introduction

The South African energy backdrop is summarized in this chapter as the setting for the formulation of the problem. Understanding the possibilities, obstacles, and development of South Africa's energy sector related to the problem formulation of this study requires knowledge about the historical energy context of the country, as well as the current situation regarding the country's National Development Plan (NDP), energy production, and renewable energy use and development.

It is a well-known fact that the electrical power output of both wind and solar renewables is fluctuating with the change in weather conditions and no two sites have identical capabilities. Consequently, a precise estimation assessment and prediction of available renewable resources are critically important before commencing any renewable investment. Thus, it is of paramount importance to examine the potential of wind and solar as power sources. Probability distribution functions are widely used to estimate wind and solar renewables and have shown great accuracy hence can be dependable on them. In addition to this renewable output unpredictability, the load demand changes as well depending on time, season, and location. As a result of these variables, a hybrid energy system consisting of a combination of renewable energy sources with a backup storage battery system is a better option to overcome these drawbacks. Thus, this Chapter in addition to the South African energy context is set to report a thorough review of the use of statistical probability distribution functions for site wind and solar energy potential assessment. A summary of both parametric and nonparametric probability techniques for solar irradiance and wind speed probability distributions is presented. Moreover, the chapter also reports on the optimal sizing of hybrid renewable energy systems as it will be a suitable solution for better sustainability and reliability of energy supply. A summary of different hybrid systems' optimal sizing approaches is discussed.

2.2 **Country profile**

In the Southern Africa region, which extends from Mozambique's eastern border to Namibia's western border, South Africa shares boundaries with six other nations. The Atlantic Ocean is located on the country's western coast, and its eastern coast is home to the Indian Ocean. The total land area of South Africa is 1,219,602 km^2. The country is divided into four regions by the Great Escarpment. The four districts are the three plateaus, the interior plateau, the eastern plateau, and the western plateau. The fourth region is called the Cape fold belt.

From the Kalahari Desert in the west to the grasslands in the east and the semi-arid Karoo in the south, the inner plateau rises to a height of around 1,200 meters above sea level. The Roggeveld Scarp, located in the southwest and rising to a height of 1,500 meters above sea level, is part of the Great Escarpment. At 3,482 meters above sea level where Drakensberg is located [6].

The geographical features of the nation range from semi-arid to desert in the drier northwest to sub-humid, humid at times, and moist near the east coast. The classification of arid or semi-dry regions applies to around half of the country. As a result of the ocean's influence on the east and west coastlines as well as the interior plateaus, South Africa has temperate and subtropical climate conditions, with warm, subtropical weather in the northeast and cool, damp conditions in the Drakensberg region. Southwest-facing regions of the nation experience a Mediterranean climate, whereas central-west and northwest-facing regions are home to warm desert climates. The Western Cape has the winter rainfall season from May to August, while the remainder of the country experiences the summer rainfall season from late November to early February. The average annual rainfall in South Africa is roughly 456 millimeters (mm). In the summer, South Africa's average temperature ranges from 18°C to 42°C, with interior regions typically experiencing these swelteringly high temperatures.

The country’s population is approximately 59.8 million people, with an annual population growth rate estimated at 1.31% [2], [6]. There are nine provinces with most of the current population residing in urban areas or surrounding townships with informal settlements. The remainder of the population resides in the former homeland’s rural area where it is sparsely situated. The people in these scattered rural areas, lead to most of them being left out of receiving basic needs like electricity and running water.

2.3 South African energy context and history

Eskom roughly supplies about 40% of the continent of Africa’s electricity. Currently, Eskom produces most of the nation's power, accounting for about 95% of the total amount needed. Municipalities, along with independent producers and distributors, provide the balance. This utility-generated electricity is sold directly to some industrial, commercial, agricultural, and residential customers. The electricity is generated from several different power stations. These power plants are owned and managed by Eskom and include nuclear, coal, gas, hydro, and pumped storage facilities [7], [8].

This generated electricity requires infrastructure for firstly generation stations and then other categories till the consumer. The electricity infrastructure involves three sub-categories, being generation phase, the transmission phase, and the distribution phase. Eskom is primarily in charge of producing power when it comes to generation. In South Africa, Eskom produces, transmits, and distributes energy to industrial, mining, commercial, agricultural, and residential clients as well as to municipalities, which then redistributes it to businesses and residences in their respective regions. In addition, the utility also buys electricity from Independent Power Producers (IPPs) through a variety of agreement schemes as well as from power-generating facilities outside of the nation [7].

The final electricity distribution used in South Africa is shown in figure 2.1. Industrial, transportation, agriculture, residential, business, and public services make up the five sectors. Unaccounted energy, or energy that has not been assigned to a certain sector, is referred to as the sector "other" [2], [8]. As can be seen in figure 2.1, the proportion of energy used in the residential sector is very small, indicating a low degree of development, especially for those deep rural areas.

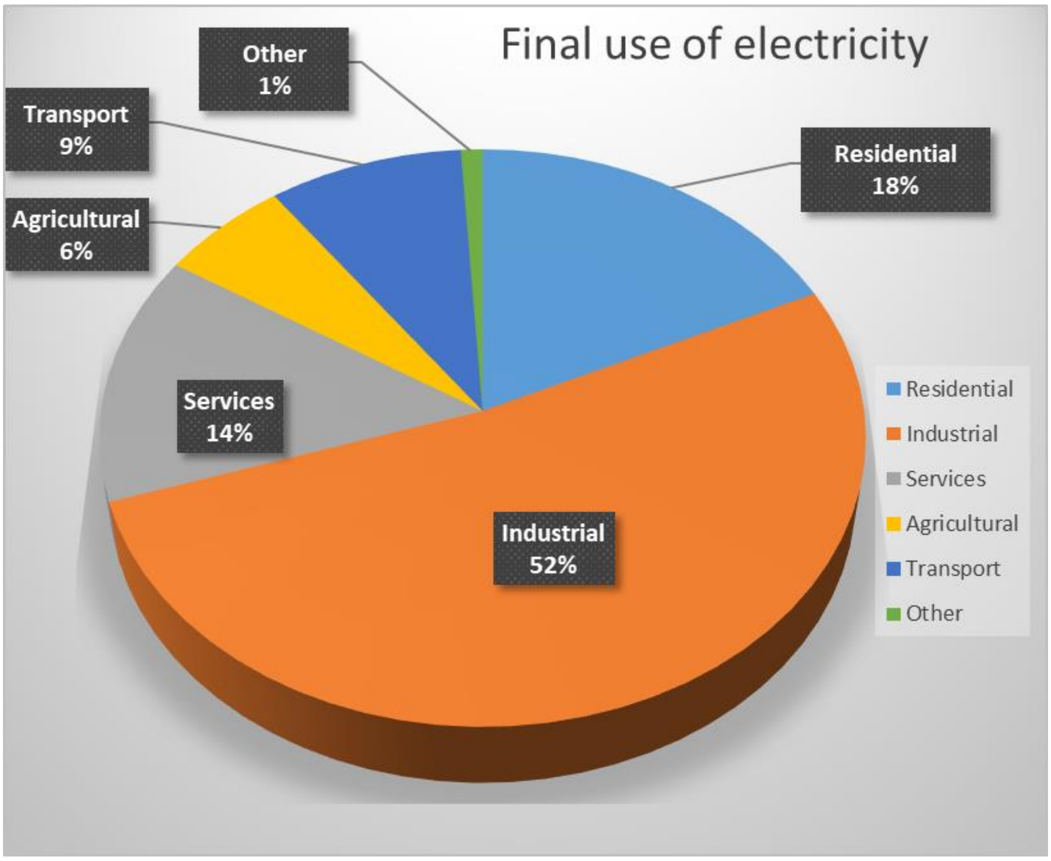

Figure 2.1 Final use of electricity in South Africa

2.4 South Africa energy matrix and electricity profile

The majority of South Africa's electricity is produced by Eskom, with the remaining percentage coming from imports and independent power providers (IPPs), according to the Department of Energy (DOE) of South Africa. Eskom also trades electricity with neighbouring nations [7]. The net maximum generating capacity is approximately 48 GW, according to Eskom's Integrated Results for 2018. 83% of the electricity produced is produced by coal-fired power plants, whereas 4% is produced by nuclear power plants. The remaining combined contribution of all other power plants at their highest generating capacity was 13%, with gas turbines accounting for 5% and pumped storage systems for 6%. Less than 1% of the nation's electricity comes from wind sources, and the Sere wind farm, with a 100 MW capacity, is small in comparison to the others.

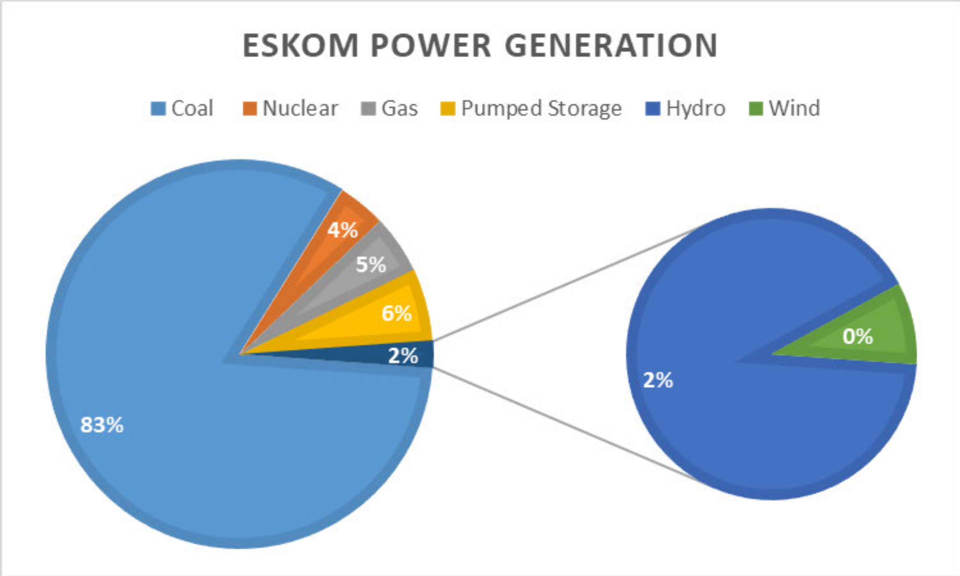

Figure 2.2 Eskom power generation by source

As can be seen from figure 2.2, there is a very small percentage of power generated from renewable energy, and very much more needs to be done to meet the country's needs, especially for the people in the deep rural areas which might be difficult to extend the national grid to them as it may not be economically viable. Consequently, stand-alone hybrid systems might play a vital role to meet this drawback.

2.5 Utilization and potential of renewable energy

The availability of fossil fuels is finite, and their costs are very unpredictable. Overuse of fossil fuels in earlier decades has also contributed to various detrimental environmental problems, such as greenhouse gas emissions, global warming, and environmental degradation. Therefore, it is more important than ever to take careful consideration and care in improving the security of the power supply chain and decreasing the emissions of hazardous greenhouse gases [9], [10].

To reduce environmental problems and encourage independence from fossil fuels, renewable energies are currently being harnessed globally at accelerating rates on all continents. The usage of renewable energy in South Africa is still in its early stages, but it is expanding quickly, and by 2030, according to the country's 2010 medium-long-term plans, renewable energy will make up around 17 500 MW of the country's overall energy mix. By the end of 2020, about 7 000 MW of this renewable ambition should be operational. In many South African areas, wind, and solar energy both seem to have the potential for widespread adoption on both a small- and large-scale basis, contributing significantly to the country's future energy output.

South Africa has a significant renewable energy potential that can be deployed for electricity generation, mainly biomass, the solar, wind, and hydroelectric for some areas (DOE). With its ample supply of wind and sun, the nation can enhance its usage of renewable energy. As seen in figure 2.2, the nation now relies heavily on burning coal to generate electricity, but it also has a few modest hydroelectric facilities and just one nuclear power plant. In addition, South Africa receives a lot of sunshine, which is ideal for solar electricity and water heating. Because traditional fossil fuel-based energy is getting more and more expensive, renewable energy is starting to look like a good alternative. South Africa is now ranked as the 12th most desirable investment location for renewable energy, according to the South African Department of Energy [1]. This is encouraging for South Africa because the program has won praise for its fairness, openness, and certainty on a global scale.

The promotion of renewable energy technology to diversify the nation's energy mix and ensure cleaner energy was made possible by the White Paper on Renewable Energy of 2003. The Integrated Resource Plan (IRP 2010) was released in March 2011 and set a more ambitious goal of 17 800 MW of renewable energy to be realized by 2030 regarding the power generating mix to fulfill the nation's commitment to a low carbon economy. The IRP 2010–2030, which was adopted, identified the optimum generation technology needed to fulfill the anticipated demand increase through 2030. According to the department of energy, the renewable energy system can significantly reduce this heavy dependency on fossil fuels as well as the other drawbacks mentioned. The country's medium-long-term targets, set in 2010 for the national development plan, state that renewables would make up around 42% of the newly developed total energy mix by 2030, even though South Africa is still at a relatively early stage in terms of renewable energy systems.

Since the 2010–2030 IRP plan was published, there have been some capacity developments, including the procurement of 6 422 MW via the REIPPP program, of which 3 876 MW are already operational and connected to the grid. Additionally, IPPs have put into service a total of 1 005 MW from two peaking Open Cycle Gas Turbine (OCGT) plants. In addition to the 1 332 MW of Ingula pumped storage, the Sere Wind Farm operated by Eskom has been expanded with an additional 100 MW of capacity. Since 2011, commitments have been made to build 18 000 MW of new generation capacity using both conventional fossil fuel-fired power plants and renewable energy sources.

2.6 Solar energy in SA

Solar energy is one of the world's most abundant types of clean, renewable energy sources. To harness solar energy, a device needs to convert the solar energy into usable electrical energy. South Africa has solar energy in abundance [11], [12]. Figure 2.3 (Solaris, 2021) illustrates the Direct Normal Irradiation (DNI), and figure 2.4 illustrates the Global Horizontal Irradiation (GHI) of South Africa. It is noted that this is a country full of potential for harnessing solar energy to assist in achieving NDP 2030 goals.

The portion of the radiation that reaches the earth's surface without experiencing any air losses is known as direct normal irradiation. When thinking about concentrated solar power (CSP) or concentrator photovoltaic (CPV) technology, the DNI is a crucial factor.

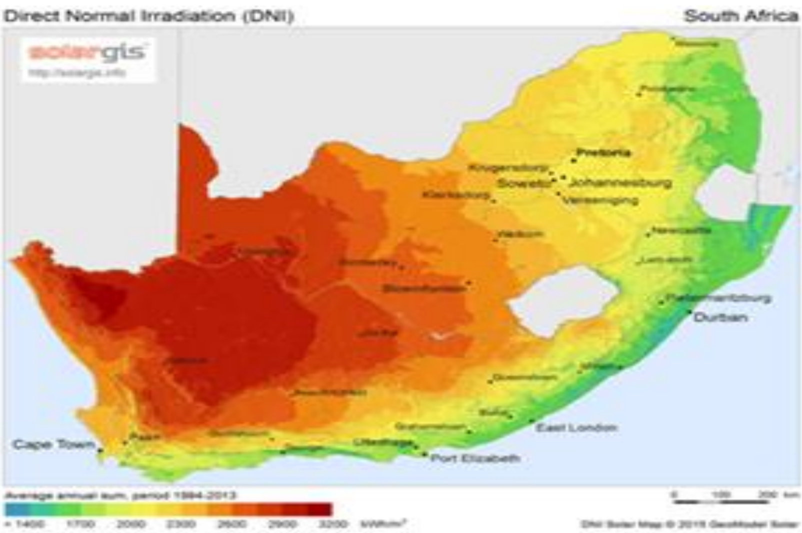

Figure 2.3 DNI for South Africa

Direct Horizontal Irradiation (DHI) and Diffuse Horizontal Irradiation are added to form Global Horizontal Irradiation (GHI) (DIF). While DIF is the irradiation that reaches a horizontal surface on the earth due to scattering, DHI is the component of radiation that reaches a horizontal surface on the earth without any atmospheric losses because of scattering and absorption. When calculating PV electricity yield, GHI is a crucial component.

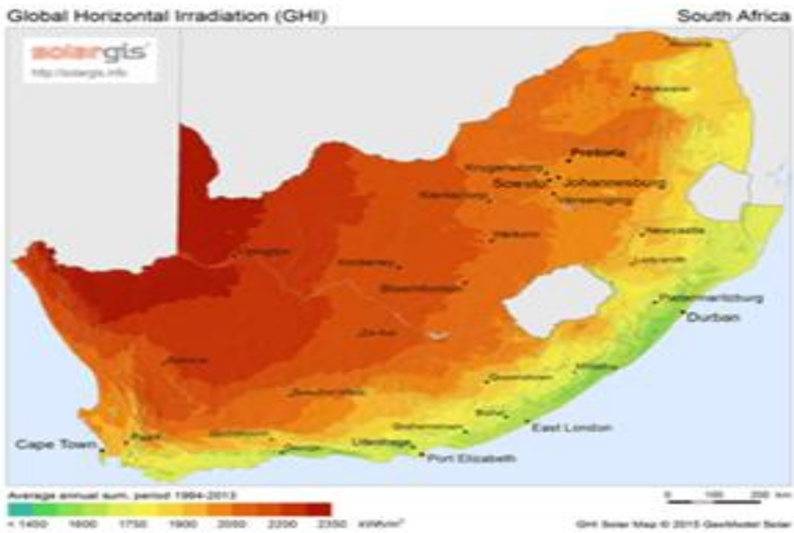

Figure 2.4 GHI for South Africa

As depicted by figure 2.3 and figure 2.4, it can be noted that the inland areas show better opportunities for use of solar PV as an alternative. Additionally, it appears that solar energy has the potential to be widely adopted on both a small scale and a large scale in many South African regions, accounting for a sizeable portion of energy generation in the future.

2.6.1 **Solar Energy potential assessment review**

To effectively evaluate solar energy availability for a certain site, studying the solar distribution model is required. Knowledge of probability distribution function together with its parameters for solar radiation series of a location is one of the utmost importance for any solar project investments. With the use of this data, someone can produce solar data that will, in the future, be identical to the location data that is collected. The design analysis, optimization, and performance assessment of solar technologies should therefore be based on reliable data that is easily accessible. Unfortunately, because the necessary measuring methods and equipment are costly, many developing nations lack the infrastructure needed for reliable and continuous measurements of solar radiation. As solar radiation is the primary factor to always take into consideration, it is, therefore, necessary to develop different methods for estimating solar radiation data. This section reports on the broad literature review done concerning the use of pdfs for solar radiation estimation.

Previously, the use of climatological data such as atmospheric pressure, relative humidity, the maximum and minimum temperature, sunshine hour, etc, could be used to model the solar radiation potential for a location as these are relatively easily measured quantities and do not require complex and sophisticated instruments to perform such measurements. However, this method proved to be an inaccurate and not true representation of solar radiation potential for most locations.

As a result, various studies have been done investigating the use of different probability distribution functions to describe solar irradiance profiles. Some of the relevant review publication work related to the assessment of the solar potential for certain regions using parametric probability distribution functions are summarized below.

The probability distribution for modelling global solar radiation and the parameters of the distribution of Ibadan, Nigeria, Southwest Nigeria was conducted by Ayodele [13] who concluded that logistic distribution presents the best probability distribution in modelling global solar radiation of Ibadan. In this study of Ibadan, the data utilized for the investigation consisted of daily average global solar radiation collected from the International Institute of Tropical Agriculture (IITA) located in this region of Ibadan. About the data used, it had a span of nine years spanning from 2000 to 2008. Numerous distribution functions were tested and evaluated using four goodness of fit to determine the most suitable ones for this region. The four goodness of fit tests used were Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Mean Absolute Percentage Error (MAPE), and coefficient of determination (R^2). Of the several distribution functions that were tested and evaluated, the seven best pdfs that the author reported on were gamma, generalized extreme value, Weibull, extreme value, logistic, normal, and lognormal distributions. However, it needs to be mentioned that more than the seven reported statistical distribution functions were also tested and found to be far from best fitting and hence not mentioned. Table 2.1 below illustrates results for the performance evaluation of statistical distribution for modelling global solar radiation in Ibadan using statistical goodness of fit.

Table 2.1 Pdf's Performance Evaluation Results for Goodness of Fit.

PDF	RMSE	MAE	MAPE(%)	R^2	Order of good fit
Logistic	0.399	0.214	3.26	0.989	1st
Normal	0.475	0.346	5.88	0.981	2nd
Weibull	0.522	0.382	6.10	0.979	3rd
GEV	0.548	0.422	6.89	0.974	4th
Gamma	0.583	0.429	7.36	0.970	5th
Extreme Value	0.619	0.452	7.99	0.966	6th
Lognormal	0.681	0.510	9.35	0.949	7th

It can be observed that the logistic distribution function best represents this region by far in all four goodness of fit results. Consequently, in predicting future global solar radiation for Ibadan, the Logistic distribution function is recommended.

Likewise, similarly, Ihaddadene Razika and Ihaddadene Nabila performed monthly global solar radiation modelling In the M'sila region [14], Algeria using six statistical distribution functions. The six functions used to estimate the monthly global solar radiation for M'sila were Weibull, Gamma, Normal, logistic, lognormal, and log-logistic functions. To determine the performance of these functions, four statistical parameters namely correlation coefficient R^2, root mean square error (RMSE), mean bias error (MBE), and mean absolute bias error (MABE) were used. Their study specifically focused on two main objectives which were to determine and estimate the ideal number of years for data required to carry out such a study in M'sila. Testing and validating several models to estimate the monthly average global solar radiation was another important goal of this study, and the best model that produced data that were more accurate for the area was selected. In reaching their conclusion, a few things were noted that need to be observed. The Weibull distribution demonstrated results to be the highest value when compared to the other distribution functions for each month over the course of the entire 15 years, which was determined to be the ideal number of years required for this region. This can be seen using the determination coefficient. The Lognormal distribution for this test showed the lowest values as it did not best fit this region as compared to the other five pdfs. Lognormal and logistic distributions showed the same results for certain months of the year. In ranking their performance according to the R^2 test, the Weibull distribution function is followed by logistic distribution, Normal distribution, log-logistic, Gamma distribution, and lastly lognormal distribution. In terms of RMSE, all distribution functions gave a low value which indicates a good performance for all pdfs considered. Consequently, from these results, the Weibull function described the best monthly distribution of global solar radiation in the M'sila region.

Numerous additional probability distributions have been studied in various parts of the world including work by Tian Pau Chang in Hualien and Taitung, Taiwan [15]. The author investigated four distribution functions for the region in Taiwan with all four probability functions showing similar results where weather conditions are relatively steady throughout the year.

This section demonstrates the use and importance of testing different distribution functions as there are no two regions with identical weather conditions hence the need for testing various functions to verify and gain knowledge about which probability distribution function best describes a certain region.

2.7 **Wind energy in South Africa**

Over the past ten years, the use of wind energy as a globally accessible, affordable, and cost-effective renewable energy source has increased significantly [16], [17], [18]. In the future, a significant amount of the world's energy needs could be efficiently met by wind energy without the release of dangerous gases. The wind industry has made significant strides in terms of wind turbines erected, and by the end of 2019, the capacity of all installed wind turbines was roughly 470 GW [19].

One of the rapidly expanding and popular renewable energy sources used to meet the needs of cities and isolated locations is wind energy [16]. Wind energy is an alternative energy source that can help solve the environmental problems that humans have generated due to the pollution that is produced by the overuse of fossil fuels and their diminishing reserves. Utilizing wind energy as a clean, renewable source of energy can help countries become less reliant on fossil fuels, which are the primary sources in their national energy supply networks. Although wind energy has been used globally over the past few decades, recent years have seen the most substantial development in its utilization. South Africa as the country has a massive potential to use wind energy to generate electricity. Figure 2.5 depicts the potential use of wind to generate electricity. It can be noted from the figure that most coastlands in the country possess this opportunity.

Wind resources assessment, particularly in terms of evaluating wind characteristics, is of particular significance for providing effective wind energy harnessing and enhancing the effectiveness of wind energy markets. An essential first stage in the creation of wind energy that is cost-effective is to assess the features and possibilities of wind energy. The wind speed probability distribution represents the wind speed data gathered over a considerable amount of time. As a result, its data is crucial for determining a location's potential for wind energy. It should be noted that due to variances in the characteristic of wind speed, wind turbines built at two places with identical average wind speeds may typically provide radically different energy outputs. This emphasizes the significance of understanding wind speed distribution even more.

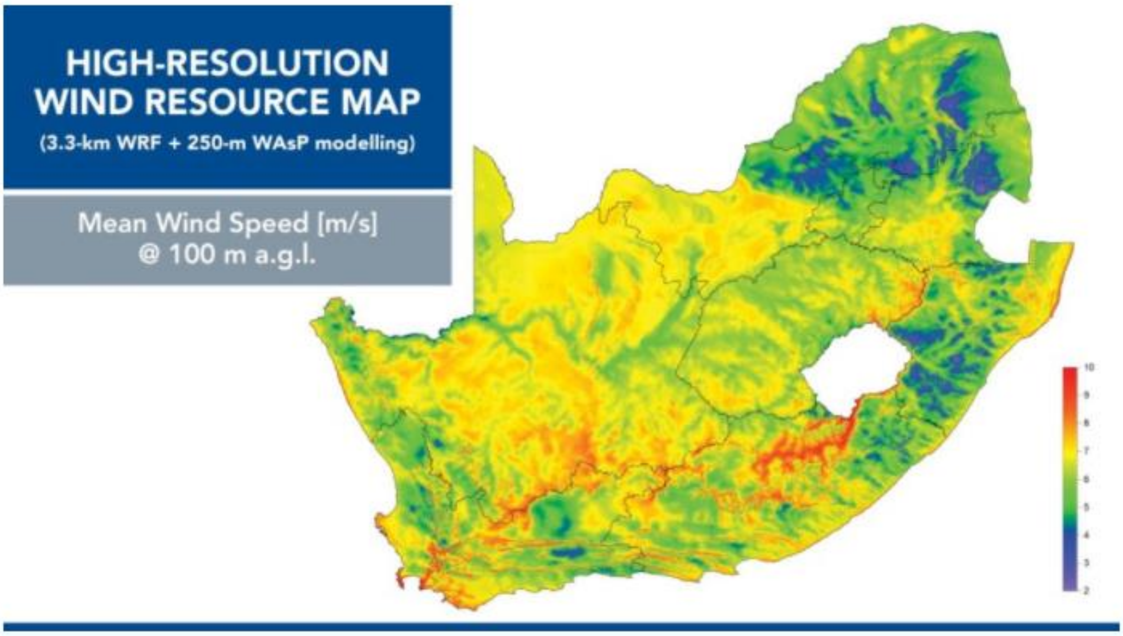

Figure 2.5 Wind Map for South Africa

2.7.1 Assessment related to parametric probability distribution functions

Studying the winds distribution model is necessary to accurately assess the wind power availability for a particular site. The employment of various probability distribution functions to characterize wind speed frequency profiles has thus been the subject of numerous studies. The following summarizes some pertinent review publications work on the evaluation of wind potential for specific regions using parametric probability distribution functions.

In [20], for sites in North Dakota, Junyi Zhou, Ergin Erdem, Gong Li, and Jing Shi conducted a thorough evaluation study of wind speed distribution models. They first used eight conventional pdf, including the Weibull distribution, Rayleigh distribution, Lognormal distribution, Gamma distribution, Inverse Gamma distribution, Erlang distribution, Inverse Gaussian distribution, and Gumbel-Maximum distribution, to investigate probability density functions for the wind speed data from five representative sites in North Dakota. They then applied the maximum entropy principle (MEP) distribution to these eight traditional pdfs. To find the appropriate distributions for the wind speed data for each site, six statistical goodness-of-fit (GOF) tests were performed. X^2, coefficient of determination (R^2), root mean squared error (RMSE), log likelihood (Log-LH), Kolmogorov-Smirnov (K-S), and index of agreement (Index A) are the six statistical GOF that were utilized to carry out the evaluation. They noticed that none of the five locations had a single distribution model that performed better than the others and that Rayleigh distribution fared poorly at many of the sites. Additionally, much like with all other conventional models, the performance of MEP-derived PDFs in fitting wind speed data differs from site to site. Their findings demonstrate the adaptability and potential of MEP-derived PDFs to record other potential distribution patterns of wind speed data. In addition to their discovery, different GOF statistics generated varying ranking orders of fit presentation among the conventional PDFs. To rate the overall performance of the selected statistical distributions, a complete metric that combines all the individual statistics is also proposed.

In [21], the quality of the wind speed fitting distribution for Palermo, Italy, was evaluated by the authors using seven probability distribution functions. Weibull, Rayleigh, Lognormal, Gamma, Inverse Gaussian, Pearson type V, and Burr are the seven PDFs that were utilized. It is imperative to mention the location of Palermo where the study was done as it is not a normal flat outside place but an urban area in Italy. Their study had two main objectives which were first to describe the numerical procedures used to study the wind speed data. The second objective which is of more relevance to this research, was to test various PDFs and obtain more suitable probability distribution functions that would best fit the data for the said location. For each PDF, the maximum likelihood estimators were used to test the fitting and estimate. Moreover, the Kolmogorove-Smirnov test was performed as the quality measure of the proposed PDFs in the fitting of the experimental data. They summarily concluded that Burr distribution was the best fit for the region while Weibull did not perform poorly in any of the stations highlighting the adaptability of this pdf in most regions.

Jie Wu, Jianzhou Wang, and Dezhong Chi assessed wind energy potential for the site of Inner Mongolia in China [22]. In their study three probability density functions namely Weibull, Logistic and Lognormal were used to evaluate wind speed distribution modelling utilizing data measured at a classic site in Inner Mongolia, China, with a data span of three years. These three pdfs were tested to compare their performance with this site’s data. The Weibull function's shape parameter estimation using three-particle swarm algorithms and 18 differential evolution approaches were compared, with the best-performing approaches chosen and used to determine the best shape parameters to produce the most accurate and dependable shape results. Even though the Weibull function is typically the most popular and preferred distribution for describing the distribution of wind speed, it performed poorly in this study and worse than the Logistic under the conditions of the measured wind speed data and the selected error evaluation criteria. Additionally, the Logistic function produced a more satisfactory outcome in wind speed distribution modelling when compared to the Lognormal function. As a result of this superiority, the Logistic function was used to assess the wind energy for their study evaluating different aspects namely availability, capacity, and turbine efficiency of a wind turbine. It was concluded that this site in Inner Mongolia in China is suitable to build a wind farm using these probability distribution functions.

To assess the applicability of wind speed probability distribution models at five distinct stations located in this region of Iran, Omid Alavi, Kasra Mohammadi, and Ali Mostafaeipour carried out a case study for the east and southeast sections of the country. [23]. A new distribution model named Nakagami distribution was used for the first time and compared against seven other probability distribution models. The seven distribution models are Exponential, Weibull, Gamma, Lognormal, Log–Logistic, Inverse-Gaussian, and Generalized extreme value. This Nakagami has been previously used successfully in other fields and assessing it in wind speed estimation was of important interest. The usefulness of all these distribution functions including Nakagami was evaluated statistically based on widely used statistical parameters. Their performance was compared and discovered that it is not possible to choose one distribution function that fits perfectly in all five stations. Moreover, wind characteristics such as wind speed and quantity together with wind quality were observed as major influencers on the performance of distribution functions. In addition to the aforementioned issue, the skewness of the recorded wind speed data influenced the precision of the Nakagami distribution. For two of the five stations, the Nakagami distribution showed the highest performance as compared to the other seven distributions used. They concluded that as much as this Nakagami distribution showed great effectiveness and performance in two of the five stations, but more assessments of its performance are required for it to be considered among the best-performing distributions in wind estimation like Weibull.

Many other reviews were done involving different PDFs which all involved different approaches. These reviews were done by [24], [25], [26], [27], [28] with all the authors for these studies arriving at different distribution models as the best fit for the study. It is clear from the review done that the Weibull distribution is the commonly used distribution for most of the studies. This however does not necessarily lead to Weibull distribution being the best distribution fit for all places in terms of wind speed evaluation. As a result of this, it is advisable to test more than one distribution function in any site envisaged on utilising wind energy resources hence the use of three distribution functions in this study. The three functions tested are Weibull, Gamma, and Lognormal as they all have been tested in different regions as mentioned in this review.

2.7.2 Wind and Solar Assessment Using nonparametric probability distribution functions

Theory and practice demonstrate that the assumed theoretical distribution function and the actual performance or characteristics of wind or solar irradiation differ significantly. This means that a supposed PDF does not always lead to the greatest possible conclusion. The approach of choosing an appropriate pdf from one region to the other is to blame for this unpredictability. Due to the unpredictable nature of wind speed and solar radiation, there are no theoretical standards for choosing probability distribution functions. Additionally, projected parameters for a particular assumed distribution may not fit historical data on wind speed and solar irradiance well, failing to satisfy the statistical evaluation for parameter approximation.

To estimate wind speeds and solar radiation probability distributions in South Africa, this work promotes the use of the kernel density estimator approach, which does not require prior knowledge of parameters. With this method, there is no need to estimate any fundamental distributional parameters and no need to make any assumptions about theoretical distributions for wind speed or solar radiation. The uncertainties associated with probability distribution functions that necessitate previous parameter knowledge are thereby avoided by the proposed paradigm. This nonparametric approach is appropriate for usage with renewable energy systems because it is widely utilized in domains such as surveillance systems, econometrics, computer vision, and many others [29], [30], [31], [32].

2.8 Review of Hybrid Power System Optimization

In this section, hybrid optimal modelling and sizing of various systems will be discussed. A hybrid energy system has been designed for a typical rural area using the studied solar and wind data from these seven different regions. The hybrid system consists of different renewable energy sources with a backup system as well as a battery storage system used to respond to given load energy requirements. As a result of renewable energy source output fluctuations due to change in conditions relating to weather or time, the hybrid system is to respond to the load demand at any time by optimally controlling each energy source including storage, together with a backup system. Thus, the design must not only meet the sizing requirements but also the operational requirements as well. Therefore, this section aims to report a detailed review presenting a hybrid renewable energy systems' optimal modelling and sizing.

2.8.1 Review of various approaches for optimal modelling and sizing for hybrid systems

Planning and developing a hybrid power system for any application be it for an individual home or farming, an educational institute, or even an industry, the designing or planning engineer needs some basic information firstly about the availability of resources for the area, knowledge on technology, economics, sizing, and government national regulations concerning such systems. A hybrid energy system is one that typically combines two or more renewable energy sources with conventional resources to serve a load with a more dependable and system-efficient energy source.

As a result of the erratic nature of both solar and wind that leads to power outages or unreliable power supplied to the load, a diesel generator is used to guarantee continuous power generation even when there is a lack of solar or wind speeds. Additionally, a storage device is integrated into this hybrid power system to match the load demands for reliable power generation.

In [33], for guaranteeing a constant power supply that satisfies the load demands of a residence located in a distant place in the Jordanian city of Al-Tafilah, Al-Rashed built and evaluated an off-grid PV-wind diesel-battery hybrid energy system. A techno-economic analysis of several hybrid system configurations was presented in the article, and the viability of utilizing renewable energy sources was assessed. To assess and identify various potential system configurations for meeting the load demand of 37.5 kWh/day with a 6.98 kW peak load, the research used the HOMER optimization model. For a household with a variety of appliances, including lights, a television, a computer, a refrigerator, a kettle, a microwave, a washing machine, an air conditioner, and a water heater, the load demand is 37.5 kWh per day with a peak of 6.98 kW. The total energy consumption for this household was determined by knowing the power rating for each appliance and the number of operations used per day. Table 2.2 below shows the computation analysis for this residential load.

Table 2.2 Residential Load Demand

Appliance	Power (W)	No.	Avg hrs/day	Avg Wh/day
Light	11	25	7	1925
TV	90	1	8	720
Computer	60	1	5	300
Refrigerator	180	1	24	4320
Kettle	2000	1	0.3	600
Microwave	1500	1	0.4	600
Washing machine	500	1	1	500
A/C unit	1550	2	6	18600
Water Heater	2500	1	4	10000
			Total Wh/day	**37,565**

To estimate the ideal size and parameters of power-generating devices, the HOMER software program was employed. For each potential combination of employing solar PV, wind turbines, diesel generators, converters, and batteries, ten outcomes were discovered to be the optimum optimization solutions. Ten best optimal solutions were obtained for this household in Jordan. Economic and feasibility considerations were used to arrive at these conclusions. The cost of electricity (COE) ($/kWh), total net present cost (NPC) ($), initial capital cost ($), and operating cost ($/yr) are all calculated using HOMER. The findings are organized starting with the lowest NPC, which is the present value of all costs incurred over the system's lifespan less the present value of all revenue generated over that time. In interpreting the results, it was found the best and most economical solution was established to be where the hybrid system did not have the wind turbines included in the system. The combination of a 12.1 kW PV system, a 7.7 kW diesel engine, a 36-kWh nominal capacity battery bank, and 4.82 kW converters was found to be the best option. This best-case scenario had a minimum Cost of Energy (COE) of 0.338 dollars per kWh and a minimum Net Present Cost (NPC) of 66,012 dollars. Along with these benefits, the system produced fewer gas emissions than some of the other methods.

Masoud Pirhaghshenasvali and Behzad Asaei developed an Optimal Modelling and Sizing of a Practical Hybrid Wind, PV, and Diesel Generation stand-alone application system for Iran as an alternative to the natural conventional fossil resources [34]. The main drive for using the above-mentioned alternatives was motivated by the gains that renewable sources offer not only for this region but in general terms which are clean and environmentally friendly energy. To provide electricity to a rural community in Kerman, Iran, the study suggested using PV-Wind-Diesel with battery storage systems. Data on wind speed and solar radiation were gathered for this study from the Iran Meteorological Organization. With the diesel generator serving as backup power to provide consistent, dependable, high-quality power, the study sought to utilize both wind and PV energy as the major energy sources for the system. The issue of a standalone hybrid system was solved using Particle Swarm Optimization (PSO) to reduce the overall cost of the wind turbines, PV systems, and batteries.

The results for this rural area of Iran showed an acceptable outcome. The study only considered one day for simulation with hourly load patterns being fixed. It can be observed that the cost of batteries per kW varies from one type of battery to the other. Moreover, the lifespan for these batteries was 4 years. In simulating this study four types of each wind turbines, solar PV, and batteries were selected.

In analysing their findings, the maximum wind turbine power that can be determined in this region, is dependent on the wind speed at various times of the day in addition to the rated power of the wind turbines. It should be noted that sometimes the electricity generated exceeds the load. As a result, throughout these periods, the battery banks are fully charged. The total output power for the different photovoltaic systems with the power that was produced and obtainable while using battery bank storages was also investigated. Accordingly, the study used the batteries' initial state of charge (SOC) at 50%. As for the output power for the diesel generator, and it can be noted that the diesel generator backs mostly in power delivery during rainfall seasons and winter seasons because of poor solar irradiance during those times. This, demonstrate the importance of such elements as this could have resulted in an unreliable system that would not deliver power constantly.

In their article, Masoud Pirhaghshenasvali and Behzad Asaei demonstrated how several costs, such as installation, maintenance, and fuel prices, can be reduced while still ensuring that consumers' access to the energy they need can be met. The findings demonstrated that the suggested optimization strategy was effective in locating the ideal design. Their model illustrated how several renewable sources may be employed simultaneously to power off-grid applications, such as the rural areas of Iran.

Many other papers dealing with similar optimization of the hybrid system were considered and used to obtain an in-depth comprehension of how to develop an optimal sizing for a typical rural area and use of HOMER [35], [36], [37], [38], [4], [39], [40], [41], [42], [43], [44], [45], [46].

2.9 Summary

This chapter has delivered a synopsis of the research developments in statistical distribution modelling for both solar radiation and wind energy. Moreover, an overview of the research developments involved in optimal sizing applied to hybrid renewable energy systems. Several papers from referenced journals in renewable statistical modelling and renewable hybrid system optimal sizing have been reviewed. The chapter commenced by providing a summary of the South African energy context, as the background to the problem formulation. One of the findings in this chapter is that there are a significant number of research articles dealing with statistical probability distribution functions for site wind and solar energy potential assessment using parametric probability techniques; however not much research has been done using a nonparametric method that is famously used in another field like surveillance systems, econometrics, computer vision, and many other fields. As a result, it is suggested to be used in the field of renewable as it best fits and is adaptable to most regions, unlike the parametric method.

Chapter 3: Mathematical Modelling of the System

3.1 Introduction

Before beginning any solar energy initiatives, it is crucial to accurately estimate the daily sun irradiation. A study was conducted because an accurate approximation of the probability distribution of wind speed is crucial in renewable energy applications. Thus, in this chapter, the different types of mathematical models of probability distribution functions used to estimate renewable energy resources are discussed.

The study provides a nonparametric density estimation method for the probability distributions of solar irradiance and wind speed. It starts by outlining the experimental setup and the data collection areas. This chapter also covers the probability density functions used to simulate the probability distribution of wind speed and solar radiation. Also presented here is a comparison of the estimated distribution and the statistical criteria used to assess the effectiveness of the used probability distribution functions.

The mean bias error (MBE) and root mean square error (RMSE) are performance test criteria for pdfs that are used to assess the effectiveness and accuracy of the appropriate modeling distributions. The findings from various probability density functions will be examined in this chapter, and the best model will be chosen to represent a typical rural area in the following chapter.

3.2 Area Under Study and Data Used

The research is in South Africa, which has a population of about 59.8 million people and is located on the African continent at latitude (-28° 28' 44.35" S) and longitude (24° 40' 22.77" E) (June 2020). This subtropical region is made up of nine provinces and is located at the southernmost point of the African continent. As was described in the literature study, the country as a whole experience a variety of climatic conditions, from the western Mediterranean climate to inner dry cold semi-desert conditions to subtropical humid weather on the east coast. The majority of the nine provinces are represented by the seven sites that have been chosen around the nation to serve as testing grounds.

In this study, data on solar radiation and wind speed were collected from seven different geographical sites that represent South Africa utilizing ground monitoring equipment. These seven locations, which are open to the public without charge, are now being used to research solar irradiance and wind speeds. The Southern African Universities Radiometric Network (SAURAN) oversees the data collection campaign. The information included wind speeds (m/s) and global horizontal irradiance in kWh/m^2/day. The data on solar radiation and wind speed given in this study cover three years (2014-2016).

Four of these SAURAN data sites are located on college campuses: the University of Stellenbosch (SU) data site at (33.9281S, 18.8654E) represents the Western Cape Winelands area; the University of Free State (UF) at (29.1107S, 26.1850E) represents the Free State; the University of Pretoria (UP) in the Gauteng Province at (25.7531S, 28.2286E) represents Gauteng and surrounding Mpumalanga The other three stations are situated on rural farms close to the towns of Graaff-Reinet (GR) (32.4854S, 245858E), Alexander Bay (AL) (28.5608S, 16.7615E), and SAURN Vryheid (VR) (27.8282S, 30.5000E), which represent the northern portions of Kwazulu Natal and the surrounding Mpumalanga regions, respectively.

3.2.1 Stellenbosch University Station

The SAURAN, the Stellenbosch University station is located at Stellenbosch University, which is in the town of Stellenbosch, South Africa, at (33.9281S, 18.8654E). On the top of an engineering building with good sun exposure, the instruments are positioned. The mountains in the area partially block the skylines. On May 24, 2010, this station was put into service. The numerous instruments used to measure the various meteorological data are displayed in Table 3.1.

Table 3.1 University of Stellenbosch Station Details

Instrument Name	Quantity Measurement	Unit of Measurement
Kipp & Zonen unshaded	Global horizontal irradiance	W/m^2
Kipp & Zonen on a SOLYS tracker	Direct normal irradiance	W/m^2
Kipp & Zonen CMP11 under a shading ball on a SOLYS tracker	Diffuse horizontal irradiance	W/m^2
Kipp & Zonen CMP11 under a shadow-band	Diffuse horizontal irradiance	W/m^2
Kipp & Zonen UVS-AB-T	UVA	W/m^2
Kipp & Zonen UVS-AB-T	UVB	W/m^2
Campbell Scientific CS215 sensor	Air temperature	°C
Vaisala PTB110 sensor	Barometric pressure	mbar
Campbell Scientific CS215 sensor	Relative humidity	%
R.M.Young 03001 sensor	Wind speed	m/s
R.M.Young 03001 sensor	Wind direction	°
R.M.Young 03001 sensor	Standard deviation of the wind direction	°

3.2.2 University of Free State Station

The SAURAN University of Free-state (UF) station is located at one of the south African Tertiary institutions named the University of the Free State, in Bloemfontein, Free State Province, South Africa. This location is cleverly positioned as it is easily accessible to researchers and the public. The instruments used in this location are positioned on the rooftop of a university building with an elevation of 1 491 meters(m) with excellent solar exposure. As a result of this great exposure, the horizon view is not obstructed by either buildings or the environment. According to SAURAN information, it reveals the station as being moved to CUT on 28 August 2017 after it was initially installed on 12 October 2013 at UF. Kipp and Zone instruments and other instruments used are shown in table 3.2. Different sensitivity factor selected for these instruments is also shown in this table.

Table 3.2 University of Free State Station Details

Instrument	Quantity Measurement	Unit of measurement	Sensitivity Factor
Kipp & Zonen unshaded	Global horizontal irradiance	W/m^2	8.67 $\mu V/W/m^2$
Kipp & Zonen on a SOLYS tracker	Direct normal irradiance	W/m^2	7.38 $\mu V/W/m^2$
Kipp & Zonen under a shading ball on a SOLYS tracker	Diffuse horizontal irradiance	W/m^2	8.13 $\mu V/W/m^2$
Campbell Scientific CS215 sensor	Air temperature	°C	
Vaisala PTB110 (CS106) sensor	Barometric pressure	mbar	0.240
Campbell Scientific CS215 sensor	Relative humidity	%	
Texas TR525i sensor	Total rainfall	mm	0.254
R.M.Young 05103-5 sensor	Wind speed	m/s	0.098
R.M.Young 05103-5 sensor	Wind direction	°	355
R.M.Young 05103-5 sensor	Standard deviation of the wind direction	°	

3.2.3 University of Pretoria Station

This University of Pretoria (UP) is situated in the Gauteng province, with Pretoria being the capital city for country South Africa. For this station like all other stations located in universities, the equipment is strategically placed on the top of a university building, which provides excellent sun exposure. It is worthwhile to mention that the instruments are installed at 1 410 m above ground level. This gives a largely unobstructed view of the horizons. The first installation date of instruments on this station was installed on the 7th of September 2013. For this station as well, they used the Kipp and Zone instrument for solar radiation measurements with R.M. Young sensors used for wind speed and direction. Detailed information about the type of instruments and type of measurements is provided in table 3.1. Table 3.3 illustrates the different measurements for solar taken using this ground equipment as compared to satellite-based measurements.

Table 3.3 Average Monthly Solar Radiation for UP

Month	Solar Irradiance ($KWh/m^2/d$) Average			
	2014	**2015**	**2016**	**NASA SSE(2016)**
January	6.60	6.62	6.58	6.79
February	5.95	7.00	6.77	6.34
March	4.27	5.80	5.51	5.75
April	4.85	4.63	5.17	5.03
May	4.50	4.68	4.08	4.58
June	4.21	3.50	3.84	4.15
July	4.41	4.13	4.20	4.51
August	5.00	5.01	4.78	5.13
September	6.22	5.44	5.70	6.05
October	6.89	6.64	6.80	6.23
November	5.70	7.42	6.47	6.47
December	6.36	7.14	6.54	6.78
Average	**5.42**	**5.67**	**5.54**	**5.65**

3.2.4 University of KwaZulu Natal Data Station

The last of the stations used that is in the university premises is found in the University of KwaZulu Natal (UZ) situated in the province of KwaZulu Natal in the city of Durban, South Africa. This station in the study will cover and represent the areas in this province going to the south representing rural areas like Bizana which geographically belong to the Eastern Cape but is closer to Durban. The instruments used in this location is like the one used in SU and UF as shown in 3.1 and table 3.2, respectively.

3.2.5 Graaff-Reinet Station

One of the stations that are not situated in the university premises is in the Eastern Cape Province at around about 26 km south of a small town in the karoo called Graaff-Reinet (GR), South Africa. The instruments are stationed within a fenced enclosure as shown in figure 3.1 on a rural farm in this semidesert location with the skyline visible and unobstructed. The annual data obtained from this station compared with the satellite-measured data are shown in table 3.4. The different types of instruments used for both wind and solar irradiance measurements are in table 3.1 and table 3.2.

Figure 3.1 Graaf-Reinet Station

Table 3.4 Average Monthly Wind Speeds for GR

Month	Wind Speed (m/s)			
	2014	2015	2016	NASA
Jan	4.67	4.75	4.95	5.00
Feb	4.99	5.10	4.80	4.80
Mar	4.27	4.27	4.13	4.60
Apr	4.37	4.68	4.07	4.40
May	3.85	2.73	3.44	4.40
Jun	3.16	5.65	3.84	4.70
Jul	3.23	3.70	3.85	4.60
Aug	3.80	3.13	3.64	4.70
Sept	4.25	5.22	4.26	4.60
Oct	5.37	4.56	4.43	5.00
Nov	5.24	5.66	5.46	4.80
Dec	5.12	4.70	4.93	4.70
Ave	**4.36**	**4.51**	**4.32**	**4.32**

3.2.6 Alexander Bay Station

In the Northern Cape province, there is a SAURAN data station called Richtersveld located 30 km east of a small town named Alexander Bay (AL). The station was installed in 2014 in this desert region which is ideal for solar and wind exploration due to its climatic favorability. The instruments are installed 140 m above ground level in an enclosed fenced station with clear visibility of the skyline as shown in figure 3.2.

Figure 3.2 Alexander Bay Data Station

3.2.7 Vryheid Station

The seventh and the last SAURAN data station utilized in the study is in the northern parts of KwaZulu Natal, in Vryheid (VR), KwaZulu Natal Province, South Africa. Table 3.6 shows the average wind speeds for all seven stations.

The measured solar data comparison for all seven used stations is shown in table 3.5.

Table 3.5 Average Solar Irradiance for All Stations

Month	Solar Irradiance (KWh/m^2/day) Average						
	SU	AL	UF	UZ	UP	GR	VR
Jan	4.78	8.02	7.06	6.10	6.58	8.02	6.91
Feb	5.17	8.55	7.45	6.81	6.77	7.91	6.55
Mar	5.27	6.73	6.10	5.47	5.51	6.29	5.21
Apr	5.17	4.91	4.72	4.13	5.17	4.71	4.81
May	3.48	3.77	3.85	4.13	4.08	3.78	4.38
Jun	2.64	2.98	3.55	3.12	3.84	2.82	3.91
Jul	2.52	3.33	3.89	2.62	4.20	3.22	3.51
Aug	2.96	4.41	5.03	4.62	5.35	4.27	4.68
Sept	4.86	5.91	5.58	4.48	5.70	5.21	4.55
Oct	5.22	7.43	7.17	4.51	6.80	6.85	5.73
Nov	5.19	8.47	7.77	4.59	6.47	8.09	5.75
Dec	5.52	9.39	8.05	6.57	6.54	8.98	6.31
Ave	**4.40**	**6.16**	**5.85**	**4.76**	**5.59**	**5.85**	**5.19**

Table 3.6 Average Monthly Wind Speeds for All Sites

Month	Wind Speed (m/s)						
	SU	AL	UF	UZ	UP	GR	VR
Jan	3.30	3.74	2.75	1.48	2.41	4.95	3.88
Feb	2.50	4.12	2.92	1.87	2.36	4.80	4.15
Mar	2.55	3.87	2.73	2.09	1.81	4.13	3.91
Apr	1.69	4.08	2.29	2.06	1.71	4.07	3.68
May	1.70	2.89	2.13	1.75	1.69	3.44	4.19
Jun	1.79	3.37	1.99	1.91	1.46	3.84	4.90
Jul	1.76	3.46	2.32	2.06	1.69	3.85	4.68
Aug	1.57	3.38	2.36	1.89	1.93	3.64	4.64
Sept	2.03	3.67	2.92	2.33	2.80	4.26	5.13
Oct	2.08	3.70	3.00	2.47	2.63	4.43	5.91
Nov	2.88	3.86	3.31	2.43	2.69	5.46	5.81
Dec	2.40	4.24	3.44	2.66	2.66	4.93	5.22
Ave	**2.19**	**3.7**	**2.68**	**2.08**	**2.15**	**4.32**	**4.68**

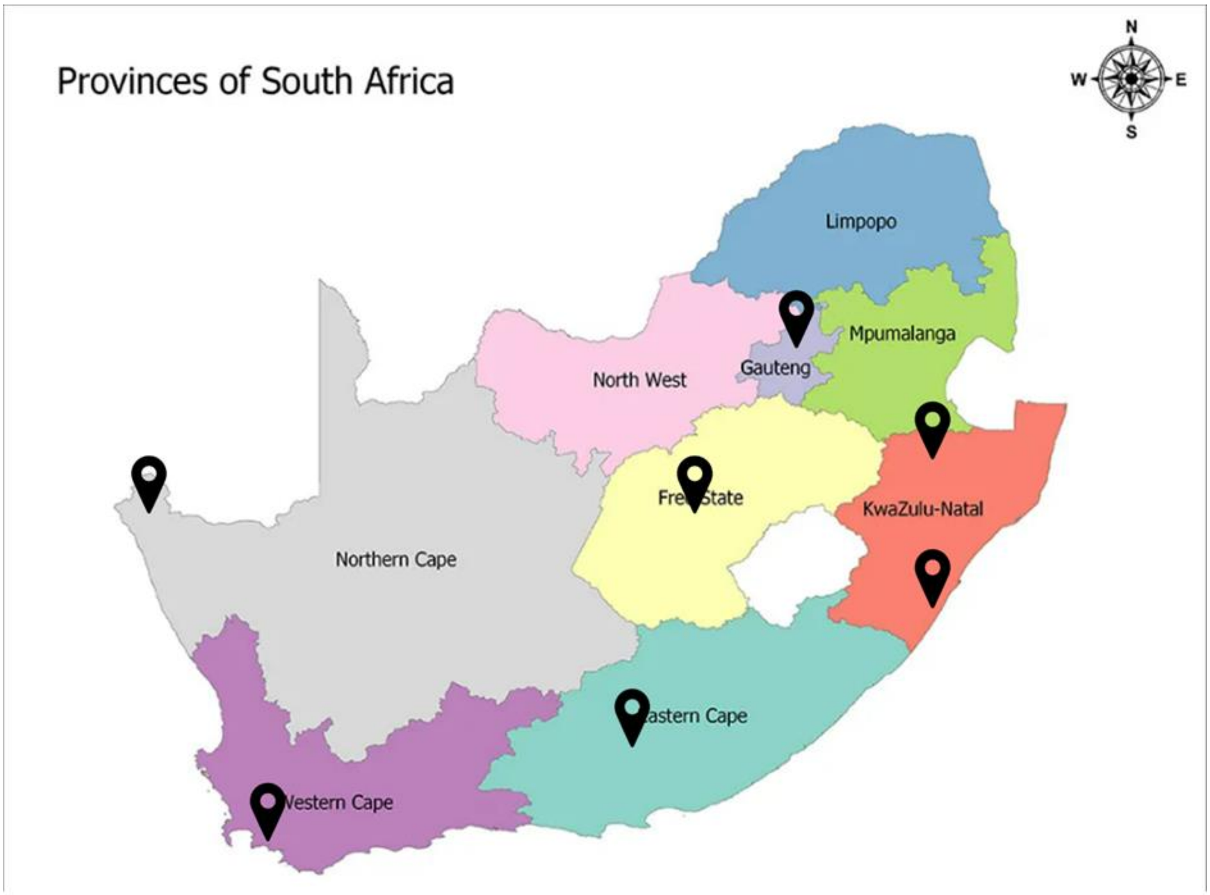

Figure 3.3 Overview of All Stations

Figure 3.3 shows the overview of all stations used across the country in all the different provinces.

3.3 Materials and Methods

As mentioned previously, meteorological information for both the wind and the sun is needed to simulate this renewable energy generating system. The most crucial phase for these renewable energy projects' economic viability is to assess the qualities and capacities of wind and solar energy. The solar irradiance and wind speed pdfs represent the long-term accumulation of wind and solar irradiance, respectively. Therefore, their data is crucial for assessing a location's capacity for producing solar and wind energy.

According to a thorough review of the literature, numerous parametric probability distribution functions have been tried to forecast solar irradiance and wind speeds, which are used to assess the dependability of these renewable energy sources. According to studies in the literature, the preferred function for wind estimation is the Weibull distribution function with two parameters [47].

Theory and practice demonstrate that there is a significant discrepancy between the assumed theoretical distribution function and the actual performance or properties of wind or solar irradiation. This means that a presumptive PDF does not always produce the greatest possible solution. The process of choosing an acceptable pdf from one location to the next is to blame for this ambiguity. Due to the unpredictable nature of wind speed and solar radiation, there is no theoretical standard for choosing probability distribution functions, and projected parameters for a particular assumed distribution may not suit historical data on wind speed and solar irradiance sufficiently.

To estimate wind speeds and solar radiation probability distributions in South Africa, this study supports the use of the kernel density estimator idea, which does not require prior knowledge of parameters. With this method, there is no need to estimate any fundamental distributional parameters and no need to make any assumptions about theoretical distributions for wind speed or solar radiation. The uncertainties associated with probability distribution functions that necessitate previous parameter knowledge are thereby avoided by the proposed paradigm. This nonparametric approach is appropriate for usage with renewable energy systems because it is widely utilized in domains such as surveillance systems, econometrics, computer vision, and many others [30], [31], [32].

3.3.1 Parametric Distribution Models

Three statistical distribution functions were tested for each of the seven stations in the application of parametric distribution functions, assessed, and their results were presented. Gamma, Weibull, and Lognormal are the three parametric distribution functions that are being used. These distribution functions were all defined by three parameters: location, shape, and scale. Theoretical literature employing the widely used preferred pdfs for renewable estimations served as the basis for the random selection of the three parametric distribution functions examined.

3.3.1.1 Gamma Distribution Function

The three-parameter distribution function is utilized in this modeling because the results from the three parameters are more accurate. The literature demonstrates that the Gamma distribution function with two parameters is commonly employed in the field of renewable energy for fitting global solar radiation. Equation (1) provides this function,

$$f_{Gamma}(x) = \left[\frac{1}{\alpha\Gamma(\beta)}\right]\left[\frac{(x-\gamma)}{\alpha}\right]^{\beta-1} exp\left[-\frac{(x-\gamma)}{\alpha}\right] \qquad (1)$$

where, the γ represents the parameter for location, α represents the parameter for scale, and beta is a shape parameter. To estimate these parameters for the gamma distribution, the maximum likelihood was applied.

3.3.1.2 Weibull Distribution Function

Weibull distribution function with three parameters was also examined for its ability to accurately fit observed wind speeds and solar radiation around the globe. This three-parameter distribution function is shown in equation (2). As proved in the literature that this function is also used in renewable data evaluation and testing showing great results in most cases.

$$f_{WB}(x) = \left(\frac{m}{l}\right)\left(\frac{x-k}{l}\right)^{m-1} exp\left[-\left\{\frac{(x-k)}{l}\right\}^{m}\right] \qquad (2)$$

where, $f_{WB}(x)$ is the Weibull distribution, with location as k, l for scale and m the shape parameters respectively. Similarly, with the gamma distribution function, the three parameters were estimated using maximum likelihood.

3.3.1.3 Lognormal Distribution Function

Equation (3) represents the lognormal distribution probability density function with three parameters.

$$f_{LN}(x;\sigma,\rho,\tau) = \left[\frac{1}{\sqrt{2\pi}\tau(x-\sigma)}\right] exp\left(-\frac{\left\{ln\left[\frac{(x-\sigma)}{\rho}\right]\right\}^{2}}{2\tau^{2}}\right) \qquad (3)$$

where, $f_{LN}(x)$ is the lognormal distribution function, σ is a location parameter, ρ is a scale parameter, and τ is a shape parameter. Likewise, the maximum likelihood was used as well for all the parameters for this distribution function.

3.3.2 Non-parametric Kernel Density Model

In the case of the nonparametric distribution functions, the Kernel Density Estimation is used. To approximate an unknown probability density function for a set of data, a method known as kernel density estimation is used. This method does not require the use of parameters. Without the requirement to approximate the defining parameters in a theoretical distribution, it makes use of the sample of data that is provided. It offers a curve smoothing option by applying bandwidth adjustment in addition to this lack of dependence on characteristic parameters. Equations 4 and equation 5 explain this nonparametric density approach.

$$f(x) = \frac{1}{N}\sum_{i=1}^{N} K(x - x_i) \tag{4}$$

where (N) is the sample size and (K) is called the kernel function. This kernel function varies and typically requires the following properties.

- It should be non-negative: $K(x) \geq 0$for every value of (x) as the probability is always non-negative.
- It should be symmetric: $K(x) = K(-x)$ for every value of (x)
- It should be decreasing: $K'(x) \leq 0$ for every $x > 0$.

In controlling the bandwidth for this kernel function, $b$is introduced to the equation and thus.

$$f(x) = \frac{1}{Nb}\sum_{i=1}^{N} K\left(\frac{x - x_i}{b}\right) \tag{5}$$

It should be noted that the best bandwidth choice determines the function's accuracy and best estimation. Because the data is unpredictable, a narrow bandwidth will produce a jagged curve because some points will fall outside the fitted curve. On the other hand, a wide bandwidth could lead to an overly smooth curve.

3.4 Comparative Analysis of Estimated Distributions

3.4.1 Statistical Test

A performance analysis was carried out to assess the accuracy and effectiveness of the anticipated data for these three parameter probability distribution functions. Root means square error (RMSE) and mean bias error (MBE) are the two tests that were conducted. The two tests are expressed in the following ways, where *n* denotes the number of data points, x_{meas} denotes the measured data for either global solar radiation or wind speed, and $x_{mod\,el}$ denotes the modeled data for either of them as previously described.

$$RMSE = \sqrt{\left[\frac{1}{n}\sum_{i=l}^{n}(x_{mod\,el} - x_{meas})^2\right]} \quad (6)$$

The accuracy of each model relative to the true value will be revealed by the root mean square error. Whether the pdf was overestimated or underestimated will be shown in the results. These factors will make it easier to choose the ideal PDF for a particular area.

$$MBE = \sum_{i=l}^{n}\frac{x_{mod\,el} - x_{meas}}{n} \quad (7)$$

The average bias for each PDF is displayed using the mean bias error. These two statistical errors when combined will make interpretation easier. Table 3.7 lists the inputs for each distribution model for all the sites under consideration.

Table 3.7

Models	Site Name						
	AL	UZ	VR	GR	SU	UF	UP
Gamma							
γ	-10,94	-6,9194	-11,692	-7,2405E-26	-3,0110E-19	-6,8979	-1,7262
α	65,606	31,3	109,36	1,9414	3,2472	35,348	13,196
β	0,2599	0,36858	0,1608	2,8091	2,0156	0,3601	0,55266
Weibull							
k	-0,515	-0,34443	-0,5483	1,8000E-42	2,4106E-35	-0,95069	1,7728
l	3,61	2,6081	4,3716	0,26322	0,22587	3,653	4,7697
m	7,3916	5,5869	7,0643	54,209	1,3750E-5	7,5706	7,9932
Lognormal							
σ	-29,291	-14,234	-34,686	-2,3880E-24	-2,0600E-17	-20,098	-21,414
ρ	0,05898	0,10894	0,04102	3,0645	1,5387	0,08112	0,06465
τ	3,5656	2,9307	3,7023	1,7141	1,8396	3,2551	3,2922

Determination of the input parameters for a probability density function (PDF) involves specifying the characteristics of the distribution that you want to model. The specific parameters required will depend on the type of distribution used.

The Gamma Distribution (3P) parameters with Shape Parameter which controls the shape of the distribution. It affects how the distribution's probability density is distributed over different values. The Scale Parameter influences the spread or scale of the distribution. It determines how much the distribution is stretched or compressed along the x-axis while the third parameter, the Shift Parameter is used to shift it along the x-axis. It is not always present, as the distribution can be centered at zero without it.

The Weibull Distribution (3P), with Shape Parameter. This parameter determines the shape of the distribution. For values of k greater than 1, the distribution is skewed to the right. For values less than 1, it is skewed to the left. The other two parameters are Scale and Location parameters influencing the scale of distribution and shifting the distribution along the x-axis respectively.

The Log-Normal Distribution (3P): This distribution has three parameters as follows:

- Mean of the Logarithm: This parameter controls the location of the peak of the distribution after taking the logarithm of the values. It is the mean of the normally-distributed logarithmic data.
- Standard Deviation of the Logarithm: This parameter determines the spread or width of the distribution after the logarithm transformation. It is the standard deviation of the logarithmic data.
- Shift Parameter: Like in the Gamma distribution, a shift parameter can sometimes be added to move the log-normal distribution along the x-axis.

3.4.2 Kernel Density Estimator

A non-parametric kernel density estimator was employed to test the accuracy of the data used. Integral Squared Error, or ISE, was used in performance analysis to assess the accuracy and effectiveness of the forecasted data for these six KDE functions.

$$ISE = \int_{-\infty}^{\infty} [f(x) - f^*(x)]^2 \, dx \qquad (8)$$

The following six kernels were employed: the Epanechnikov kernel, the Triweight kernel, the Quatric kernel, the Triangular kernel, the Uniform kernel, and the Gaussian kernel. Results from these kernels will demonstrate the accuracy of the data utilized, and ISE will demonstrate the performance of the model under consideration, with values indicating either an overestimation or an underestimation of the values for global solar radiation and wind speed. The development of a design with behaviour like the actual data of the place as intended will be made possible by modelling renewable data.

3.5 Station Results and Discussions

The performance tests were conducted using the RMSE and MBE approaches, as indicated in Table 3.8, and an evaluation study between the raw measured data and the estimated model utilizing the three proposed models was conducted. To determine which model performed the best and the worst across all seven sites, an evaluation was conducted. A low RMSE indicates that the suggested model is presented well in the findings, and an MBE result tells us how well the model was estimated. The positive MBE assists in establishing the extent to which the model overestimates the amount of global solar radiation, whereas the negative MBE assists in determining the extent to which the model underestimates.

The University of Free State provides the lowest repeatable result for RMSE, which is 0.0405 for both the gamma and lognormal distributions. Given the low RMSE value, the technique used to estimate all distribution functions is likely to be effective. Figures 3.3 to 3.8 also show an image presentation of the three pdfs for six of the sites used. Figure 3.6 illustrates that for UP, the Weibull probability function gives the best description of the data. On this site, the sun radiation and the wind speeds are both presented more favourably.

By statistically analysing ISE for six kernels of each site, as shown in table 3.9, the outcomes of the suggested nonparametric technique are first shown. The first estimate, or initial estimate, is the first estimate derived from values from the observed pdf using a probabilistic technique, and the final estimate is the error estimate derived from the various kernels. The first thing that is noticed is that, compared to a regular traditional pdf, all kernels performed better across the board for all sites. Gaussian KDE outperformed the other individual kernels for three of the seven sites, UF, VR, and UZ, when they were compared against one another. In addition, the findings indicate that most sites can accept all six kernels. The modelling outcomes for the seven sites are displayed in Figures 3.9 to 3.14 according to how well they performed. The findings for all the sites were also limited to Gaussian KDE. From the modelling outcomes, it can be shown that using the kernel density estimation method improves adaptability, and with the option of bandwidth adjustment, it properly fits all site data.

Table 3.8 Statistical analysis for each pdf

Site Name	Gamma		Weibull		Lognormal	
	RMSE	***MBE***	***RMSE***	***MBE***	***RMSE***	***MBE***
VR	0.0598	-0.005	0.0598	-0.004	0.0603	-0.005
UZ	0.0743	-0.0076	0.0746	-0.0061	0.0735	-0.0076
AL	0.0610	-0.0134	0.1070	-0.0781	0.1075	-0.0613
SU	0.0600	-0.0136	0.1151	-0.0990	0.0957	-0.0384
UF	0.0405	-0.0024	0.0417	-0.0011	0.0405	-0.0023
UP	0.0479	-0.0031	0.0458	-0.0003	0.0432	-0.0011
GR	0.0532	-0.0062	0.0531	-0.0044	0.0537	-0.0058

Table 3.9 Statistical Error Results for Solar Irradiance

SITE	ISE	Kernel					
		Gaussian	Uniform	Triangular	Quatric	Triweight	Epanechnikov
AL	Initial	0.00361299	0.00361299	0.00361299	0.00361299	0.00361299	0.003613676
	Final	0.000410871	0.000439622	0.000413461	0.000433584	0.000351298	0.000487451
UZ	Initial	0.001290591	0.001290591	0.001290591	0.001290591	0.001290591	0.001290591
	Final	0.000208879	0.000177459	0.000378044	0.000424804	0.000507099	0.000301052
VR	Initial	0.001083273	0.001117895	0.001121174	0.001129164	0.001121174	0.001121174
	Final	-0.00068744	-0.00154401	-0.00219905	-0.00213786	-0.00213827	-0.002235941
GR	Initial	0.001381076	0.001608114	0.001608114	0.001608114	0.001608114	0.001608114
	Final	0.00026581	-3.15087E-05	-0.00019357	-0.00018237	-0.00016849	-0.000170563
SU	Initial	0.005424434	0.005424434	0.005424434	0.005424434	0.005424434	0.005424434
	Final	0.001950812	0.001198444	0.000978001	0.000959787	0.000906345	0.0010322
UF	Initial	0.00129295	0.00129295	0.00129295	0.00129295	0.00129295	0.00129295
	Final	-0.000110961	-0.000147578	-0.00057969	-0.00065302	-0.00093005	-0.000390814
UP	Initial	0.001047326	0.001047326	0.001047326	0.001047326	0.001047326	0.001047326
	Final	-0.000864355	-0.001052116	-0.00067703	-0.00061818	-0.00043509	-0.00085152

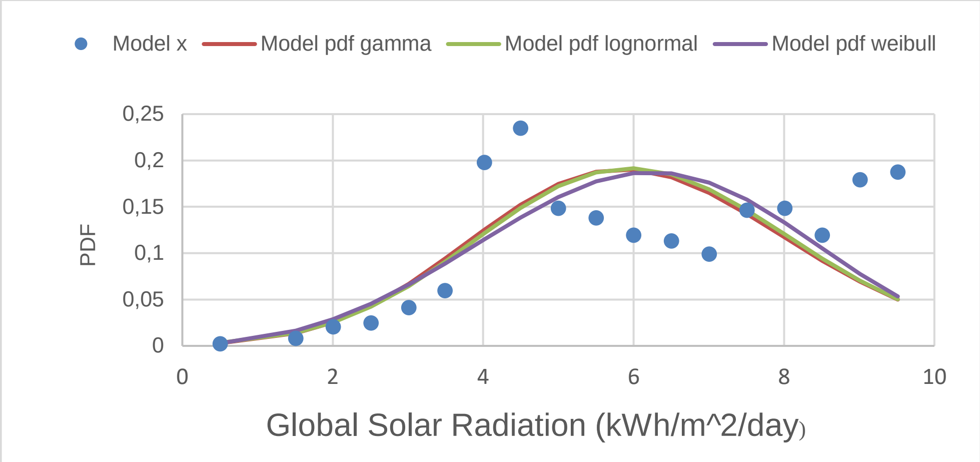

Figure 3.4 Fitting of pdfs for AL

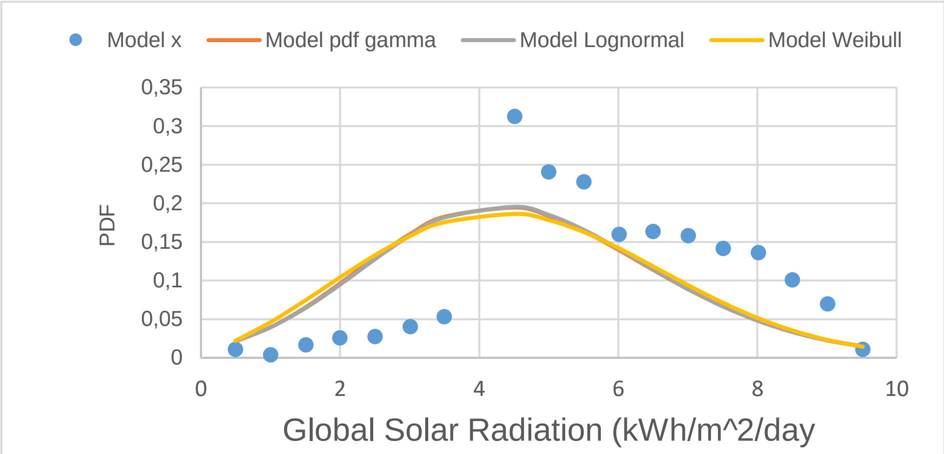

Figure 3.5 Fitting of pdfs for UZ

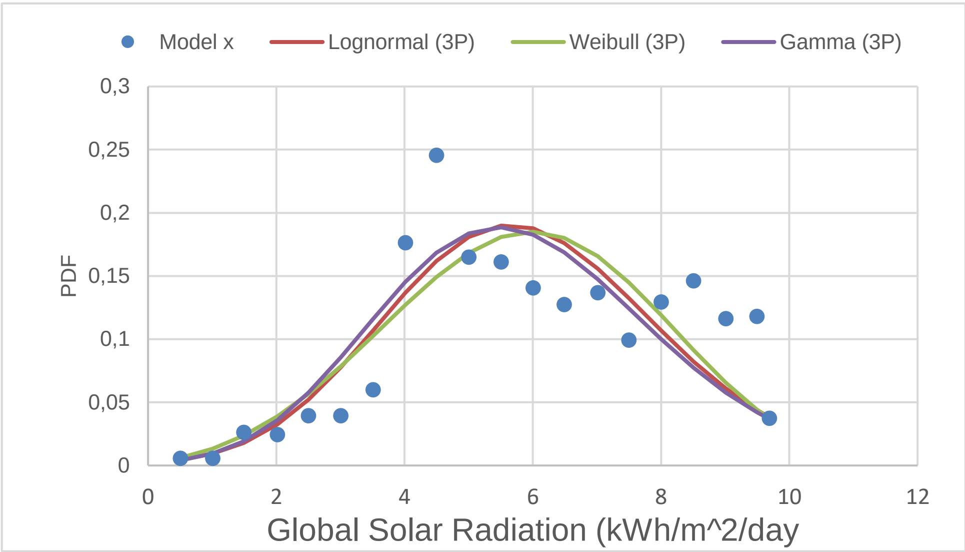

Figure 3.6 Fitting of pdfs for UF

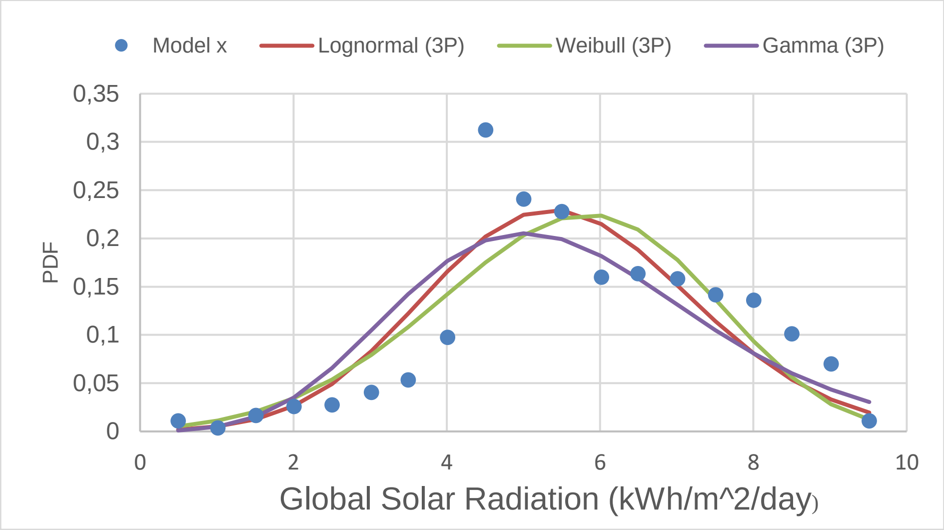

Figure 3.7 Fitting of pdfs for UP

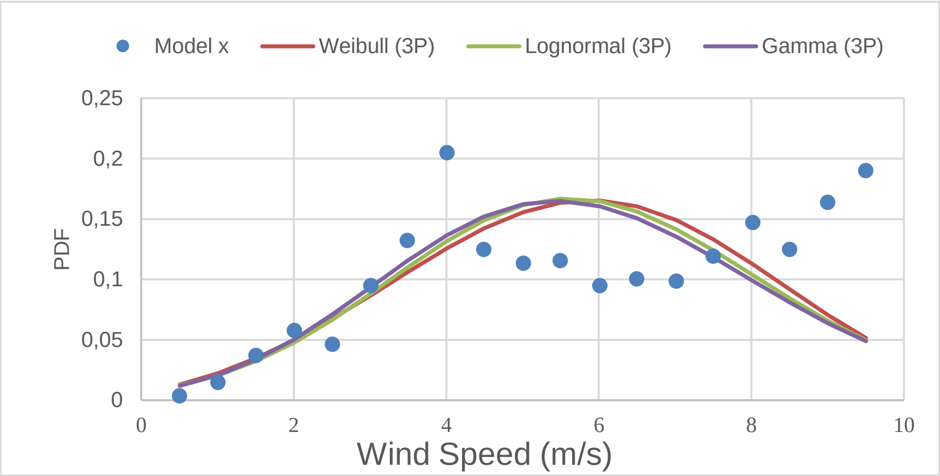

Figure 3.8 Fitting of pdfs for GR

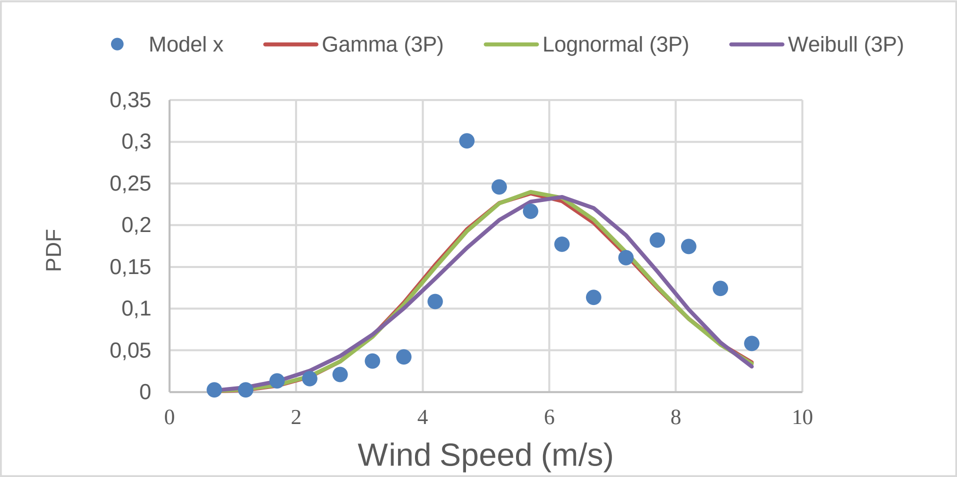

Figure 3.9 Fitting of pdfs for VR

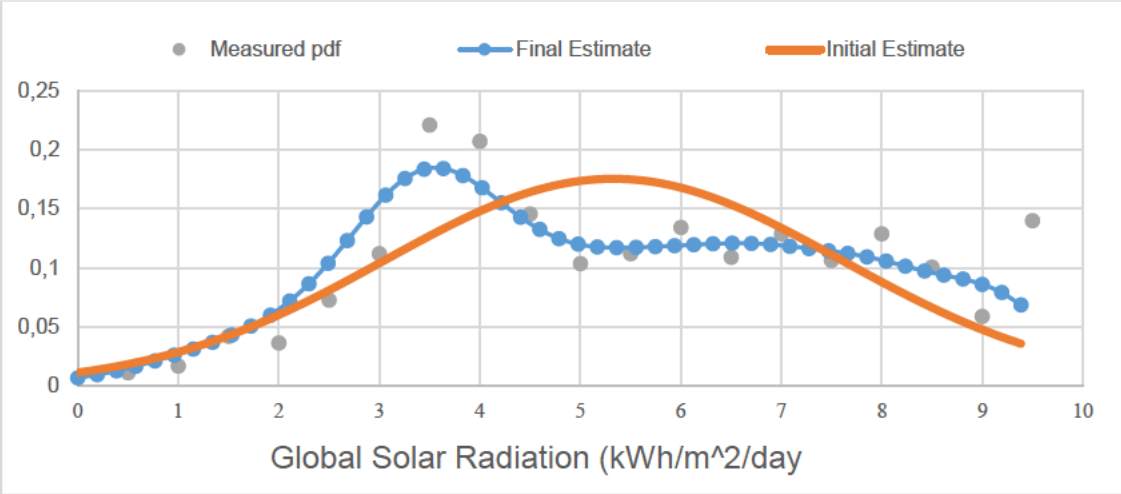

Figure 3.10 Gaussian KDE for AL

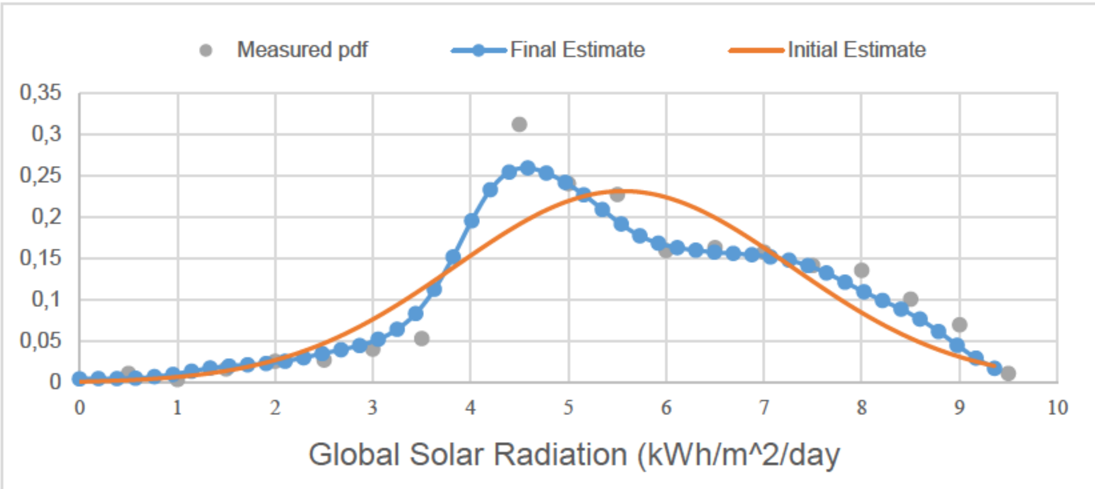

Figure 3.11 Gaussian KDE for UZ

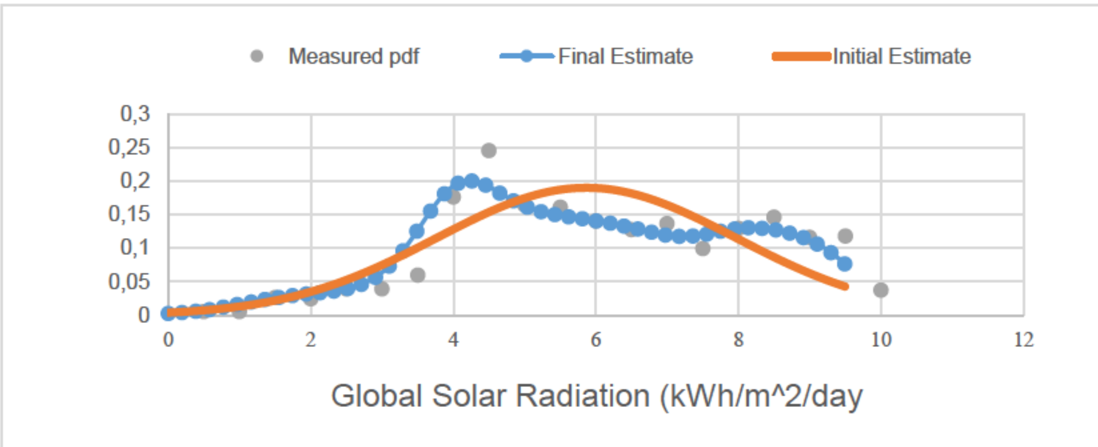

Figure 3.12 Gaussian KDE for UF

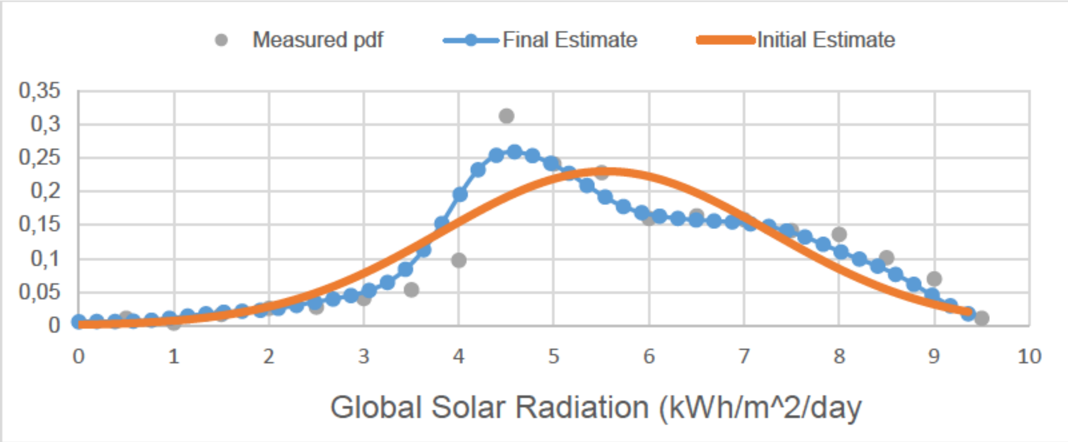

Figure 3.13 Gaussian KDE for UP

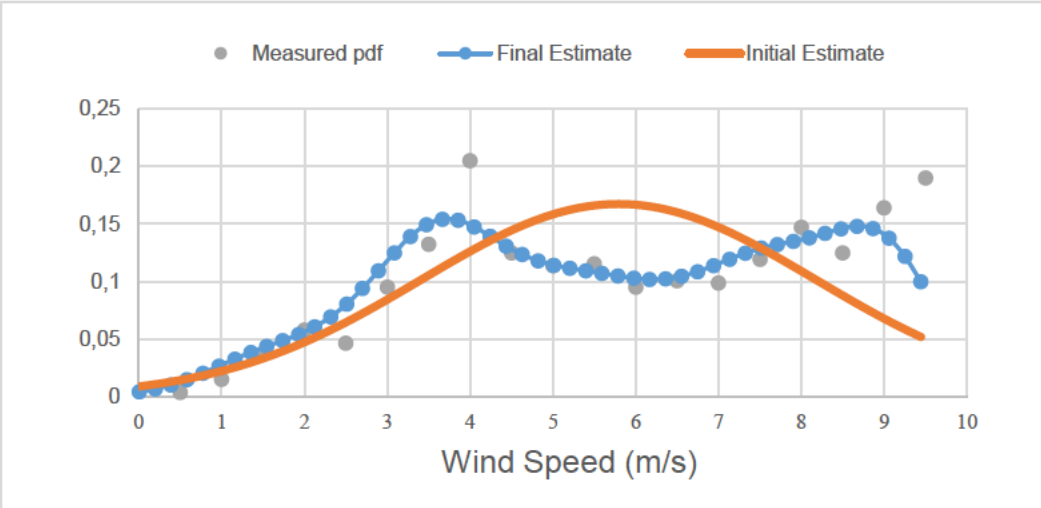

Figure 3.14 Gaussian KDE for GR

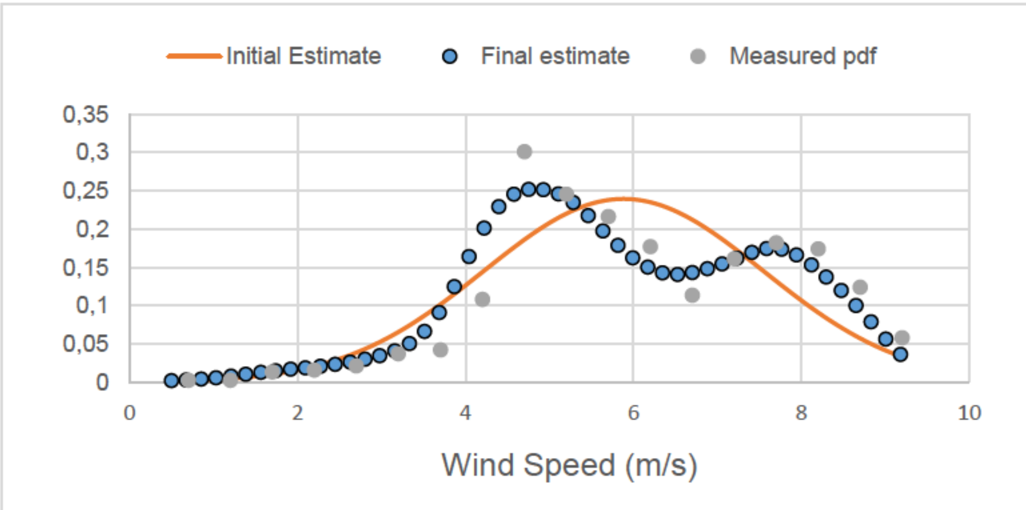

Figure 3.15 Gaussian KDE for VR

3.6 Summary

In this chapter, global horizontal solar irradiance and wind speed measured at seven sites in South Africa from 2014 to 2016 were modelled parametrically and non-parametrically using three distribution functions: Gamma, Weibull, and Lognormal. For non-parametric modelling, a kernel density estimator was used. The seven places were named, along with information about their surroundings, including the climate and weather. Actual measured data from highly dependable on-site ground equipment were utilized to determine whether the three parametric distributions and proposed nonparametric kernel estimate approach were appropriate for modelling these seven sites. Three statistical tests, including mean bias error and root, mean square error, were used in an evaluation study to determine whether parametric distributions were adequate. To compare the effectiveness of the new nonparametric technique with the traditional parametric normal distribution, an integral squared error, or ISE, was used.

The ability to obtain the site's solar and wind properties beforehand is crucial when using a parametric distribution approach. Furthermore, not all sites can be used with the parametric distribution functions, therefore finding the appropriate function for any site requires a system of trial and error. These parametric distribution functions lack the capability of smoothing the curve represented by the available data. As shown, all the problems can be resolved by applying the suggested nonparametric kernel density approach. The findings of this research are crucial for South Africa's future usage of solar and wind energy.

With the results of this chapter, a standalone hybrid energy system is designed in chapter 5 for a typical rural household found in most of these villages. Chapter 4 to follow will discuss the systems components modelling for the standalone hybrid system.

Chapter 4: Optimal Modelling for A Typical South African Rural Household

4.1 Introduction

This chapter will discuss hybrid optimal modelling and sizing of various systems used in a typical rural household. A hybrid energy system has been designed for a typical rural area using the studied solar and wind data from these seven different regions. A battery storage system and a backup system are both included in the hybrid system, which is made up of various renewable energy sources. The battery storage system is utilized to respond to the energy demands of a particular load. The components for this hybrid system are DG, WT, PV, and battery storage system, and will be studied their interactions with each other. The primary objective is to demonstrate the viability of the approach and to provide insight into the intricate interactions between the loads, energy sources, and components for energy conversion and storage in a hybrid system.

4.2 Selection of HOMER Pro Software

Due to the diverse generation systems, which call for software tools for the designing, analysis, optimization, and economic viability of the systems, an examination of a hybrid system design is a challenging process [48]. This hybrid renewable energy system is complicated; hence HOMER software is used for modelling and optimization. A simulation program called the Hybrid Optimisation Model for Electric Renewables (HOMER) is used to choose the system design to meet the given demand using various technological options and resource availability. The simulation results are established, and the optimal configuration is chosen. Based on estimates of the costs for installation, replacement, operation and maintenance, fuel, and other restrictions, HOMER simulates the hybrid system under consideration [48].

4.2.1 HOMER: Simulation

To simulate the design of the system configuration under consideration, Homer uses the designer's chosen components. Over the course of a year's worth of hours, it calculates the cost and assesses the viability of a system design. To calculate the technical viability and life-cycle cost, HOMER models the performance of the contemplated micropower system configuration for each hour of the year. The system under consideration for this thesis consists of a battery bank for backup, along with PV, WT, DG, and a converter. The simulation is carried out to identify the optimum optimal system configuration that would effectively meet the energy demand. Using an estimate of installation cost, replacement cost, operation, and maintenance cost, and fuel, HOMER mimic the proposed system.

4.2.2 HOMER: Optimization

To find the system configuration that best satisfies the technical requirements at the lowest life-cycle cost, HOMER simulates a variety of potential system configurations. By doing this, it establishes the variables' ideal values, such as the combination of system components and their sizes and numbers. It replicates each system configuration, and the results are listed by Total Net Present Cost (TNPC). The ideal system configuration is suggested after analysing these various system configurations, with the least preferred choice being the one with the largest TNPC. The user's or designer's choice of sensitivity will affect how this TNPC-based system is configured.

4.2.3 HOMER: Sensitivity Analysis

Each sensitivity variable used in the system is subjected to optimization by HOMER. For this hybrid renewable energy system, the sensitivity variable will go through numerous iterations to achieve the best result for each choice. Global solar radiation, the speed of the average wind, and the price of diesel fuel make up this system's sensitivity variables. The best option will be a hybrid renewable energy system with the lowest TNPC, and multiple system configurations for this hybrid renewable energy will be offered. Each of these configurations will use a different set of input assumptions.

4.3 Hybrid System Components

Increased usage of renewable energy is essential for addressing the difficulties associated with energy shortages, which have gotten much worse over the past ten years and must also be addressed to minimize greenhouse gas emissions. The adoption of these renewable energy technologies, such as solar and wind power, has increased quickly around the globe. To determine the most appropriate renewable energy sources and uses, location-specific research must be carried out because it is difficult to define the sustainability of the usage of these renewable energy technologies across the globe because it is highly reliant on local conditions.

As a reliable method of coping with the intermittent nature of solar and wind resources, the usage of hybrid energy systems is growing in popularity. Particularly for remote community applications where expanding the grid supply is expensive, such as in rural locations like the subject of this thesis, these hybrid energy systems can be employed to optimize the power supply [48].

In this part, the many elements that make up a hybrid system's architecture are discussed, along with how they interact and can be managed. The primary goal is to explain how the loads, energy sources, and components for storing and converting energy interact with each other in a hybrid system.

4.3.1 Diesel Generator

Diesel engines power generators, which are powered by diesel generators. They come in a variety of capacities ranging from tiny kW to over MW and are the most popular method of supplying AC power to isolated locations that are not linked to the grid. Equation 9 describes how much energy a DG produces at its rated power output [49].

$$\boldsymbol{E_{Gen}} = \boldsymbol{P_{Gen}} \times \eta_{\boldsymbol{Gen}} \times \boldsymbol{t} \qquad (9)$$

Where: E_{Gen} is the energy generated by the diesel generator (DG), $\mathrm{P_{Gen}}$ is the rated output power for the generator, $\eta_{Gen}$the efficiency of the DG, and *t,* is the time (s).

In contrast to the renewable sources used in this design, these DGs have low upfront capital expenditures and produce electricity as needed. However, they have some drawbacks, including high expenses for operation and maintenance, transportation and storage, noise pollution, and environmental pollutant discharge [50].

The DGs are not connected in series since the AC DG output voltage often equals the AC bus voltage. If one wants to have larger system current requirements, they can be connected in parallel.

It is important to exercise caution when using DGs because doing so will reduce fuel efficiency. When the demand for the load is low and the fuel efficiency is good, it is typical to employ a dump load to disperse energy. Additionally, DGs should not be turned off for an extended period because frequent restarts will cause wear and tear.

When a hybrid system's renewable energy sources and backup batteries are unable to supply enough energy, DGs are integrated as a backup and utilized. The cost savings from three areas, namely fuel, fuel replenishing, and maintenance, can be realized because of the incorporation of DGs into a hybrid system arrangement.

4.3.2 Wind energy technology

The kinetic energy of moving air is converted by wind energy systems first into mechanical energy and subsequently into electrical energy. The main component of a wind turbine, which uses revolving blades to harness the wind's kinetic energy to generate electricity, is the device. The wind's kinetic energy, which is utilized to turn the turbine's blades when it blows, is transformed into rotary motion by a rotor, which then powers a generator. According to the various manufacturers, wind turbines come in a variety of forms, sizes, and price ranges [51]. Because the wind resource fluctuates frequently, a WT's output power is variable. As a result, in standalone hybrid systems, it may be challenging to keep the output frequency of the wind system constant. Due to this problem, the WT output current is usually rectified to DC, stored in batteries, and then changed back to AC.

The electrical power generated by WT is defined by the equation (10):

$$P_{wt} = \frac{1}{2} \times \rho \times A \times v^3 \times C_p \qquad (10)$$

Where;

P_{wt} is the electrical power generated (in watts or kilowatts).

ρ is the air density (in kg/m^3).

A is the swept area of the wind turbine blades (in square meters).

v is the wind speed (in meters per second).

C_p is the power coefficient, which represents the efficiency of the wind turbine in converting the kinetic energy of the wind into electrical power.

In the same way that DGs may be connected in parallel, wind turbines can also be connected in parallel to match the system's current requirements, resulting in higher current applications. Wind energy systems provide electricity that is highly erratic and thus unreliable due to changeable wind speed, as was indicated in the section above. The performance of the system is increased while the size and overall cost of the system are decreased when the wind turbine is incorporated into a hybrid system together with other sources. The resultant generated energy is more consistent.

4.3.3 Photovoltaic system

A process known as photovoltaic energy is created when sunlight strikes a PV cell, producing a current and voltage that is used to create electricity. Electricity produced is clean since it does not emit any pollutants, has a long operational life and costs nothing to maintain.

The production of DC electricity is achieved by connecting several PV cells to create modules, which are then combined to create PV arrays. Figure 4.1 illustrates this process of building PV arrays out of modules and cells.

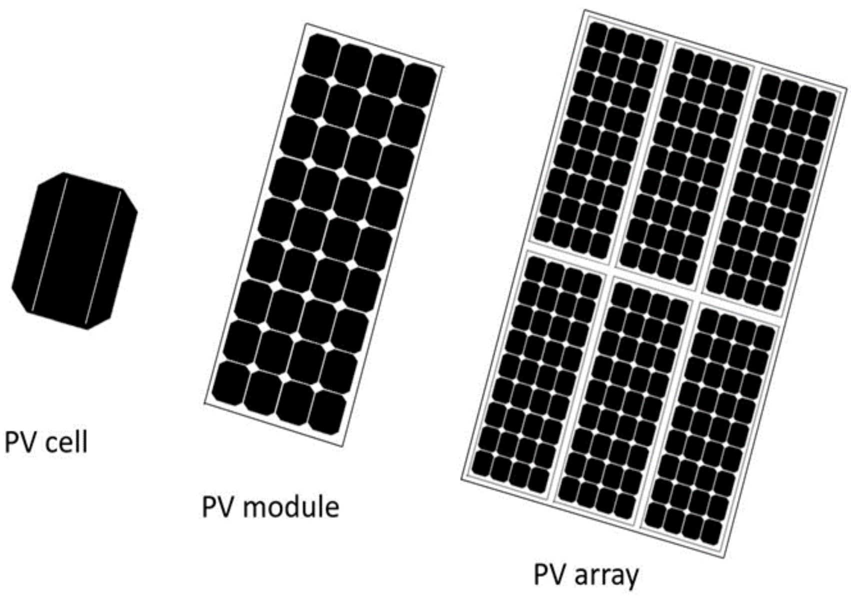

Figure 4.1 Construction of a PV cell, a PV module, and a PV array

An inverter is utilized to accomplish this conversion of the DC output power from the array to match the AC load needs. The nominal efficiency, nominal peak power, open circuit voltage, and short circuit current of PV panels are normally provided by the manufacturer. At Standard Test Conditions (STC), which are performed at a cell temperature of 25°C and an irradiation of 1000 W/m2 with an air mass of 1.5 spectrum, all these PV panel parameters are determined [52]. Equation (11) is used to represent how much output electricity the PV system produces.

$$P_{solar} = I_r \times P_e \times P_{pf} \times \lambda_{pv} \times \iota_{me} \qquad (11)$$

where $I_r$is the hourly irradiance, $P_e$is the power condition of efficiency, P_{pf}representing packing factor, λ_{pv} is the total area of PV, and ι_{me} as the module efficiency.

Depending on the demands of the load, PV panels can be linked in series or parallel, unlike DGs and WTs. The number of PV panels connected in parallel is a design variable; the number of PV panels connected in series does not affect the design variable.

To maintain other variables like temperature and irradiance constant while running PV panels, a specific voltage-current relationship from the manufacturer known as an IV-curve is used. The irradiance and temperature levels at a particular time and place have a significant impact on a PV system's performance [53]. Because of this, it is essential to have a thorough understanding of how the PV system operates under various conditions to choose the right modules and estimate their performance accurately.

4.3.4 Battery storage system

With the rapid increase of renewable resources connected to the grid or standalone hybrid system, the use of batteries has as well increased in demand to balance demand and supply power and to regulate the grid frequency. Thus, energy storage is a vital part of a renewable hybrid system. Batteries commonly function as electricity storage. To transform chemical energy into electrical energy, batteries are employed. Batteries are built up of multiple cells connected in series, each cell consisting of electrolyte plates. The process of storing and using electricity is done through the charging and discharging process. They come in a variety of styles, sizes, voltages, and current ratings. The number of batteries linked depends on the nominal voltage of the DC bus, which is a constant, and batteries can be connected either in series or parallel.

Depending on the control algorithm employed on such a system, a battery's life duration when used in a hybrid system arrangement may occasionally be extended. Additionally, the size of the battery can be adjusted and reduced when utilized in a hybrid system, saving money.

4.3.5 Inverter

An inverter is a tool that changes the DC output of a PV module or battery into an appropriate AC for the load. It is a crucial part of a hybrid system since it allows the solar PV system's output to be changed to accommodate the load, which primarily uses AC-powered equipment. When choosing an inverter, it should be able to produce the desired output frequency and that the current and voltage input sides match those of the system. Additionally, while staying within the safety boundary, the inverter must be able to produce the power needed to satisfy the peak power demand. There are inverters ranging in power from a few hundred watts to hundreds of kilowatts.

4.3.6 Load Profile and Electricity Demand

A load profile is a pattern representation of how much power is used in a system for the area under investigation. When utilizing HOMER, a load profile input gives an hourly pattern of power use over the course of a day (24 hours), and the pattern throughout a year is displayed as an hourly load average for each month, giving insight into the seasonal demand profile. In this study, a typical rural home in the village of Vryheid was examined. It included a variety of used but still-necessary appliances. The different devices being used include light units, a TV, a refrigerator, a kettle, a microwave, an electric iron, and a water heater (geysers). The power ratings of all appliances are considered, and the quantity and operation hours for each item are also determined and mentioned, to calculate the total amount of electricity used. The total daily demand is shown in Table 4.1 along with all the appliances in use.

Table 4.1 Load Demand

Appliance	Power (W)	No. of Items	Avg. hrs/Day	Avg. Wh/day
Lights	11	10	6	660
Electric Iron	500	1	0.3	150
Kettle	1 000	1	0.15	150
TV	90	1	6	540
Refrigerator	180	1	24	4 320
Water Heater	1 000	1	4	4 000
Total Wh/day				**9 820**

The total daily load demand for this rural household is 9.820 kWh/day with a 5.349 kW peak load, as shown in figure 4.2.

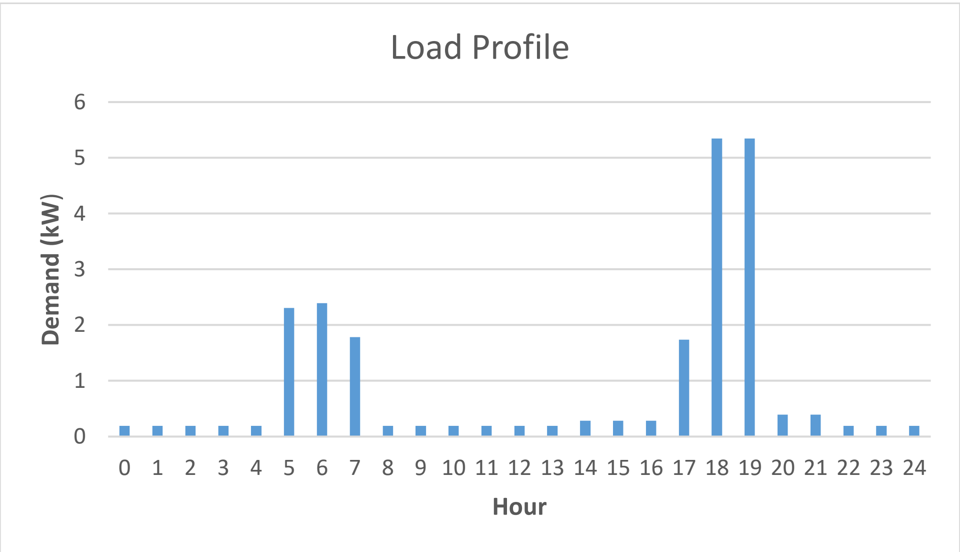

Figure 4.2 Daily Load Profile

When utilizing Homer, the residential load type was chosen, and the average load and peak load settings were set to match demand.

4.4 Summary

The components of the hybrid system configuration have been discussed in this chapter. The components discussed are energy sources, energy storage system, load profile as well as the simulating software used. The discussion mentioned the design description, both hybrid and standalone operation, as well as the load demand for the envisaged area. The chapter provides one with an understanding of the complex interface of all these components in a hybrid system.

Chapter 5: Rural House-hold Simulation and Results Discussion

5.1 Introduction

Instead of relying on satellite-based data, HOMER is used in this Chapter to simulate the hybrid energy system's optimal sizing model. The objective of the simulation is to establish the feasibility of using standalone hybrid renewable systems for those rural areas which are not connected to the grid. To analyse and assess each scenario's technical performance, economic impact, and environmental impact, five distinct scenarios were created, including a hybrid PV-WT-DG, a hybrid PV-WT, a diesel generator, a pure Photovoltaic, and a pure Wind energy system. A sensibility analysis was performed on the daily operation cost savings for each simulated scenario while using a typical rural area load profile as described in the previous chapter and data resources. Using HOMER, these simulations were run to calculate the Initial Capital (IC), Total Net Present Cost (NPC), and Cost of Energy (CE), as well as the system Capacity Shortage, of the various supply choices. The chapter commences with a brief background of the site and data collection. Before concluding with system results and discussion, it then moves on to discuss various system configurations, component sizes, and costs.

5.2 Site Description and Data Collection

From the seven SAURAN monitored data stations, the Vryheid station will be used to simulate the rural household found in this area. The wind and solar data logged for this location will be used as inputs to HOMER software. With an average daily observed wind speed of 4.68 m/s and an average daily solar radiation of 5.19 kWh/m^2, this region offers significant potential for wind and solar resources.

5.3 System Configuration

Figure 5.1 illustrates the suggested hybrid system layout.

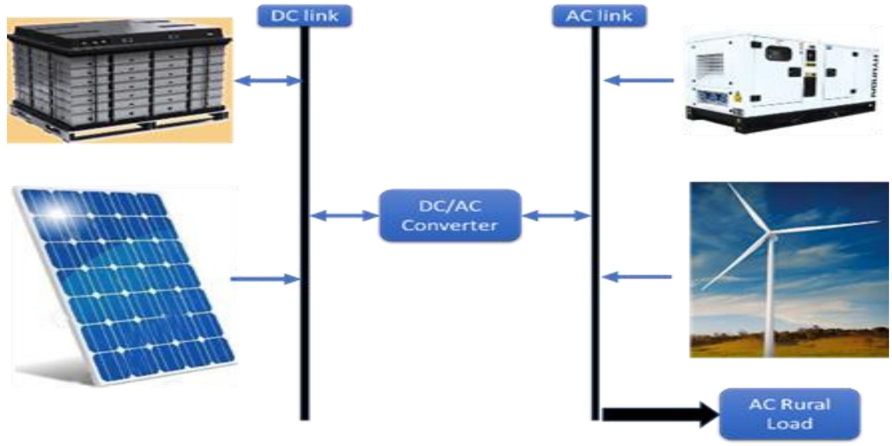

Figure 5.1 Hybrid System Diagram

PV modules, a wind turbine, a diesel generator, a battery, a converter, and a rural AC load make up the system. While the wind system is immediately connected with the diesel generator to the AC bus connection supplying the load, the PV and battery systems are connected to the DC bus link. The two buses, AC and DC links are connected with the bi-directional converter in-between allowing synchronous power flow between the renewable systems and the battery to avoid a risk of power loss or shortage. When the amount of power generated by wind and solar energy is greater than what is required by the load, the extra energy is stored in the battery bank and can be used later when the roles are reversed.

5.4 Sizing Of the Proposed Hybrid System

Various options are available for sizing stand-alone hybrid systems, varying from the most unfavourable month sizing method, yearly monthly average method, the Loss of Power Supply Probability (LPSP) method, and other software-based sizing methods. The yearly monthly average method was used as the date had been tested as shown in chapter 3.

5.5 Component Cost

5.5.1 PV System cost

The actual PV system specifications that were inserted into HOMER when doing the sizing optimization were assumed for the capital cost of 3500 $/kW, with a replacement cost of a lower price of 3000 $/kW and Operation and Maintenance (O&M) of 0 $.

5.5.2 Batteries

The battery bank is utilized as a storage system for the excess power generated by both PV and WT systems and makes use of this power when either PV or WT fails to meet the load demands. The study makes use of Trojan LP16 deep cycle batteries which has the nominal specifications of a nominal voltage of 6 V, nominal capacity of 360 Ah, and 2.16 kWh. The lifetime throughput for these batteries is 1.075 kWh.

The batteries were specified in HOMER with a capital cost of 130$, and a replacement cost of 100$ with an O&M of 15$.

5.5.3 Wind Turbine

The selection of a wind turbine is highly influenced by the wind speed changes which will result in the energy produced by the system. Consequently, wind turbines are usually selected at a higher rating compared to the load power demand. The WT specifications in HOMER are given in terms of the total capacity of the wind system based on the minimum NPC and COE.

In this study, WT was considered with a rated capacity of 10 kW with a capital cost of $ 26 900, a replacement cost of $ 15 000, and an O&M cost of $65/year. The lifetime and height of the turbine were 20 years and 25 m, respectively.

5.5.4 Converter cost

The load for this rural household is an AC load therefore a converter is essential as the energy produced by these renewables is DC in the case of PV and battery storage systems. The converter is utilized to provide AC power from DC power or vice-versa. The converter was specified with a capital cost of 1500 $/kW, replacement cost was set to $ 1200, and an O&M cost of $ 15. Various sizes of converter made it possible for HOMER so to select the best size considering all systems constraints and specifications.

5.5.5 Diesel Generator Costs

DG in this study is used to supply power when the renewables are unable to meet the load demands. While HOMER calculates the DG capacity based on the peak load demand, the specifications were set to $/kW. The DG capital cost was set at 600 $/kW, the replacement cost stipulated at $ 500, and O&M costs at $ 1.50/L which includes oil and fuel costs. The lifetime for the DG is 15 000 hours as specified in HOMER.

5.6 System Results, Analysis and Discussion

Once the location, as well as the technical and financial information for HOMER inputs, have been established, simulation, analysis, and computations can begin. HOMER performs the simulation and estimates the costs, feasibility of various possible hybrid systems, and capacity based on Net Present Cost (NPC).

5.6.1 Economic Analysis

HOMER provides an opportunity for financial parameters with costs estimated for an annual interest rate, Cost of Energy (COE), replacement costs, initial capital cost, and operating and maintenance costs for all different possible configurations.

The results on HOMER are organized based on NPC. The net present cost (NPC), in its computation, includes the initial cost of the project, the operation cost, the project maintenance cost, the replacement cost for any possible damaged equipment, and the overall energy cost for the full project lifespan [54], [55].

Another parameter taken into consideration by HOMER during optimization is the Cost of Energy (COE) which is defined as the average cost per kilowatt-hour of useful electrical energy ($/kWh) as shown by equations (10) and (11) [56].

$$COE = C_Y / E_P \qquad (10)$$

$$C_Y = C_{Y\_INI} + C_{Y_{O\&M}} + C_{Y\_REPL} \qquad (11)$$

Where, C_Y is the annual cost which is the sum of initial capital cost, operation and maintenance costs, and the cost for replacement.

The life cycle emission (LCE) cost is also another import cost that informs about the CO_2 emission from the energy used per annum [57].

5.6.2 System architecture and cost analysis

HOMER found seven different optimized system scenarios to meet the load demand for the rural household. The system architect configurations are summarized in table 5.1.

Table 5.1 Optimized System architectures for the rural household

System Config	PV (kW)	WT (kW)	DG (kW)	Number of batteries	Inverter (kW)
PV/DG	3	0	6	32	4
PV/WT/DG	2	1	3	36	8
WT/DG	0	1	6	32	4
PV/WT	5	1	0	36	10
DG	0	0	6	52	4
PV	14	0	0	56	10
WT	0	3	0	52	10

Table 5.2 Cost analysis of the rural household architectures

System Config	NPC ($)	COE ($)	Initial Capital ($)	O&M ($)
PV/DG	72,720	0.675	29,660	3,368
PV/WT/DG	79,272	0.736	55,080	1,892
WT/DG	80,090	0.743	46,060	2,662
PV/WT	86,760	0.805	64,080	1,774
DG	91,757	0.851	21,760	5,476
PV	100,236	0.930	71,280	2,265
WT	130,428	1.211	102,460	2,188

Table 5.1 shows seven optimized systems with four hybrid energy systems and three with only one energy resource. Moreover, three of the seven energy systems are pure green energy supplied and not utilizing any DG. This illustrates the abundant availability of renewable resources to supply energy demand for rural areas in this region. In terms of the best-optimized system, the system contains both PV energy and DG resource. The best hybrid system with all the resources used came as the send best-optimized system with the best only renewable resources system coming as the fourth best system behind systems that all contain some DG in it. The best-optimized system requires the least amount of storage requiring 32 batteries. In addition, all systems that stand alone require a certain higher number of batteries for storage hence the least preferred optimized system.

Table 5.3 Electrical analysis for the rural household

System Config.	Electricity generation (kWh/y)	Total fuel (L)	Capacity shortage (kWh/y)	Unmet load (kWh/y)	Excess electricity (kWh/y)
PV/DG	10,346	2,036	0.852	0.0000120	124
PV/WT/DG	17,580	334	2.77	1.49	7,185
WT/DG	16,982	1,308	0.852	0.0000120	6,957
PV/WT	21,127	0	3.11	1.50	10,820
DG	10,775	3,660	0.852	0.000	0.000323
PV	21,042	0	3.00	1.09	10,404
WT	40,835	0	7.03	5.46	30,682

Table 5.2 show the best-optimized system as rated in terms of NPC. As mentioned above, the best renewable hybrid system came second as it is more expensive than the system which contains PV/DG with the cost of $ 86,760 as compared to the best hybrid system consisting of PV/DG with an NPC of $ 72,720 as shown in table 5.2. Moreover, this high cost is influenced by two aspects the high O&M cost associated with DG and the large storage capacity required where they are renewables. It is also noted that the cost for O&M is high in all systems which have a DG while all standalone systems are expensive as they require a large storage system as mentioned above. However, pure green hybrid systems that contain PV/WT require the least capital for operation and maintenance. In terms of initial capital required, the DG standalone has the best costs, but it was the fifth-best system in overall performance.

Table 5.4 Electrical production analysis

System Config.	Electricity production by PV (kWh/y)	%	Electricity production by WT (kWh/y)	%	Electricity production by DG (kWh/y)	%
PV/DG	4,509	44	0	0	5,837	56
PV/WT/DG	3,006	17	13,612	77	963	5
WT/DG	0	0	13,612	80	3,371	20
PV/WT	7,515	36	13,612	64	0	0
DG	0	0	0	0	10,775	100
PV	21,042	100	0	0	0	0
WT	0	0	40,835	100	0	0

Table 5.3 and Table 5.4 show the detailed results of the electrical analysis. Table 5.3 shows the electricity generated by each system for the year and details the amount of diesel used in such electricity production, the capacity shortage with unmet load, and excess electricity for all seven systems. The WT standalone system produces the highest amount of energy with a total generated energy over the year sitting at 40,835 kWh and with excess energy of 30,682 kWh and unmet load energy of 5.46 kWh. This demonstrates that even though there is abundant wind energy in this region, it requires a large storage system to harness this energy. The best system of PV/DG presents the least amount of energy generated and it meets the load demand with minimum unmet load and excess load amount. This accurate electricity production is

because of DG use in the system with the PV contributing only 44% of energy as demonstrated in table 5.4. Apart from the PV/DG system and standalone DG system, the contribution of DG to the electricity generated is below 20% and presents a certain possibility for renewable investment with low CO_2 emission. The best-suggested system for use in this region is a system that contains PV/WT/DG which is the second-rated system from the optimized results, and it consists of 17% PV, 77% from WT, and 5% from DG. This gives an accumulation of approximately 95% renewable dependent and low carbon footprint. This system uses a total diesel litre of 334, for a production of 17,580, with an NPC of $ 79,272, requiring an initial cost of $55,080 and an operation and maintenance cost of $ 1,892. This is the second-best O&M cost behind the hybrid system with only renewables. It also requires 36 batteries for storage purposes with the system which requires the least number of batteries requiring 32. The inverter required in this system is 8 kW with 4 kW being the smallest inverter used in any system.

Figures 5.2 – 5.8 show a detailed cash flow summary for these seven systems.

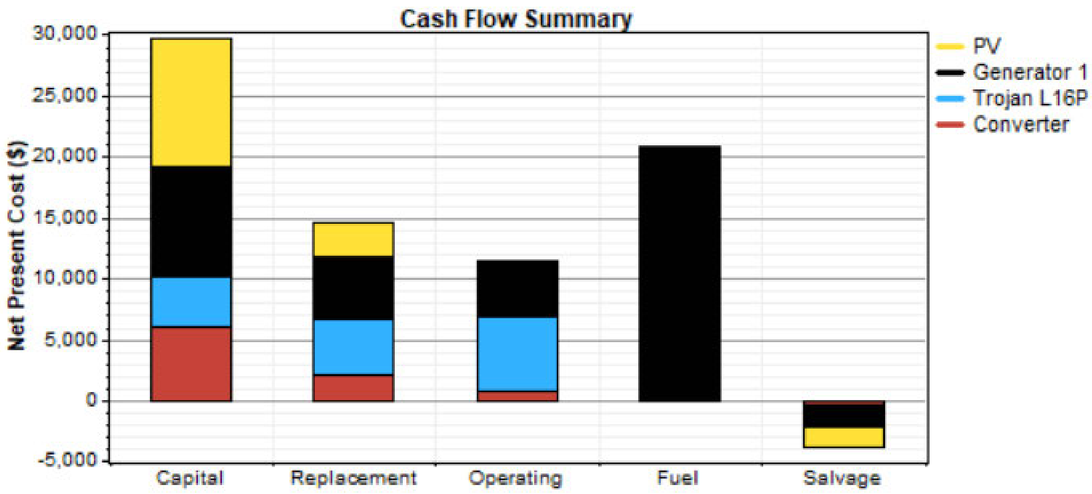

Figure 5.2 NPC for PV/DG system

Figure 5.2 shows a summary cost for the best-optimized system with the system capital cost of $ 29,660, with PV costing $ 10,500, the DG costing $ 9,000, and the remaining cost of $ 4,160 towards storage and $ 6,000 for the converter. The other costs are $ 14,566 for replacement costs, $ 11,513 towards O&M with fuel costing $ 20,823, and the system salvaging $ -3,842.

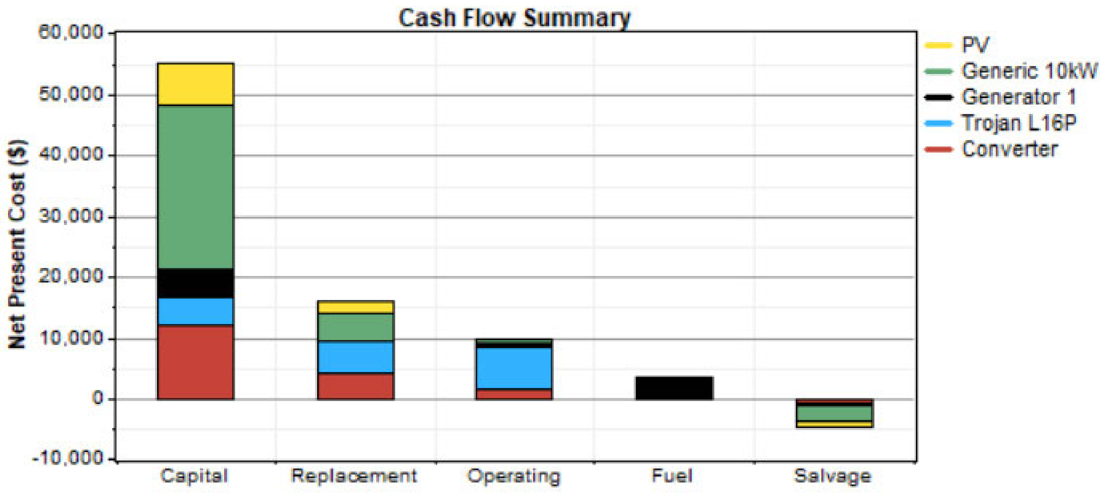

Figure 5.3 NPC for PV/WT/DG system

Figure 5.3 represents the summary cash flow for the suggested system. In this system, the capital cost is $ 55,080 with most costs towards WT with a total of $ 26,900 and the converter costing $ 12,000. This system demonstrates an O&M cost of less than $ 10,000 with fuel amounting to $ 3,419 and salvage of $ -4,874.

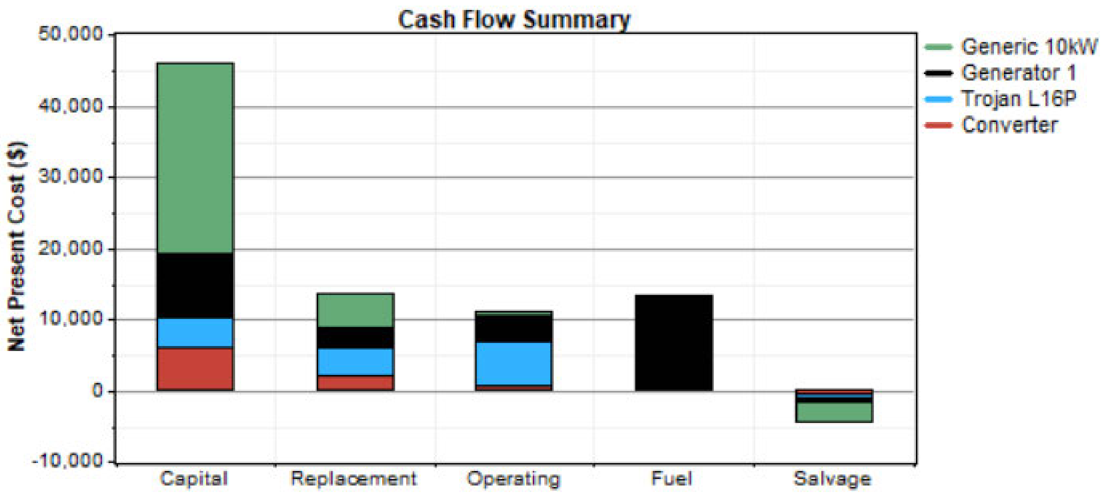

Figure 5.4 NPC for WT/DG system

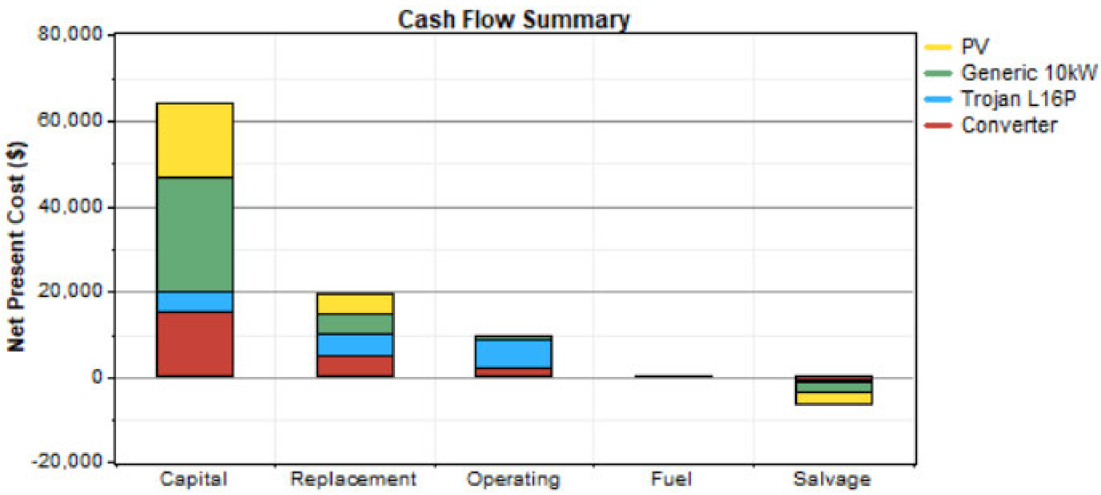

Figure 5.5 NPC for PV/WT system

The only green hybrid system has a capital cost of $ 64,080 with WT amounting to most amount of $ 26,900 and PV costing $ 17,500. As the system uses an 8-kW converter, an amount of $ 15,000 is pent towards this converter with the storage system costing $ 4,680. A large amount of $ 19,593 is needed for replacement purposes with O&M costing $ 9,460. The system has the highest salvage amounting to $ -6,373.

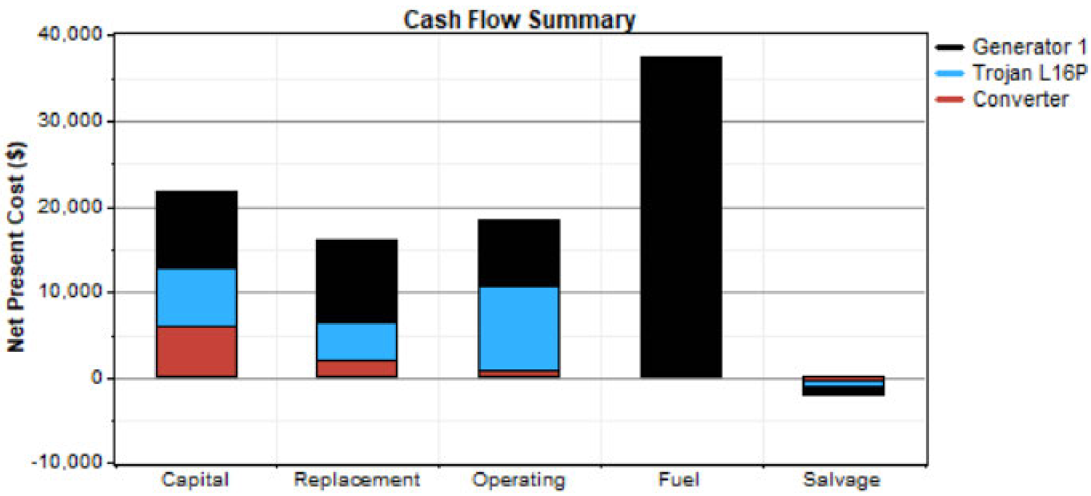

Figure 5.6 NPC for DG system

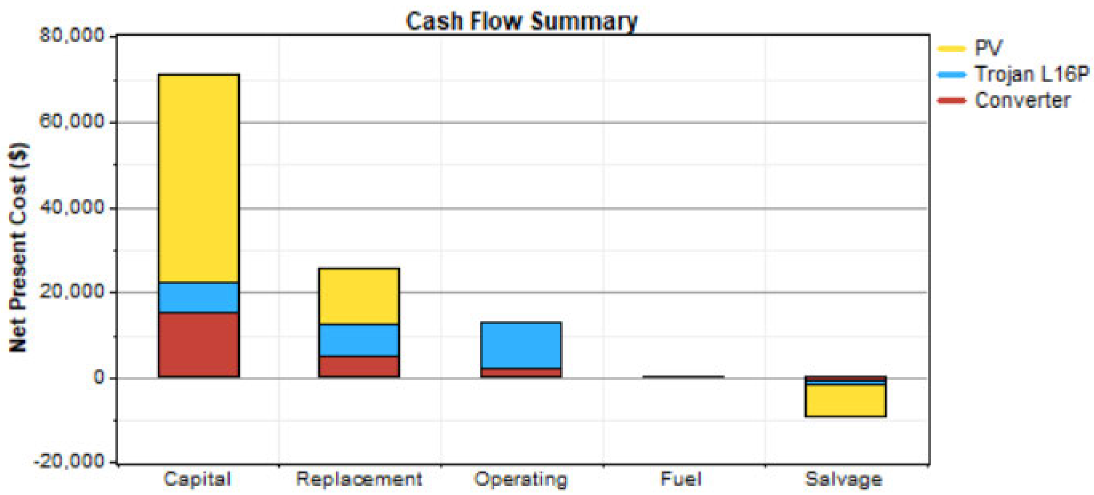

Figure 5.7 NPC for PV system

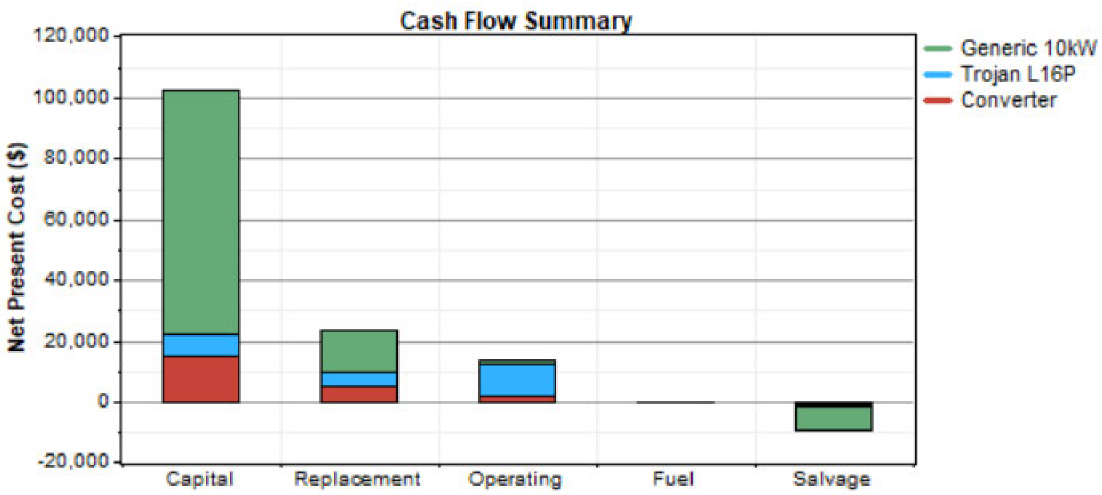

Figure 5.8 NPC for WT system

Figures 5.6 – 5.8 show the NPC breakdown for standalone systems with major costs towards the capital cost of those systems and storage systems. Moreover, a large sum will be spent on fuel for the DG-only system equalling $ 37,430 which is larger than the total capital cost required for the system which is $ 21,760. This drawback is additional to the typical disadvantage of using DG which is CO_2 emissions.

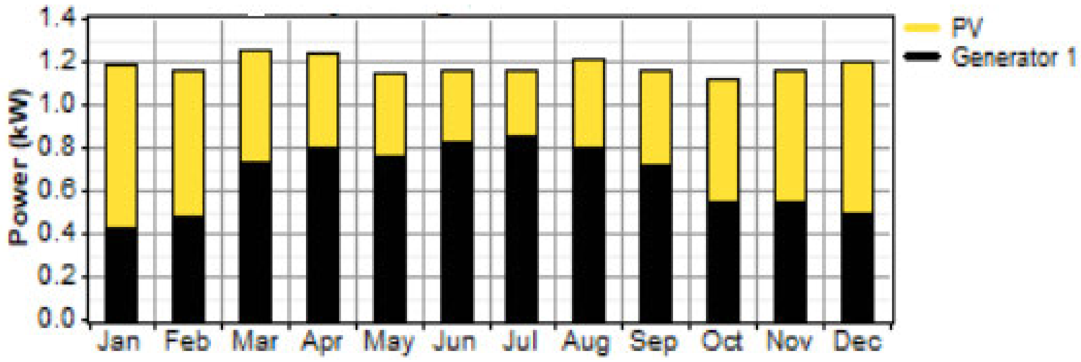

Figure 5.9 Monthly average electricity production for PV/DG system

Figures 5.9 -5.15 shows the average monthly production for each of the seven best systems detailing the contribution of each energy source. In figure 5.9, it can be observed from March to September, there is heavy reliance on diesel generators with the maximum peak observed in the month of July. This is understandable as it is the autumn to spring season for the southern hemisphere and there is less sunlight. However, the PV system contributes best during the months from October to February with January being the peak month. This is the season of Spring and summer for the country.

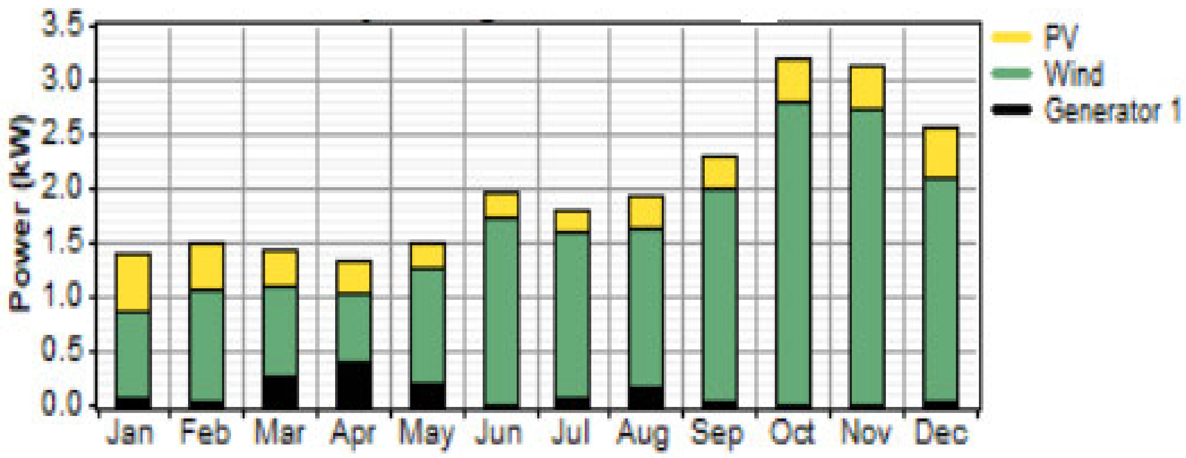

Figure 5.10 Monthly average electricity production for PV/WT/DG

Figure 5.10 shows the average monthly detailed electricity production for each source towards the preferred hybrid system. From the figure, it is seen that most of the electricity produced is from the wind turbine, with PV added to make the renewables contribute the majority for each month. The month where DG will be most used is in April as both winds and solar resources are at their weakest. The months of October and November show the least amount of DG resources required as both renewables will be peaking.

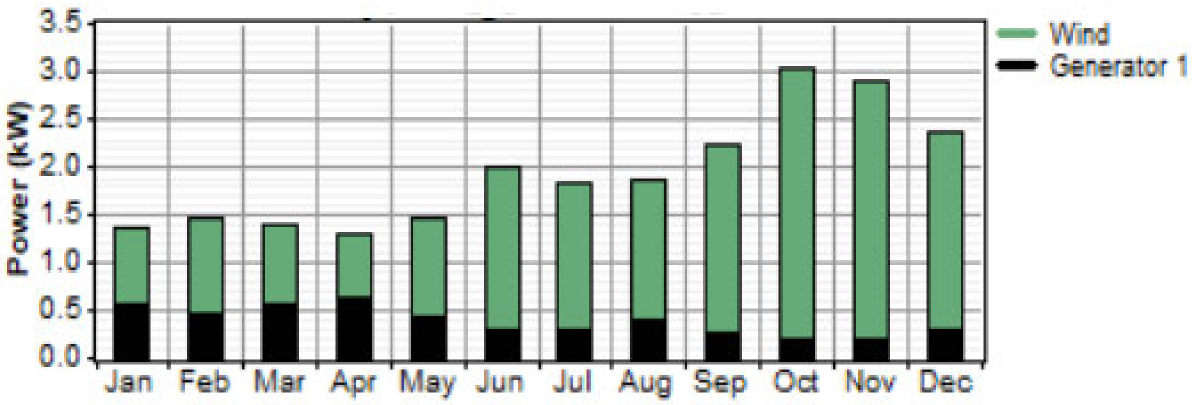

Figure 5.11 Monthly average electricity production for WT/DG system

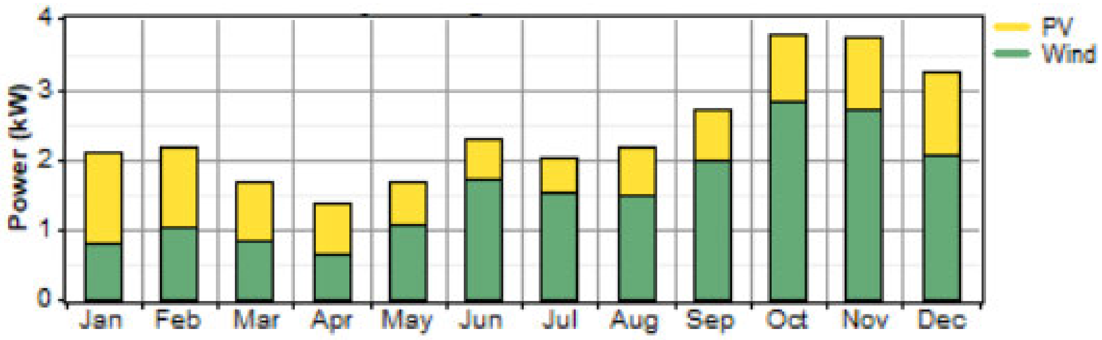

Figure 5.12 Monthly average electricity production for PV/WT system

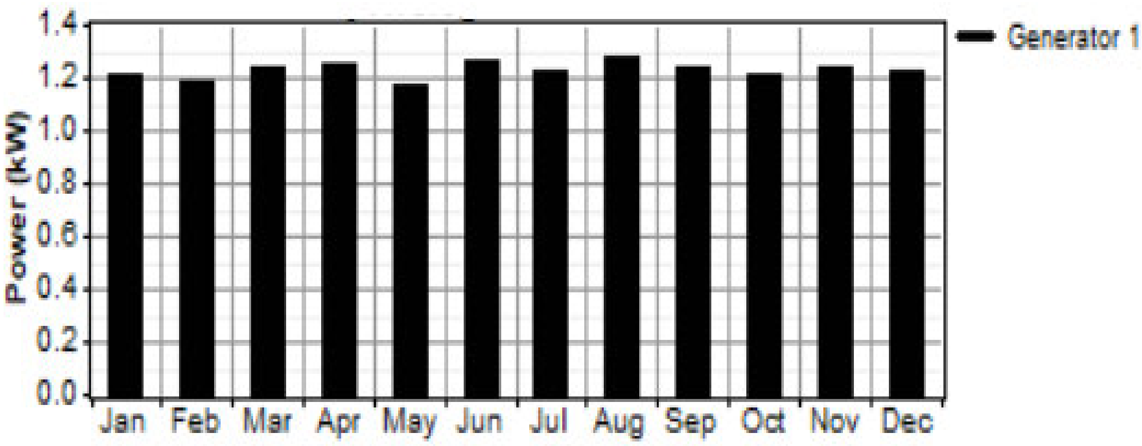

Figure 5.13 Monthly average electricity for DG

From figures 5.11 – 5.15, we observe the peaks and lowest performances for each resource. The wind resources are best available in the month of October and at lowest in the month of April as shown in figure 5.15. As for PV with solar resources, it has its peak in the month of January and worst case in the month of July.

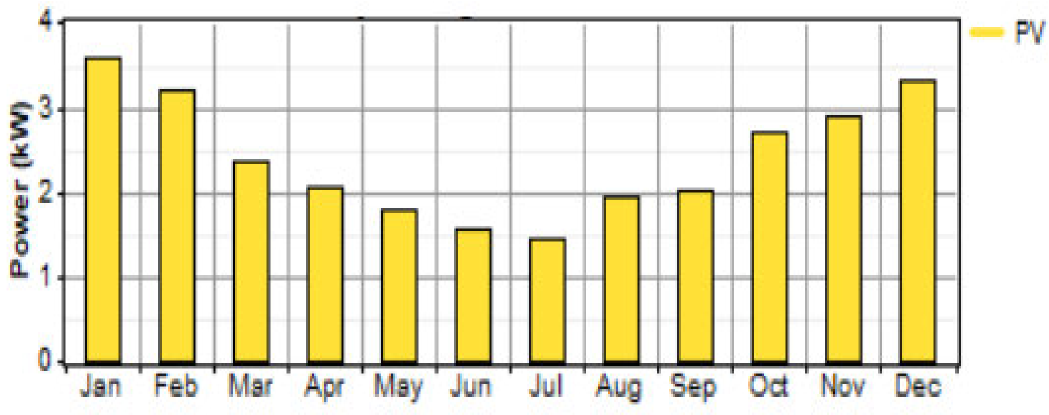

Figure 5.14 Monthly average electricity production for PV system

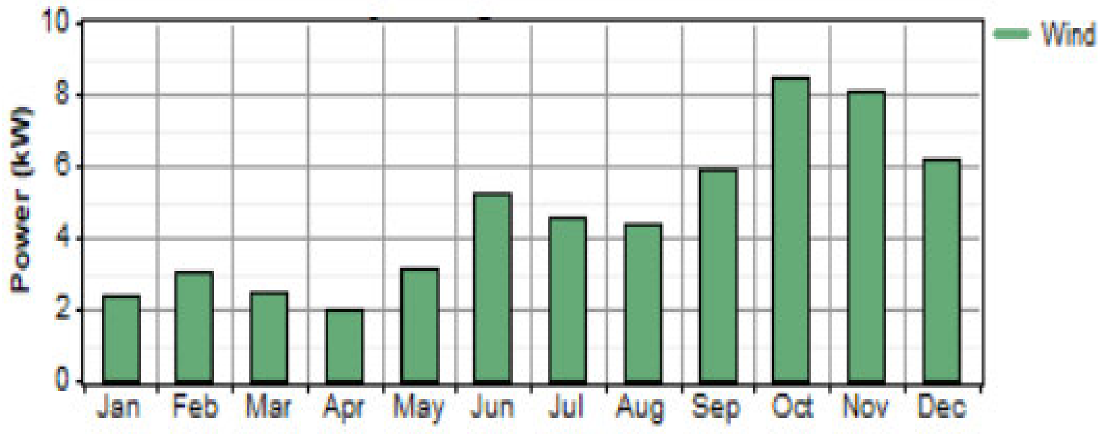

Figure 5.15 Monthly average electricity production for the WT system

The CO_2 emission results together with converter output, PV output, and WT output are shown in the appendixes.

The results show that the optimized energy system proposed has the potential to sufficiently supply these rural areas with this system largely relying on renewables.

5.7 Summary

In this chapter, HOMER has been used to simulate the hybrid system's ideal sizing model. In the modelling, actual measured data was used instead of conventional satellite-based data. A load profile for a typical rural household was developed using household needs and low-energy consumption equipment or energy-saving equipment. The hybrid system consisted of two renewable resources namely PV and WT with the third resource as a DG. A battery backup storage system was used with the best system utilizing all resources requiring 36 batteries.

Seven best-optimized system architectures were obtained with the best system consisting of PV and DG. This system consists of 3 kW PV, 6 kW DG, 32 batteries, and an 8 kW converter. The system costs are $ 72,720 net present costs, requiring $ 29,660 initial costs for the project and $ 3,368 of operation and maintenance costs. The system has an electricity generation of 10,346 kWh/y with an excess of 124 kWh/y and utilizes a total fuel of 2,036 litres.

The system which utilized all resources available came ranked send best with a total electricity generation of 17,580 kWh/y, leading to an excess of 7,185 kWh/y, and using a total fuel of 334 litres such a system requires 2 kW PV, 1 kW WT, 3 kW DG, 36 batteries, and an 8-kW converter. The system comes at a higher cost than the one utilizing PV and DG with NPC of $ 79,272, and an O&M cost of $ 1,892, requiring initial costs of $ 55,080.

The best hybrid green energy system came fourth-ranked with a total electricity generation of 21,127 and 36% contributed by PV and 64% from WT. 36 batteries are required for this system with a 10-kW converter and NPC of $ 86,760.

These results demonstrate that it is feasible to have a standalone hybrid system for those sparsely scattered areas like rural areas as there are abundantly available renewable resources. Moreover, with the average cost of grid extension in the country estimated at $ 20,000/km for an 11 kV line cost alone and with this cost going to $ 25,000/km, if you consider other electrification components and the inflation rate. This as a result can be too costly for rural area dwellers and hence a need for a standalone hybrid system.

Chapter 6: Conclusion and Recommendations

This chapter concludes firstly on nonparametric kernel density estimation modelling of renewable data resources using ground-measured data. The chapter further reports on the simulation and optimal sizing of a hybrid energy system consisting of a photovoltaic module, wind turbine, battery bank, and diesel generator for a typical South African rural household using the tested ground-measured data. The context of this research looked at two important aspects. It began with the precise determination of renewable data resources that is essential when envisioning to do electrification of a certain region utilizing unpredictable renewable resources. The second important point dealt with the inclusion of rural areas that are not benefiting from the gains of accessible electricity due to several constraints.

When planning to do reticulation for an area, the first step is to perform a feasibility study on the availability of resources in such an area. Typically, this study is performed using parametric probability distribution functions to ascertain and determine the best pdf that describes the area. In this study, global horizontal solar irradiance and wind speed measurements made at seven sites in South Africa between 2014 and 2016 were modelled using both parametric and non-parametric methods. For the parametric modelling, three distribution functions—Gamma, Weibull, and Lognormal—were used, while for the non-parametric modelling, a kernel density estimator was employed. The information utilized to determine whether the three parametric distributions and suggested nonparametric kernel estimate approach were adequate for modelling these seven sites was derived from actual measured data taken at ground level using top-notch equipment available on these sites. Three statistical tests—root mean square error, mean bias error, and mean bias error—were used in an evaluation study to determine whether the parametric distributions were suitable. The performance of the suggested nonparametric technique and the traditional parametric normal distribution were compared using an integral squared error, or ISE. The ability to obtain the site's solar and wind properties in advance is crucial when using a parametric distribution method. Additionally, not all sites can be accommodated by the parametric distribution functions, therefore finding the appropriate function for any site requires a system of trial and error. These parametric distribution functions cannot adapt to the supplied data and smooth the curve representation in accordance. All the aforementioned problems can be resolved by applying the suggested nonparametric kernel density approach.

With a value of 0.0405, the University of Free State has the lowest RMSE for both gamma and lognormal distributions. The low RMSE score illustrates an accurate assessment of the methodology used for all distribution functions. For both the solar radiation and the wind speeds at that location, the Weibull probability function offered the best description of the data for UP. First, it is noted that all kernels outperformed conventional traditional pdfs for all sites in terms of the suggested nonparametric technique. The Gaussian KDE fared best for three of the seven sites, UF, VR, and UZ, where the rural home is located, when the individual kernels were compared to one another. All the examined sites could adjust to the six chosen kernels. The modelling results revealed that the kernel density estimation approach provides higher adaptability, and, with the option of bandwidth adjustment, it fits all sites' data adequately. As a result, it is advised to utilize it instead of the more common classic pdf method.

In terms of simulation and optimal sizing of a hybrid energy system for a typical South African rural household, the study was performed using the area of Vryheid. The area of Vryheid has good potential in wind and solar resources like most South African regions with an average daily measured wind speed of 4.68 m/s and daily average solar radiation of 5.19 kWh/m^2. The total daily load demand for this household was established to have a load demand of 10.820 kWh/day with a 5.349 kW peak load. These parameters were used as inputs for the study. The HOMER results gave seven best-optimized systems with four hybrid energy systems, three with only one energy resource, and of those seven, three were pure green energy supplied and not utilizing any DG. One can conclude that renewable resources are abundantly available in this area as illustrated by the results. The best-optimized system for this area consisted of PV/DG with an NPC of $ 72,720, while the system which utilized all resources available was second-ranked with an NPC of $ 79,272. The use of only renewable resources for this region was fourth-ranked with NPC of $ 86,760. These results demonstrate the feasibility and viability have having these rural areas benefit from having electricity access.

In addition to these benefits, according to [58], the average cost of grid extension in Sub-Saharan Africa is $20,000/km for just the 11 kV line cost. These costs grow to $26,000/km or even higher if you consider inflation and other electrification components. The cost of extending the grid to scattered villages is generally higher than places in good terrains as these villages can be far away from the existing high voltage line up to 500 km. The cost of electricity in South Africa using grid extension is sitting at $0.865/kWh as of the end of 2022. This cost higher than the proposed method which is sitting at $0.675/kWh.

The results are resilient to unpredictability in component costs, resource availability, and moderate load growth. Furthermore, microgrids should be seriously considered as an electricity alternative for off-the-grid, unconnected rural families in South Africa, at least from a technological and economic standpoint. Additionally, the RES microgrid offers certain advantages for the environment because it will help keep forests intact and reduce pollution from wood burning. The RES microgrid would also lessen some health and safety issues related to cooking, heating, and lighting using wood, paraffin, and candles. Lastly, this study will contribute towards the strides of just energy transition envisaged by the country in solving the energy crisis currently being experienced.

As a recommendation, the findings of this research have substantial policy implications. Policymakers and energy planners should consider incorporating the nonparametric kernel density estimation approach in their resource assessment and feasibility studies. This approach can provide a more accurate representation of renewable data resources, which is essential for effective electrification planning, particularly in rural and resource-constrained areas. Moreover, the optimized hybrid energy system results underscore the economic and environmental benefits of embracing renewable energy solutions. These findings can guide policy decisions and incentivize the adoption of clean energy technologies. Policymakers can leverage these findings to enhance the alignment of electrification initiatives with the broader energy transition agenda.

References

[1] Department of Mineral Resources and Energy. Republic of South Africa, “Renewable Energy,” DME, [Online]. Available: www.energy.gov.za/files/renewables_frame.html. [Accessed 03 04 2019].

[2] Department of Statistic South Africa, “South African Population,” Stats SA, [Online]. Available: www.statssa.gov.za. [Accessed 17 April 2022].

[3] B. van Ruijven, J. Schers and D. van Vuuren, “Model-based scenarios for rural electrification in developing countries,” *Energy,* vol. 38, pp. 386-397, 2012.

[4] R. Sen and B. C. Subhes, “Off-grid electricity generation with renewable energy technologies in India: An application of HOMER.,” *Renewable energy,* vol. 62, pp. 388-398, 2014.

[5] K. Kusakana, “Techno-economic analysis of off-grid hydrokinetic-based hybrid energy systems for onshore/remote area in South Africa.,” *Energy,* vol. 68, pp. 947-957, 2014.

[6] The World Bank Group, “Climate Risk Profile: South Africa,” World Bank Publications, Washington, 2021.

[7] ESKOM, “www.eskom.co.za,” ESKOM, [Online]. Available: www.eskom.co.za/about-eskom/company-information/. [Accessed 10 May 2022].

[8] DIRECTORATE: ENERGY DATA COLLECTION, MANAGEMENT AND ANALYSIS, “THE SOUTH AFRICAN ENERGY SECTOR REPORT,” Department of Energy, Pretoria, 2019.

[9] M. Goedecke, T. Supaporn and S. H. Gheewala, “Life cycle cost analysis of alternative vehicles and fuels in Thailand.,” *Energy Policy,* vol. 35, no. 6, pp. 3236-3246, 2007.

[10] B. C. Subhes, “Energy access programmes and sustainable development: A critical review and analysis.,” *Energy for sustainable development,* vol. 16, no. 3, pp. 260-271, 2012.

[11] R. Munzhedzi and A. Sebitosi, “Redrawing the solar map of South Africa for photovoltaic applications.,” *Renewable Energy,* vol. 34, no. 1, pp. 165-169, 2009.

[12] A. Pegels, “Renewable energy in South Africa: Potentials, barriers and options for support.,” *Energy policy,* vol. 38, no. 9, pp. 4945-4954, 2010.

[13] T. R. Ayodele, “Determination of probability distribution function for modelling global solar radiation: case study of Ibadan, Nigeria.,” *International Journal of Applied Science and Engineering,* vol. 13, no. 3, pp. 233-245, 2015.

[14] R. Ihaddadene and N. Ihaddadene, “Modeling of monthly global solar radiation in M'sila region (Algeria),” in *IEEE*, 2016.

[15] T. P. Chang , “Investigation on frequency distribution of global radiation using different probability density functions.,” *International Journal of Applied Science and Engineering,* vol. 8, no. 2, pp. 99-107, 2010.

[16] K. Mohammadi, O. Alavi, A. Mostafaeipour, N. Goudarzi and M. Jalilvand, "Assessing different parameters estimation methods of Weibull distribution to compute wind power density.," *Energy Conversion and Management,* vol. 108, pp. 322-335, 2016.

[17] K. Gabbasa, K. Sopian, Z. Yaakob, M. Faraji Zonooz, A. Fudholi and N. Asim, "Review of the energy supply status for sustainable development in the Organization of Islamic Conference," *Renew Sustain Energy,* vol. 28, pp. 18-28, 2013.

[18] M. Islam, S. Mekhilef and R. Saidur, "Progress and recent trends of wind energy technology," *Renew Sustain Energy,* vol. 21, pp. 456-468, 2013.

[19] Global Wind Energy Council, "Global Wind Energy Council," GWEC, [Online]. Available: http://www.gwec.net/. [Accessed 11 March 2021].

[20] J. Zhou, E. Ergin, L. Gong and S. Jing, "Comprehensive evaluation of wind speed distribution models: A case study for North Dakota sites.," *Energy Conversion and Management,* vol. 51, no. 7, pp. 1449-1458, 2010.

[21] Brano, V. Lo, A. Orioli, G. Ciulla and S. Culotta, "Quality of wind speed fitting distributions for the urban area of Palermo, Italy.," *Renewable Energy,* vol. 36, no. 3, pp. 1026-1039, 2011.

[22] W. Jie, J. Wang and D. Chi, "Wind energy potential assessment for the site of Inner Mongolia in China," *Renewable and Sustainable Energy Reviews,* vol. 21, pp. 215-228., 2013.

[23] O. Alavi, M. Kasra and M. Ali , “Evaluating the suitability of wind speed probability distribution models: A case of study of east and southeast parts of Iran.,” *Energy Conversion and Management,* vol. 119, pp. 101-108, 2016.

[24] I. Y. Lun and J. C. Lam, “A study of Weibull parameters using long-term wind observations.,” *Renewable energy,* vol. 20, no. 2, pp. 145-153, 2016.

[25] A. N. Celik, “On the distributional parameters used in assessment of the suitability of wind speed probability density functions.,” *Energy Conversion and management ,* vol. 45, no. 11-12, pp. 1735-1747, 2014.

[26] I. Pobočíková, Z. Sedliačková and M. Michalková, “Application of four probability distributions for wind speed modeling.,” *Procedia engineering,* vol. 192, pp. 713-718., 2017.

[27] G. Li and J. Shi, “Application of Bayesian model averaging in modeling long-term wind speed distributions.,” *Renewable Energy,* vol. 35, no. 6, pp. 1192-1202, 2010.

[28] V. L. Brano, A. Orioli, G. Ciulla and S. Culotta, “Quality of wind speed fitting distributions for the urban area of Palermo, Italy.,” *Renewable Energy,* vol. 36, no. 3, pp. 1026-1039., 2011.

[29] Z. Qin, W. Li and X. Xiong, “Estimating wind speed probability distribution using kernel density method.,” *Electric Power Systems Research,* vol. 81, no. 12, pp. 2139-2146, 2011.

[30] A. Elgammal, R. Duraiswam, D. Harwood and L. S. Davis, “Background and foreground modeling using nonparametric kernel density estimation for visual surveillance.,” *Proceedings of the IEEE,* vol. 90, no. 7, pp. 1151-1163, 2002.

[31] A. Ullah and A. Pagan, Nonparametric econometrics, Cambridge: Cambridge university press, 1999.

[32] H. Wang and D. Suter, “Robust adaptive-scale parametric model estimation for computer vision.,” *IEEE transactions on pattern analysis and machine intelligence,* vol. 26, no. 11, pp. 1459-1474, 2004.

[33] R. Al-Rashed, T. Faza and O. Ayadi, “Potential of using Off-grid PV/Wind/Diesel Battery Hybrid Energy System in Jordan.,” in *IEEE*, 12th International Renewable Engineering Conference (IREC), 2021.

[34] M. Pirhaghshenasvali and B. Asaei, “Optimal modeling and sizing of a practical hybrid wind/PV/diesel generation system,” in *IEEE*, The 5th Annual International Power Electronics, Drive Systems and Technologies Conference (PEDSTC 2014)., 2014.

[35] K. Kusakana and H. J. Vermaak, “Hybrid renewable power systems for mobile telephony base stations in developing countries,” *Hybrid renewable power systems for mobile telephony base stations in developing countries,* vol. 51, pp. 419-425., 2013.

[36] K. Kusakana and H. J. Vermaak, “Hydrokinetic power generation for rural electricity supply: Case of South Africa.,” *Renewable energy,* vol. 55, pp. 467-473, 2013.

[37] M. Pirhaghshenasvali and B. Asaei, “Optimal modeling and sizing of a practical hybrid wind/PV/diesel generation system.,” in *The 5th Annual International Power Electronics, Drive Systems and Technologies Conference (PEDSTC 2014)*, 2014.

[38] X. Wang, A. Palazoglu and N. H. El-Farra, "Operation of residential hybrid renewable energy systems: Integrating forecasting, optimization and demand response.," in *American Control Conference. IEEE*, Portland, Oregon., 2014.

[39] A. Singh, P. Baredar and B. Gupta, "Computational simulation & optimization of a solar, fuel cell and biomass hybrid energy system using HOMER pro software.," *Procedia Engineering,* vol. 127, pp. 743-750, 2015.

[40] S. Rehman and I. El-Amin, "Study of a solar pv/wind/diesel hybrid power system for a remotely located population near Arar, Saudi Arabia," *Energy Exploration & Exploitation,* vol. 33, no. 4, pp. 591-620, 2015.

[41] P. Kumar, R. Pukale, N. Kumabhar and U. Patil, "Optimal design configuration using HOMER," *Procedia Technology,* vol. 24, pp. 499-504, 2016.

[42] G. Sandeep and V. Vakula, "Optimal combination and sizing of a standalone hybrid power system using HOMER.," in *International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT). IEEE*, 2016.

[43] A. Ogunjuyigbe, T. Ayodele and O. Akinola, "Optimal allocation and sizing of PV/Wind/Split-diesel/Battery hybrid energy system for minimizing life cycle cost, carbon emission and dump energy of remote residential building," *Applied Energy,* vol. 171, pp. 153-171, 2016.

[44] B. Ceran, Q. Hassan , M. Jaszczur and K. Sroka , "An analysis of hybrid power generation systems for a residential load.," *E3S web of conferences.,* vol. 14, p. 01020, 2017.

[45] L. Aghenta and M. T. Iqbal, "Design and dynamic modelling of a hybrid power system for a house in Nigeria.," *International Journal of Photoenergy,* 2019.

[46] A. S. Aziz, M. F. N. Tajuddin, M. R. Adzman, M. A. Ramli and S. Mekhilef, “Energy management and optimization of a PV/diesel/battery hybrid energy system using a combined dispatch strategy.,” *Sustainability,* vol. 11, no. 3, p. 683, 2019.

[47] Z. Qin, W. Li and X. Xiong, “Estimating wind speed probability distribution using kernel density method,” *Electric Power Systems Research,* vol. 81, no. 12, pp. 2139-2146, 2011.

[48] S. Sinha and S. S. Chandel, “Review of software tools for hybrid renewable energy systems,” *Renewable and sustainable energy reviews,* vol. 32, pp. 192-205, 2014.

[49] Y. Hu and P. Solana., “Optimization of a hybrid diesel-wind generation plant with operational options,” *Renewable Energy,* vol. 51, pp. 364-372, 2013.

[50] M. M. Mahmoud and I. H. Ibrik, “Techno-economic feasibility of energy supply of remote villages in Palestine by PV-systems, diesel generators and electric grid.,” *Renewable and sustainable energy reviews,* vol. 10, no. 2, pp. 128-138, 2006.

[51] J. Schallenberg-Rodriguez, “A methodological review to estimate techno-economical wind energy production.,” *Renewable and Sustainable Energy Reviews,* vol. 21, pp. 272-287, 2013.

[52] N. I. Aain and M. S. Birkha, “TECHNICAL AND ECONOMICAL ANALYSIS ON THREE TYPES OF PHOTOVOLTAIC MATERIALS.,” *International Journal of Renewable Energy Resources,* vol. 6, no. 2, pp. 31-44, 2016.

[53] . W. De Soto, S. A. Klein and W. A. Beckman, “Improvement and validation of a model for photovoltaic array performance.,” *Solar energy,* vol. 80, no. 1, pp. 78-88., 2006.

[54] H. S. Das, A. Yatim, C. Tan and K. Lau, “Proposition of a PV/tidal powered micro-hydro and diesel hybrid system: A southern Bangladesh focus.,” *Renewable and Sustainable Energy Reviews.,* vol. 53, pp. 1137-1148, 2016.

[55] M. S. Ngan and C. W. Tan, “Assessment of economic viability for PV/wind/diesel hybrid energy system in southern Peninsular Malaysia.,” *Renewable and Sustainable energy reviews,* vol. 16, no. 1, pp. 634-647, 2012.

[56] A. Hiendro, R. Kurnianto, M. Rajagukguk and Y. Simanjuntak, “Techno-economic analysis of photovoltaic/wind hybrid system for onshore/remote area in Indonesia,” *Energy,* vol. 59, pp. 652-657, 2013.

[57] A. Brka, Y. M. Al-Abdeli and G. Kothapalli, “The interplay between renewables penetration, costing and emissions in the sizing of stand-alone hydrogen systems.,” *International Journal of Hydrogen Energy,* vol. 40, no. 1, pp. 125-135, 2015.

[58] O. M. Longe, K. Ouahada, F. C. Ferreira and S. Chinnappen, “Renewable energy sources microgrid design for rural area in South Africa,” in *IEEE ISGT*, America, 2014.